Investigative Study of Conjunctive Use Opportunities in the Stony Creek Fan Aquifer

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Abstract: A USGS MODFLOW model is developed to aid in understanding the interaction between Stony Creek and the underlying, unconfined Stony Creek Fan Aquifer near Orland, CA. Simplifying assumptions are used to simulate the aquifer boundary conditions and focus on the stream-aquifer interaction. The model is used to test various release patterns from the Black Butte Reservoir, located on Stony Creek, near the boundary of the Stony Creek Fan. Release magnitude, frequency, and duration are tested to estimate the volume of recharge that occurs through the streambed. Release efficiency, defined as the recharge volume divided by the release volume, is also evaluated. A preliminary benefit-cost analysis is presented for a hypothetical new yield from conjunctive use operations. Recommendations for further study include model refinements and suggested release patterns for recharge.

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CHAPTER ONE: INTRODUCTION

Conjunctive use is the integrated management of both surface and groundwater supplies. Commonly, conjunctive use involves using surface water supplies in periods of ample rainfall and runoff and groundwater supplies when surface water is limited or unavailable. The practice has been employed in California since the late 1890s with the diversion and spreading of stream flow in the channels of the San Antonio Creek (Banks et al. 1954).

The Stony Creek Fan aquifer (Figure 1.1) is an area that has been closely studied as a potential area for conjunctive use operations. The Orland-Artois Water District (OAWD), the Glenn-Colusa Irrigation District (GCID), and the Orland Unit Water User's Association (OUWUA) are particularly interested in conjunctive use operations in the fan and have sponsored modeling efforts and feasibility investigations (WRIME, 2003). The DWR and the US Bureau of Reclamation have also been involved in studies and data collection activities to assist in developing a conjunctive use management plan. The Stony Creek Fan is a shallow, unconfined aquifer underlying primarily agricultural lands and is connected to Stony Creek via saturate groundwater flow in much of the study area. Stony Creek originates in the eastern slopes of the Coastal Range and was dammed to create three surface water storage facilities for flood control, water supply, hydropower generation, and recreation purposes. The largest of these three reservoirs is Black Butte Lake that sits at the apex of the Stony Creek Fan aquifer and releases water into the lower reach of Stony Creek. Water released from Black Butte Lake flows down Stony Creek, providing the opportunity for natural infiltration into the unconfined aquifer below, before discharging into the Sacramento River.

This study is primarily focused on the stream-aquifer interaction between waters in Stony Creek and those in the underlying aquifer. To better understand the interaction, and to develop a tool for estimating optimal flows for recharge to the aquifer, a groundwater model of the Stony Creek Fan aquifer was developed. The purpose of this model is to assist in examining optimal conjunctive use release strategies from Black Butte Lake on a seasonal time frame that coincides with the operations of Black Butte for water supply and flood control. An optimal strategy for groundwater recharge is a pattern of releases that maximizes infiltration into the Stony Creek Fan aquifer. This strategy would be implemented in the late summer and fall when excess water is evacuated from the reservoir to increase flood control storage.

This report details the model development, calibration, and results, and provides a preliminary cost-benefit analysis of conjunctive use operations on the Stony Creek Fan.

Project Objective

The model is being developed for the Northern District of the DWR, who provided data, direction, and assistance throughout the model's development. The model is primarily conceptual in nature and focuses on the integrated management of ground and surface waters. It is not an attempt to improve modeling tools or methods for simulating the interaction between surface and groundwater. It will be used to better understand the aquifer system. Particular emphasis is placed on the stream-aquifer interaction between Stony Creek and the underlying aquifer. DWR personnel have found a significant natural recharge opportunity in this interaction. The streambed is composed of permeable material and the aquifer heads in wells near the stream indicate the aquifer water table is below the bottom of the stream. Additionally, wells near the stream show a seasonal rise in aquifer heads during the spring when flows in the nearby stream are high (Dudley, 2003). The model is used to explore how the stream can be used for conjunctive use operations.

Project Location

The Stony Creek Fan is an unconfined aquifer system between the Sacramento River on the east and the Coastal Range mountains on the west in the area underlying Orland, CA. The aquifer is mainly large areas of unconsolidated, unweathered gravel and sand, with areas of clay interspersed creating thinner layers between the gravel and sand (Dudley, 2004). The aquifer is approximately 20 miles wide from the mountains to the river, and 50 miles long from a few miles north of the creek to south of Willows, CA. A consulting firm estimated the approximate borders of the fan using digitized soil survey maps provided by Glenn County. The aquifer’s general size, shape, and location are shown in Figure 1.1.

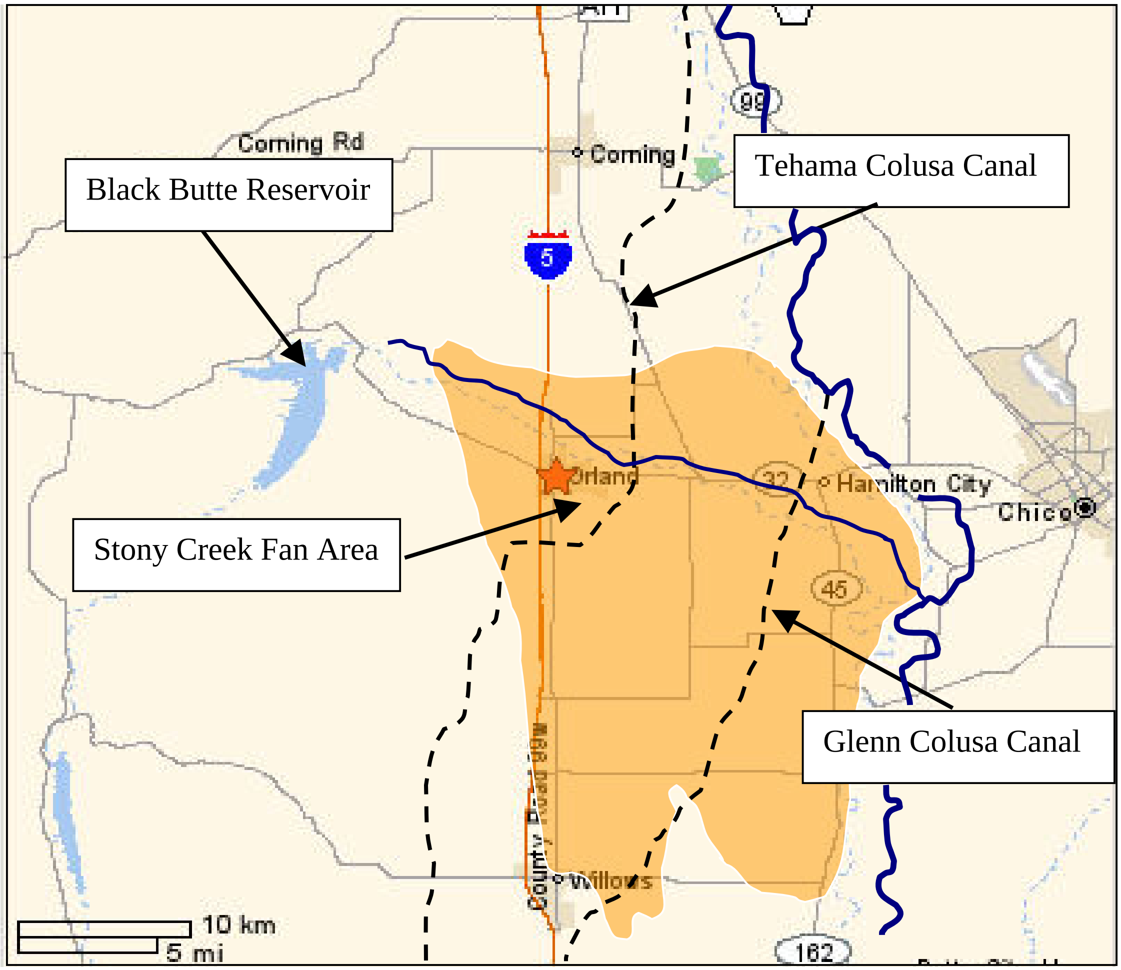

Figure 1.1 Project location.

This report will detail the development of the groundwater model, including the assumptions and limitations on the model's use. A chapter on model calibration compares the model performance against a four-month period of observed stream flows and well water elevations and discusses the model's sensitivity to specific parameters. Results of model response to various releases from Black Butte Reservoir are presented in chapter four. Chapter 5 is a preliminary benefit-cost analysis of some of the economic implications of conjunctive use management of the Black Butte Dam and Stony Creek. A summary of results and conclusions is also provided.

Literature Review

There is a significant volume of work covering conjunctive use operations and most studies show considerable benefit over independent management of surface and groundwater supplies. The following section provides a very brief summary of a few of the relevant articles covering a very active area of research and investigation.

Conjunctive Use in California

Coe provides a very good overview of conjunctive use (CU), particularly as it has been applied in California (Coe, 1990). He enumerates the advantages of CU while also detailing the significant physical, operational, institutional and legal issues that must be overcome to implement conjunctive use operations. The four case studies of successful California conjunctive use serve to highlight both the advantages and constraints. These case studies are located throughout the state to include the coastal plains of Los Angeles and Orange Counties, the Santa Clara Valley, and Kern County.

Maddock provides a general study of conjunctive use operations for a generic stream and aquifer system with uncertain supplies and demands (Maddock, 1974). He offers that it is possible to develop management and operating rules to optimally manage (by reducing costs) the system over time. Basagaoglu and Marino present a similar study for conjunctive management of a generic stream-aquifer system (Basagaoglu and Marino, 1999).

Matsukawa et al. provide a more specific study of conjunctive use through the development of a conjunctive use planning and management model and its application to the Mad River Basin on the North Coast of California (Matsukawa et al, 1992). The optimization model incorporates the groundwater and surface water hydraulics with the costs and benefits of water supply, hydropower, and groundwater. The basin is similar to the Stony Creek Fan and includes a single, multi-purpose reservoir, a stream reach that is hydraulically connected to the aquifer and used for surface water diversion, and an area of groundwater pumping. The model demonstrated the advantages of conjunctive use operation for the basin and provided insight into potential operational decisions to increase benefits over a one-year planning period.

Pulido-Velazquez, Jenkins, and Lund present a more recent and specific study of the potential economic values of conjunctive use and water banking in southern California (Pulido-Velazquez, Jenkins, and Lund, 2004). This study examines the interrelated benefits derived from conjunctive use and water market transfers and shows there is considerable value to be gained from the simultaneous application of both.

Knapp and Olson present results showing limited value of conjunctive use operations in Kern County (Knapp and Olson, 1995). Their model does not show artificial recharge to be economically beneficial. However, they note it may still be an important management strategy in other areas and under different circumstances.

Conjunctive use operations often require cooperation on a regional basis among numerous water districts. As noted by Coe, often institutional and legal constraints are the most prohibitive to establishing CU operations. Foley-Gannon provides an overview of these constraints, offers a theoretical statewide model for operations within the current legal framework, and recommends legal reforms to further conjunctive use (Foley-Gannon, 2000).

The National Heritage Institute completed one of the largest conjunctive use studies in California in 1998. The feasibility study looked at conjunctive use on a statewide basis including re-operation of numerous large reservoirs, the suitability of various banking locations around the state, and perhaps most importantly the legal and institutional issues surrounding large-scale conjunctive-use operations (NHI, 1998). The study estimated that large-scale CU operations could generate approximately 1 million acre-feet of new yield annually in the state at a very reasonable cost compared to the development of additional surface storage (NHI, 1998).

Groundwater Model Calibration

A significant portion of this project involves the development and calibration of a groundwater model to simulate the interaction between the stream and aquifer. The process of groundwater model calibration is well documented in the literature. Model calibration is often referred to as solving the inverse problem wherein the modeler knows the results the model should produce, but must determine the correct mix of parameter values to produce those results.

There are numerous different methods for parameter identification and estimation. Yeh (1986) provides one of several reviews of different procedures used to solve the inverse problem. He covers techniques for determining spatial aquifer parameters and methods for estimating the uncertainty in those parameters. McLaughlin and Townley (1996) provide a more recent assessment of the inverse problem as it relates to hydrogeology. They present a method using functional analysis to estimate the parameters as scalar spatial functions rather than vectors of variables. They apply this technique to the estimation of hydraulic conductivity and suggest its suitability for estimation of boundary flux and transport parameters. Other methods suggested in the literature include a statistical approach suggested by Carrerra and Neuman (1986), where the inverse problem is solved using maximum likelihood theory based on some prior knowledge of the aquifer parameters. Hoeksema and Kitanidis (1985) also present a statistical method for estimating how parameters are spatially distributed and interrelated. They attempt to correlate changes in parameter values and changes in location with the first and second statistical moments. Neuman, Fogg, and Jacobson (1980) provide an earlier statistical method and apply the method to a basin in southern Arizona.

The model in this study was calibrated through a trial and error process and the solution to the inverse problem is not unique. The problem of non-unique sets of parameter values that provide reasonable solutions to the inverse problem has also been well described in the literature (McLaughlin and Townley, 1996). More recent work has examined ways to limit the number of possible solutions through the use of transport modeling. Castro and Goblet (2003) look at four solutions to the flow equations for a regional aquifer in Texas with sparse information on aquifer parameters, and test them using an independent tracer to evaluate how the aquifer parameters model transport. Using this method three of the four solutions are invalidated. A similar technique is applied to three different sets of calibrated parameter values for an aquifer in Florida (Saiers, Genereux, and Bolster, 2004). The three sets of parameter values were determined by calibrating the model based only on head, head and a boundary flux, and head, boundary flux, and chloride concentration. They found that the addition of information other than head values was critical in improving model performance and limiting the solutions to the inverse problem.

Stony Creek Fan

The Stony Creek Fan has been modeled as part of previous conjunctive use studies. The natural recharge opportunity through the creek, and the ability to regulate creek flow through the outlets at Black Butte Reservoir make it a good potential area for conjunctive use operations. The largest and most recent study was conducted by WRIME Inc. and funded by the Glenn-Colusa Irrigation District, Orland-Artois Water District, and Orland Unit Water Users' Authority. This study created a large surface and groundwater model, using DWR's Integrated Groundwater and Surface Water Model (IGSM) as a base and refining it for the Stony Creek Fan and surrounding areas. The objective of the project was to develop an analytical tool to provide quantitative information and compare various conjunctive use alternatives (WRIME, 2003). The IGSM model included a larger geographic region, four aquifer layers, and additional surface water flows in Thomes Creek (approximately 15 miles north of Stony Creek), a longer reach of the Sacramento

River, and the Glenn Colusa Canal and Colusa Basin Drain. The study provided more flexibility for evaluating different regional conjunctive use operations but did not provide the same level of detail for the interaction between Stony Creek and the upper, unconfined Stony Creek Fan. WRIME used IGSM version 6.0 as the starting base code for of the model, and modified the code to suit this application. The code should be free from the problems identified with IGSM version 5.0 (LaBolle, Ahmed, and Fogg, 2003).

In addition to the Stony Creek Fan IGSM study there is also a Stony Creek Fan Conjunctive Water Management Program Feasibility Investigation ongoing. This study evaluates various conjunctive water management alternatives from a technical, institutional, legal, and economic perspective (WRIME, 2003). The results of this study are not yet available.

The upper reaches of Stony Creek, and Little Stony Creek in particular, have also been studied. Rains and Mount (2004) have done considerable research on the shallow groundwater tables near Little Stony Creek and East Park Reservoir. Their work includes a groundwater model of the unconfined aquifer near the creek and reservoir that is used to estimate the effect of various surface water operational strategies on vegetation.

Additional studies covering the Stony Creek Fan and surrounding areas are listed below:

- Groundwater Flow in The Central Valley, California, Regional Aquifer System Analysis (RASA), 1989, USGS Professional Paper 1401-D.
- Groundwater Modeling in Upper Sacramento Valley, 1979, DWR, Northern District
- Evaluation of Groundwater Resources in Sacramento Valley, 1978, DWR Bulletin 118-6

- Geologic Features and Groundwater Storage Capacity of the Sacramento Valley, California, F. H. Olmstead and G. H. Davis, 1961, USGS Water Supply Paper 1497.
- Progress Report on Groundwater Development Studies, North Sacramento Valley, 1976, DWR Northern District, Memorandum Report

This study focuses on the specific interaction between Stony Creek and the Stony Creek Fan to investigate the opportunity for recharge. This focus is much narrower than any of the listed studies or models. It was developed using stream flow measurements and well water elevations collected specifically for the purpose of developing a groundwater model.

CHAPTER TWO: GROUNDWATER MODEL DEVELOPMENT

Software Package

The modeling software used is USGS MODFLOW (1996 version) to include the block-centered flow, stream, and recharge packages. MODFLOW is the most widely used groundwater-modeling software and uses a finite difference approach to solve the groundwater flow equations. I used a pre and post-processing program called Groundwater Vistas to create the MODFLOW data files and interpret the results. Vistas also provides a graphical user interface that helps to visualize the model area and results.

Hydrogeology of the Fan

The Stony Creek Fan is hydrogeologically bordered on the west by the Coastal Range and on the east by the Sacramento River. Borders on the north and south edges of the fan are more difficult to define with certainty. To the south of the fan, no large streams leave the Coastal range to deposit coarse alluvial material, so this area is believed to be comprised of smaller, less permeable deposits (DWR, 1978). The area north of the Stony Creek Fan is also comprised of significantly less permeable deposits (DWR, 1978).

Deposits in the Stony Creek Fan are from two sources: alluvial fan deposits from the creek and alluvium deposits from the Sacramento River (DWR, 1978). It is difficult to determine where these two materials meet, and it is likely that they are interspersed in the areas close to the river. The Sacramento River floodplain is about 6 kilometers wide between Red Bluff and Colusa (DWR, 1978). The lithologic character of both deposits is unconsolidated gravels and sands, interspersed with varying amounts of silt and clay beds (WRIME, 2003). Both types of deposits are Quaternary and date to the Holocene epoch (WRIME, 2003). The average thickness of the fan is approximately 80 feet, with thinner areas along the eastern and western borders. The bottom of the fan is not easily distinguished and, according to well logs, does not appear to be uniform. A thick clay layer, up to 100 feet thick, separates the Stony Creek Fan from the underlying Tehama formation. The top of this clay layer is assumed to be the bottom of the Stony Creek Fan. During deposition of the fan, Stony Creek meandered across various streambeds creating and abandoning many channels in time (WRIME, 2003). These channels were then buried to create a complex system of fine and coarse-grained material. There are likely pockets and areas of high and low permeability in the fan that are difficult to estimate and model.

Stony Creek Fan is a thin aquifer on top of the much thicker and older Tehama formation. The Tehama formation is a semi-confined and confined aquifer that underlies most of the area between the Sacramento River and the Coastal Mountains (DWR, 1978). The Tehama formation is comprised of Tertiary and Quaternary deposits whose age is from upper Pliocene to middle Pleistocene. Deposits are moderately consolidated sandstone and siltstone, with pockets of varying size and composition of sands and gravels (WRIME, 2003). WRIME (2003) estimates the hydraulic conductivity of the Tehama formation within the range of 40 to 300 ft/day, the exact calibration value was not provided. The hydraulic connection between the overlying Stony Creek Fan and the Tehama formation is not well known (WRIME, 2003). Estimates of the fluxes from the WRIME model are not available. As mentioned, a thick clay layer separates the two formations over at least a portion of the Stony Creek Fan. Further studies are needed and recommended to more accurately determine the aerial extent of this layer and verify the assumption of limited connection between these two aquifers.

Conceptual Model

The conceptual model is perhaps the most important step in groundwater modeling as an incorrect or incomplete conceptual model will not provide accurate results, even if well calibrated (Bredehoeft, 2003). There are three main components of a conceptual model: hydrostratigraphy, the water budget, and the flow system (Anderson and Woessner, 1992). Each of these is discussed in greater detail in the following sections.

Hydrostratgraphic Units

The Stony Creek Fan will be modeled as a single-layer, unconfined aquifer. A single-layer model assumes there is no change in how water flows vertically. The Stony Creek Fan consists primarily of bands of coarse sands and gravels. It also contains some clay layers, of spatially varying thickness. These clay layers act to retard vertical flow and so the fan is not vertically homogenous. However, estimating the location of these clay layers is beyond the scope and objectives of this study. The influence of the clay layers is discussed in the later chapters on streambed conductivity. The thickness of the fan layer will be estimated from well construction logs.

Water Budget

The water budget, how and at what rates water flows into and out of the model area, is the primary focus of the conceptual model. This modeling effort is concerned with the interaction between the aquifer and Stony Creek, but other means of water movement across system boundaries must be considered. In addition to the stream flux, other water inflows and outflows include,

- ☐ groundwater pumping
- ☐ flow in and out of adjacent and underlying aquifers
- ☐ interaction with the Sacramento River
- ☐ deep percolation of precipitation and applied irrigation water
- ☐ evapotranspiration.

To develop the conceptual model, some assumptions are made to limit the focus of the model to the significant sources and sinks. One of the primary considerations is the length of the model calibration period and end purpose of the model in exploring aquifer response to different Stony Creek flow patterns in the late summer and fall. The four-month, seasonal calibration period, and focus on stream-aquifer interaction allow some modes of water movement to be ignored.

It is assumed that flow between the Stony Creek Fan and adjacent and underlying aquifers can be ignored for the purpose of this study. Aquifer material bordering Stony Creek Fan is significantly less permeable than materials within the fan based on well construction logs, so flux across these boundaries may be limited. Similarly, well construction logs indicate a clay layer, up to 100 feet thick separating the alluvial fan deposits from the underlying Tehama formation. Construction logs located throughout the fan showed evidence of this layer. It is assumed the leakage across this layer is minimal during a four-month simulation period. This is a working assumption to be validated or disproved during model calibration. It would not be valid for a long-term simulation model. These assumptions likely have a limited effect on flux across the stream-aquifer boundary in the short term, because in most areas the stream is not near these boundaries. It is difficult to predict the effect on the stream-aquifer flux if these assumptions are not valid, as they may serve to both increase and decrease the flux across that boundary.

The model is being developed for a summer and early fall calibration and simulation period. It is expected that this is the time when excess surface water supplies would be available for groundwater recharge. This is the period after agricultural water needs have been met or are at least well identified. Any water in excess of these needs and encroaching in the reservoir flood control space will be available for recharge. During this period groundwater pumping and deep percolation of applied irrigation water are important factors in the water budget. However, this is typically a time of limited precipitation. Evapotranspiration from crops is included indirectly in the calculation of deep percolation of applied surface water, as explained later in this chapter. Evapotranspiration from native grasslands located primarily on the western edge of the fan is ignored in the conceptual model; this assumption will be examined during the model calibration. Evapotranspiration from trees near Stony Creek and in other areas of the model was not included, but is an area for future improvement of the model.

Interaction between the aquifer and the Sacramento River depends on river stage and water levels in the aquifer. Currently it is believed that the aquifer tends to contribute water into the river along the Stony Creek Fan, although the amount has not been quantified. Regional head maps indicate a gradient that slopes from the northwest corner, south and east toward the Sacramento River. However, during dry periods with increased pumping, aquifer heads near the river may be drawn down so flow is from the river into the aquifer in some areas of the fan.

Flow System

The general trend of flow from the Stony Creek Fan has been studied by DWR for many years. Based on contour maps developed from well-water elevations at different times of the year, the general flow of groundwater is from the northwest apex of the fan, near Black Butte Reservoir, to the southeast toward the Sacramento River. Contours show a trend of groundwater mounding in the vicinity of Stony Creek during the winter and spring seasons, with the mound slowly flattening during the summer and fall periods of lower creek flows. Pumping from irrigation wells in the center section of the fan also lowers water levels.

Initial Model Parameters

The grid size, time step, stress periods, and layers were selected early in the model development. The model was created as a single layer, unconfined aquifer. A grid size of 2,000 feet by 2,00 feet was selected based loosely on knowledge of the variations in head gradients in the aquifer. The grid spacing was reduced to 1,000 in both directions in the area of Stony Creek to provide better resolution of the head gradients.

Time steps in the model were held at a constant one-day because when testing the aquifer response to various release patterns into Stony Creek, there was a need to vary the releases on a daily basis.

Stress periods were determined based on the data available for calibration. Lengths were decided based on the shortest period of varying model inputs. Transient model inputs include stream flows in Stony Creek and net recharge values based on land use and irrigation. The calibration data set included weekly varying stream flows. Data on evapotranspiration of applied water (ETAW), which is used to calculate a net recharge, are collected monthly. Therefore, the model was developed with weekly stress periods, containing seven, uniform time-steps of one day. After the initial model development and calibration, the stress period was changed to daily to enable the reservoir release pattern to change on a daily basis. It may be possible to improve the model performance with more accurate evapotranspiration data developed with the Simulation of Evapotranspiration of Applied Water (SIMETAW) model (DWR, 2005). The use of daily evapotranspiration data from the California Irrigation Management Information System (CIMIS) Orland gage may also improve the model accuracy. However, CIMIS data are not available for many of the crop types being grown in the model area.

Boundary Conditions

Setting boundary conditions for water moving in and out of the model grid is the next step in model development. Boundary conditions are specified along the edges of the model grid, a stream boundary condition represented the stream-aquifer interaction, and the initial heads file is used for starting conditions. Each boundary condition is explained below.

Stream Boundary Conditions

The interaction between Stony Creek and the underlying aquifer is the primary subject of interest for this model. Stream boundary conditions in MODFLOW can be simulated with either the stream or river package. The stream package is used because of its additional features.

One advantage of using the stream package (instead of the river package) for modeling Stony Creek is the capability of the stream package to perform a simple surface routing down the stream reaches. It also handles situations where all stream flow seeps into the aquifer by setting the flow in all downstream reaches to zero. This capability is important because of the range of potential releases to be tested when exploring release patterns. The stream package is a form of a general head boundary condition, where the modeler specifies a conductance, or terms used by the model to calculate a conductance, and a specified head, and the model calculates a flux for each cell by the equation,

$$\text{Flux} = \text{Conductance}*(\text{head}_{\text{specified}} - \text{bottom of streambed elevation}) \tag{2.1a}$$

when the material between the aquifer and stream is not fully saturated ($head_{aquifer} <$ bottom of the streambed elevation), and

$$\text{Flux} = \text{Conductance}*(head_{specified} - head_{aquifer}) \tag{2.1b}$$

when the materials are fully saturated ($head_{aquifer} >$ bottom of the streambed elevation). In the stream package the conductance is calculated as,

$$\text{Conductance} = -K_{streambed}*\text{Length}*\text{Width}/\text{Thickness of the Streambed} \tag{2.2}$$

Where Length = length of the streambed in the model cell

Width = average width of the streambed in the model cell

Data for the stream boundary condition are entered into each model cell containing the stream. Model cells for the stream were selected by overlaying the grid on a map of the stream and aquifer fan. The model currently has 126 stream cells, or MODFLOW stream reaches. The 126 stream cells are divided into five different stream sections where stream parameters within a section are constant. These five sections were set based on the location of stream flow and cross-sectional measurements made during collection of the calibration data.

Stony Creek, where it flows atop the aquifer, is treated as a simple stream with no tributary inflow or agricultural returns or diversions, during the model time period. This translates to a single stream segment in MODFLOW, where a segment is a stream section with inflow only at the first reach and outflow only at the last reach. In reality there are returns and diversions from Stony Creek between the reservoir and the Sacramento River. However, these were accounted for in the calibration data set by including them in the mass balance equations used to estimate stream flux. It is assumed their affect on aquifer heads is minimal.

Streambed lengths in each cell were estimated by measuring the line segments on the map imported into Groundwater Vistas using a measuring feature in Vistas. The stream widths range from 58 to 102 feet for the five different sections of Stony Creek in the model. The model could be improved with more detailed stream cross-sectional data or a stage-area curve for different sections of the stream. Currently, there are no additional stream cross-sections available for Stony Creek between Black Butte Reservoir and the Sacramento River, other than those collected as part of the calibration data.

The top of the streambed was estimated as a constant difference from the model ground surface elevation for each cell. It was assumed that the top of the streambed is approximately four feet below the ground surface elevation in the surrounding model cell. The four-foot difference was based on the maximum water depth during the collection of stream flow data in 2003. The maximum depth was measured as 3.15 ft, and was increased to four feet to account for freeboard in the stream at the time of the data collection. Actual field measurements or observations of the stream and surrounding topography would verify or improve this assumption.

The streambed conductivity and thickness are calibration parameters in the model. No physical data exist on the thickness of the streambed material. These parameters were changed within a reasonable range to match the estimated stream gains and losses from the 2003 calibration period. These two values contribute to the overall conductance factor for the general head boundary condition (equation 2.2). Because both parameters contribute to the overall conductance, there are likely to be multiple, non-unique combinations of plausible streambed conductivity and thickness values that provide reasonable agreement with observed stream fluxes.

The stream package routes surface water using Manning's Equation.

$$Q = (1.486/N)*(A*R^{2/3}*S^{1/2}) \tag{2.3}$$

Where Q = stream flow in cubic feet per second

N = Manning's roughness coefficient

A = cross sectional area of flow in square feet

R = hydraulic radius in feet

S = slope of the stream channel

Flow is made available instantaneously to all downstream reaches. This assumption is generally considered valid because surface water velocities are typically much greater than groundwater velocities (Prudic, 1989). A uniform Manning's roughness coefficient, n, of 0.025 is used in all stream cells. This n value is on the lower end of the range for a clean, straight natural channel (Prudic, 1989). Estimating the starting and ending streambed elevations, and then dividing by the total stream length, estimates an approximate stream slope.

The specified head value in equations 2.1a and 2.1b is either provided by the modeler or calculated by MODFLOW based on the flow. MODFLOW calculates the depth of the water by rearranging Manning's equation and assuming stream depths are much smaller than stream widths to simplify the calculation of cross-sectional area and wetted perimeter (Prudic, 1989). MODFLOW then adds the calculated depth to the streambed elevation to estimate the head in the stream.

It can be difficult to get the stream package to converge when the model calculates the stream stage/specified head term because the stream stage, stream flux, and aquifer head are all being solved for and depend on the other two terms. I was unable to get the model to converge when it was set to calculate the stream stage and therefore I specified the stage as recorded by DWR personnel when making the stream flow measurements for the calibration data.

Specified Head Boundary Conditions

The Sacramento River along the eastern border of the aquifer is modeled as a specified head boundary condition. It is assumed the aquifer is fully saturated below the riverbed, so the heads are the heads of the river. River stage is recorded a few miles upstream of the fan, at the Vina-Woodson Bridge, and near the southern portion of the aquifer, at Ord's Ferry. Daily stage data were downloaded from the California Data Exchange Center (CDEC) website. Daily data were converted to weekly averages coinciding with the model stress periods to estimate how much the stage varied over the calibration period. The average weekly stages varied by approximately two feet and therefore a period average head for each station was used as constant head values for each river cell. Lengths of the river in each cell were estimated with linear line segments in Groundwater

Vistas, and used to calculate a slope of the stage between the two gage stations. The stage in individual cells was calculated using the slope and river length.

No Flow Boundary Conditions

The northern, western, and southern borders of the model are assumed to be no flow cells. This assumption is based on large differences between hydraulic conductivity of the fan materials and those in the surrounding formations. Based on discussions with Toccoy Dudley, head of the groundwater section, Northern District of DWR, the conductivity may vary by four to five orders of magnitude (Dudley, 2004). This is consistent with a limited number of well construction logs reviewed for areas bordering the fan that show thick clay deposits over most of the fan depth. Historical groundwater elevation maps show contours that are largely perpendicular to the fan boundaries, supporting this assumption. The perpendicular contours indicate a head gradient parallel to the fan border, creating flow lines along the border and limiting flux normal to the border. However, the number of data points used to develop the maps is unknown and may not be sufficient to support this conclusion.

This assumption is likely valid for the purposes of this study. However, some water probably crosses these boundaries. These boundaries also could be modeled as general head boundary conditions with a specified head and conductance term to allow some flux in and out of the model. Based on historic groundwater elevations, there is likely some flow coming in from the northern and western model boundaries and flowing out the southern boundary. These boundaries are far enough away from Stony Creek and the calibration period is short enough that this assumption is probably adequate for this study.

Initial Heads

Initial head estimates are needed for each cell in the model. Several options exist for creating an initial head file. I used water surface elevations from a set of wells screened only in the upper, unconfined aquifer to create a Surfer grid file of water table elevations. Starting with these wells, elevations in the weeks and months surrounding the start of the calibration period were reviewed to establish a more consistent elevation. Wells with erratic data, perhaps influenced by nearby pumping wells, were not used. Additionally, using only finite points to create the initial head surface results in unnatural high points when contoured in Surfer. Preliminary model runs using these initial head files developed a groundwater mound along a line of well data points south of Stony Creek. This gradient prevented recharge from the creek from reaching the southern portion of the fan and did not agree with field observations. Therefore it was necessary to add estimated water surface elevations in the northwest corner of the fan where no well data are available. These additional points created a more accurate initial head surface. A total of 23 wells, and three estimated points were entered into Surfer to create a grid file containing an initial head for each model cell. The Surfer grid file is read prior to making a model run in Vistas.

Other options for creating an initial head file include running a steady-state model to equilibrium and creating a model “warm up period” prior to the calibration or simulation period. In either option the initial heads have some time to come to equilibrium prior to attempting to mirror observed data. Extending the model period to cover an entire year, or at least a few months prior to the calibration period may improve the model performance. As shown in the next chapter, the model proved very sensitive to the initial head file. Combining an initial head file created in Surfer with a short calibration period showed some tendencies for the model to spend the first few stress periods either filling in holes or flattening out high points in the initial head file.

Additional Data Requirements

After the boundary conditions were decided, the aquifer properties were estimated. These properties included the ground surface elevation, aquifer thickness, hydraulic conductivity, and net recharge values.

Hydraulic Conductivity

Transmissivity and the storage coefficient were estimated from data collected during a pumping test conducted by DWR in the aquifer. The data were analyzed using a spreadsheet to fit the Theis solution to the data (Charbeneau, 2000). Draw down data were available from two co-located observation wells and estimated transmissivity and storage coefficients were similar for both wells. Transmissivity ranged between 30 and 50 ft^2/minute, and the storage coefficient between 0.00001 and 0.00003. The aquifer is approximately 70 feet thick at the test site, and therefore the hydraulic conductivity is approximately 820 ft/day. This value is within the range of unconsolidated sand and gravel, but is likely too high for the aquifer average given the presence of clay layers in the aquifer (Charbeneau, 2000). This value was used as an initial estimate for both K_x and K_y in the entire fan. Additional pumping tests from other locations in the fan would be useful in estimating hydraulic conductivity. Lacking further field data, hydraulic conductivity is a calibration parameter in the model. Values used in previous studies will be used to verify conductivity determined through calibration.

Specific Yield

An initial value of ten percent is assumed for the specific yield. This value is in the range associated with fine sands and assumed to be representative of the average aquifer value even though most of the aquifer is comprised of more coarse sand and gravel (Charbeneau, 2000). This assumption was tested during the calibration process and the model sensitivity to this parameter explored.

Ground Surface Elevations

The ground surface elevations were estimated using Surfer and data from the well data library at DWR. Data included the UTM coordinates of the wells and the ground surface elevation at the well. Data were available for 66 wells throughout the Stony Creek Fan. The data were passed to Surfer as an XYZ formatted set along with the grid size and spacing used in the model. Surfer then created a grid file of the individual cell elevations based on the data. It is possible to import the Surfer grid file directly into the model with Groundwater Vistas. Elevations estimated in Surfer were then checked against existing USGS topographic maps.

A digital elevation map was also obtained from DWR and checked in the model. However, the elevations did not match those obtained with Surfer and the well heads or the USGS maps. The model could be improved with the use of a more accurate digital elevation map.

Aquifer Thickness

The well construction logs at DWR provided the information for estimating the aquifer thickness. The file for every well located in or near the approximate area of the Stony Creek Fan was reviewed and the well drilling log, when available, was examined for the driller's comments on layer materials and thickness. Logs that recorded thick layers of coarse sand and gravel, bound on the bottom by thick clay layers, and known to be inside the borders of the fan were used to estimate the bottom of the aquifer. The top of the confining clay layer was assumed to be the bottom of the unconfined aquifer and the depth to that layer was subtracted from the well's ground surface elevation to get an aquifer bottom elevation. The aquifer thickness ranges from 35 to 106 feet with an average thickness of 73 feet. A data set of 33 wells with UTM coordinates and aquifer bottom elevations was imported into Surfer to create a grid file of the layer bottom elevations. The Surfer grid file was imported directly into Vistas and aquifer bottom elevations assigned from the file.

Recharge Values

In addition to the Stony Creek-aquifer interaction, the second primary method for water to enter and exit the aquifer is through net recharge values calculated for each grid cell.

The net recharge for each cell was based on the land use within the cell. Most lands overlying the aquifer are used for agriculture. For these areas, the recharge values were also based on the source of irrigation water, either groundwater, surface water, or mixed, and an assumed irrigation efficiency. Land use and water supply data from 1998, the most recent comprehensive survey conducted by DWR, were combined with a geo-referenced model grid to create a large data set detailing the land use and water supply for every portion of every grid cell. This data set was then combined with data on applied water and evapotranspiration of applied water (ETAW) from 2000 to estimate the recharge occurring for each combination of land and water use. Land uses from the 1998 survey were more detailed than those the Department uses to track water use. Therefore, 1998 land uses were aggregated into 31 different categories matching those used to track water source as well as more general uses such as urban areas and idle lands. An initial assumption was made to set the net recharge to zero for all non-agricultural areas including native riparian vegetation, native pastures, urban areas, and idle lands. Model sensitivity to this assumption was tested during calibration.

An assumption also was made to reduce the water supply sources to ground, surface, or none. It was assumed that areas with a “mixed” source in 1998 most likely used surface water because surface water supplies were adequate during the calibration period. The net recharge value for areas without an identified water source was zero.

A net recharge value was calculated for the agricultural areas with an identified water source based on the estimated ETAW calculated by DWR and assumed irrigation efficiency. DWR estimates ETAW numbers each month, therefore net recharge is a transient variable in the model that changes approximately every four stress periods. Irrigation efficiencies were assumed to be 80% for all areas on ground water, 50% for rice patties on surface water, and 70% for all other areas on surface water. These assumptions are based on estimates provided in personal communication with Toccoy Dudley at DWR, who is familiar with the area and local irrigation practices (Dudley, 2004). The assumed irrigation efficiencies do not include ETAW or irrecoverable losses as defined and described below.

Equations for recharge in groundwater and surface water irrigated areas were developed from the basic equation:

$$\text{ETAW} + \text{Irrecoverable Losses} + \text{Deep Percolation} = \text{Applied Water} \tag{2.4}$$

Irrecoverable losses include evaporative losses during conveyance of irrigation water and water that runs off of fields and flows down the Sacramento River to the Pacific Ocean. Additionally, it is assumed that the irrecoverable losses are 10% of ETAW and that,

$$\text{Applied Water} = \text{ETAW}/\text{Efficiency}_{\text{irrigation}} \tag{2.5}$$

The deep percolation can then be expressed in terms of ETAW and irrigation efficiency as,

$$\text{Deep Percolation} = \text{ETAW}/\text{Efficiency}_{\text{irrigation}} - 1.1*\text{ETAW} \tag{2.6}$$

This equation is used to estimate the net recharge values for areas irrigated with surface water. For areas irrigated with groundwater, it is assumed that the applied water is taken from the same area that it is applied to, so the net recharge for these areas is equal to the irrecoverable losses and the ETAW,

$$\text{Deep Percolation} = \text{Net Recharge}_{\text{groundwater}} = -1.1*\text{ETAW} \quad (2.7)$$

A weighted average of the recharge values for each cell was calculated as the summation of all land use and water supply combinations, multiplied by the area of the cell containing that combination, divided by the total area of the cell. Net recharge values were converted into units of feet/day and imported directly into Groundwater Vistas for each stress period.

Net recharge values did not consider precipitation during the calibration period. The Orland, CA precipitation gage records were reviewed for rainfall during the calibration period. In July, September, and October there was less than 0.2 inches of rain. In August there was 1.03 inches and in November 3.61 inches. It was assumed that only some of this small amount of water would contribute to groundwater levels, and for the purpose of this study it could be ignored.

Model Limitations

The model was developed to investigate potential conjunctive use operations between Black Butte Reservoir and the Stony Creek Fan aquifer. The calibration period will allow some confidence in the model results when testing other release patterns and flows down Stony Creek. However, the model should be considered more conceptual than predictive because of the limited data and short calibration period.

The model is developed for a specific set of land uses. Significant changes in land use and irrigation methods would require revised calculations of recharge and perhaps additional calibration. It would not be difficult to update the model with new land use data as it becomes available.

The model is also only valid for periods of very low precipitation, such as the late summer and fall period used for calibration. It would be possible to adjust the recharge values to include precipitation during other times of the year, but this would likely require recalibration. The model is also being calibrated at the end of the agricultural season as irrigation begins to taper off. The model would not be applicable for the winter or spring when precipitation and irrigation are greater, and initial soil moisture would be higher.

CHAPTER THREE: MODEL CALIBRATION

The process of model calibration can be described as "…a process that uses a model to achieve a match between the recorded (i.e. historic) and simulated distribution(s) of dependent variable(s) by choosing a range of possible values of the independent variable(s)." (AWWA, 2001). Historical values are needed as calibration targets and to establish the similitude of those historical values with model results. This section discusses the historical data used as calibration targets, potential errors associated with the data, and the goals for how closely the model must match the data. The model parameters varied to match those targets, ranges of acceptable parameters, and final values for calibration also are covered. The model sensitivity to changes in these parameters concludes this chapter.

Calibration Data

The model was calibrated against five months of data collected in the summer and fall of 2003. In anticipation of a model being developed, DWR coordinated with the US Bureau of Reclamation to make a series of releases of excess water from Black Butte Reservoir at several release rates. Starting in mid-July, releases ranging between 30 cfs and 350 cfs were made from the reservoir and maintained for one week. Releases were made for 17 weeks, until mid-November. During this time, DWR personnel collected water table elevations in wells near Stony Creek and measured stream cross-sections and flow rates at five different points along Stony Creek. Stream measurements were taken using a Price Current meter that typically has an accuracy of +/- 8% for streams with coarse bottoms and cobbles. Figure 3.1 shows the location of the stream measurements.

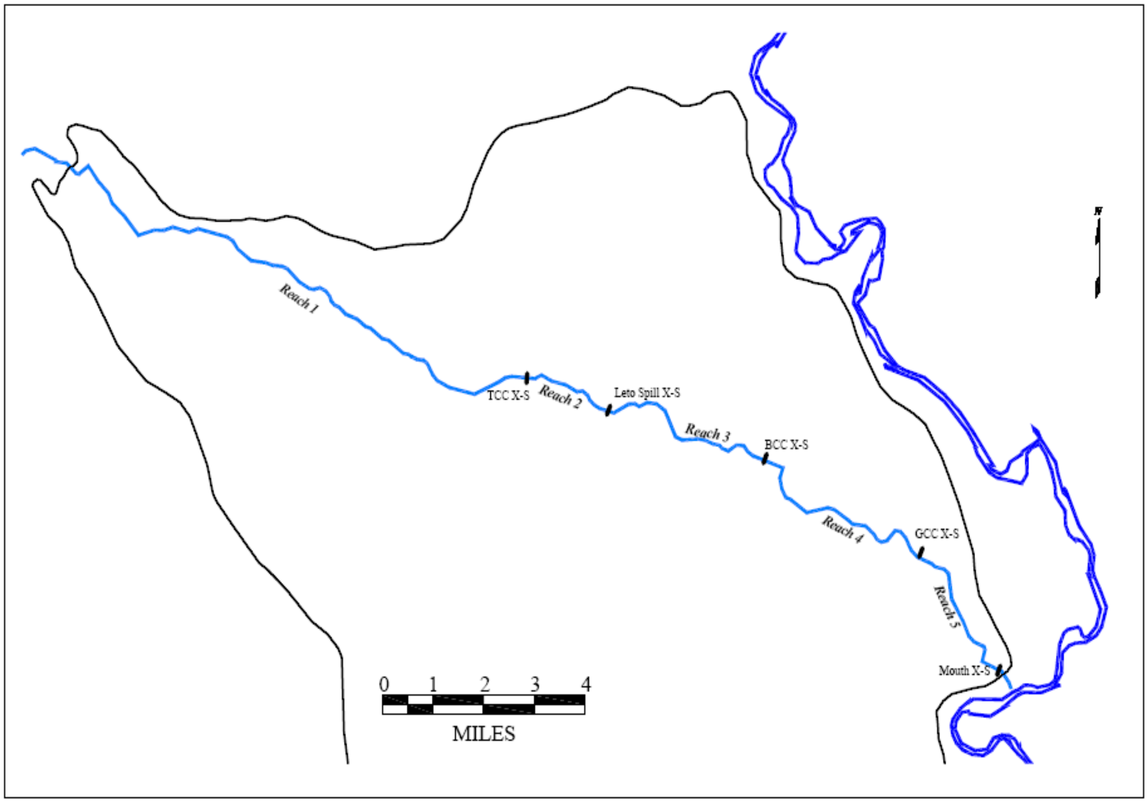

Figure 3. 1 Stream measurement locations.

The stream flow measurements were analyzed to estimate gaining and losing sections of Stony Creek. In the upper reaches of the creek there were agricultural returns and local irrigation that likely increased flows. The USBR provided estimates of these stream gains to improve the accuracy of the stream loss estimates (Kibby, 2004). The stream flow measurements, adjusted for the agricultural returns, combined with the known reservoir releases, provide estimated fluxes between the stream and aquifer for use in combination with observed well water surface elevations. Table 3.1 provides the gain or loss per stress period as well as the percent loss of the total stream flow.

Observed Stream Gains/Losses and Percent of Release Lost (Mcf/d)													
Release	**Return Flows**	**Reach 1**		**Reach 2**		**Reach 3**		**Reach 4**		**Reach 5**		**Total Stream Loss**	**Total % Loss**
		(Gain)/ Loss	**% Gain/ Loss**	**(Gain)/ Loss**	**% Gain/ Loss**	**(Gain)/ Loss**	**% Gain/ Loss**	**(Gain)/ Loss**	**% Gain/ Loss**	**(Gain)/ Loss**	**% Gain/ Loss**		
4.32	4.41	0.05	0.9%	No Measurement		No Measurement		2.42	27.8%	No Measurement		No Measurement	
7.00	3.20	1.15	14.4%	2.34	22.9%	0.84	8.2%	2.76	27.0%	1.10	10.8%	8.19	80.3%
8.64	3.11	1.81	18.3%	No Measurement		No Measurement		2.67	22.7%	1.28	10.9%	10.17	86.5%
7.86	3.24	2.92	27.9%	No Measurement		No Measurement		2.22	20.0%	1.99	18.0%	7.78	70.0%
4.58	2.98	0.18	3.8%	No Measurement		No Measurement		No Measurement		No Measurement		No Measurement	
7.52	2.33	0.44	4.9%	0.52	5.2%	1.27	12.9%	2.20	22.4%	1.67	17.0%	6.10	61.9%
21.69	3.07	(2.71)	-12.1%	1.82	7.4%	0.40	1.6%	7.11	28.7%	5.23	21.1%	11.85	47.9%
30.24	4.88	3.43	10.6%	1.73	4.9%	1.55	4.4%	2.17	6.2%	1.25	3.6%	10.13	28.8%
25.75	3.80	(0.77)	-2.8%	3.09	10.4%	1.56	5.3%	1.87	6.3%	0.10	0.3%	5.84	19.8%
9.00	3.89	0.59	6.0%	3.21	25.1%	0.37	2.9%	1.91	15.0%	0.36	2.8%	6.44	50.3%
25.49	2.25	(0.47)	-1.8%	2.25	8.1%	(1.32)	-4.8%	5.71	20.6%	0.05	0.2%	6.22	22.4%
8.64	4.10	2.39	23.0%	2.27	17.8%	(0.13)	-1.0%	1.61	12.7%	1.45	11.4%	7.59	59.6%
25.92	2.98	1.48	5.6%	1.39	4.8%	0.95	3.3%	2.66	9.2%	0.77	2.7%	7.25	25.1%
25.92	2.20	0.55	2.1%	0.06	0.2%	(1.55)	-5.5%	3.50	12.5%	1.00	3.5%	3.56	12.7%
8.64	3.50	1.27	12.1%	0.44	3.6%	1.24	10.2%	1.74	14.3%	1.10	9.1%	5.78	47.6%
2.59	5.79	(0.05)	-1.1%	3.83	45.7%	1.01	12.0%	1.82	21.7%	1.04	12.4%	7.65	91.3%
2.59	0.00	0.10	3.7%	(0.11)	-4.4%	0.67	26.0%	0.99	38.0%	7.60	29.3%	2.40	92.7%
2.68	0.00	0.21	7.9%	(0.18)	-6.9%	0.71	26.5%	0.95	35.3%	8.20	30.6%	2.50	93.4%
Averaged Observed Loss			6.9%		10.4%		7.3%		20.0%		11.5%		55.7%

Table 3.1 Observed stream reach gains, losses, and percent loss.

Table 3.1 shows the upper stream reaches gain a small amount of water during some weeks in the calibration period. A check was made of these weeks against observed local well water elevations. Local well water surfaces are still significantly below the bottom of the streambed elevation. The gaining reaches can be explained in several ways. Most gains are small and within the range of stream measurement error. Gains may also indicate unaccounted for agricultural returns. Perhaps groundwater mounding directly below the streambed puts the aquifer in connection with the stream without significantly raising heads in the closest monitoring wells. Small, perched aquifers also may be in close proximity to the bottom of the streambed.

The average loss rates indicate the majority of recharge occurs in the lower two reaches, close to the Sacramento River, while the upper reach has the lowest loss. The upper reach is located partly in the foothills of the Coastal Range where the streambed slope is higher and water flows faster. The lower reaches overlie an area of higher groundwater extraction where aquifer heads may be lower. Also, there is more riparian vegetation along Stony Creek in some of the lower reaches.

Table 3.1 also shows the fluxes vary widely with time and release rate and are likely functions of additional factors not fully understood. A limited number of variables within the MODFLOW stream package can be used to calibrate the stream flux, and of those variables only the width and stage of the stream will vary with release. DWR recorded both of these terms while measuring stream flow for the calibration data. The other terms that affect flux such as streambed thickness and conductivity and stream length will not vary with time. Therefore, instead of attempting to match the flux as estimated in each reach, for each date, the calibration target is to match, within one percent, the average percent lost for each reach. The average percent lost gives a more general trend to the stream losses during the modeling period and an attainable goal for calibration.

In addition to the stream flow measurements, DWR personnel collected weekly data at 23 wells located along the entire length of Stony Creek. Of these wells, 17 are screened only in the Stony Creek Fan and were used as targets for comparison against calculated model heads.

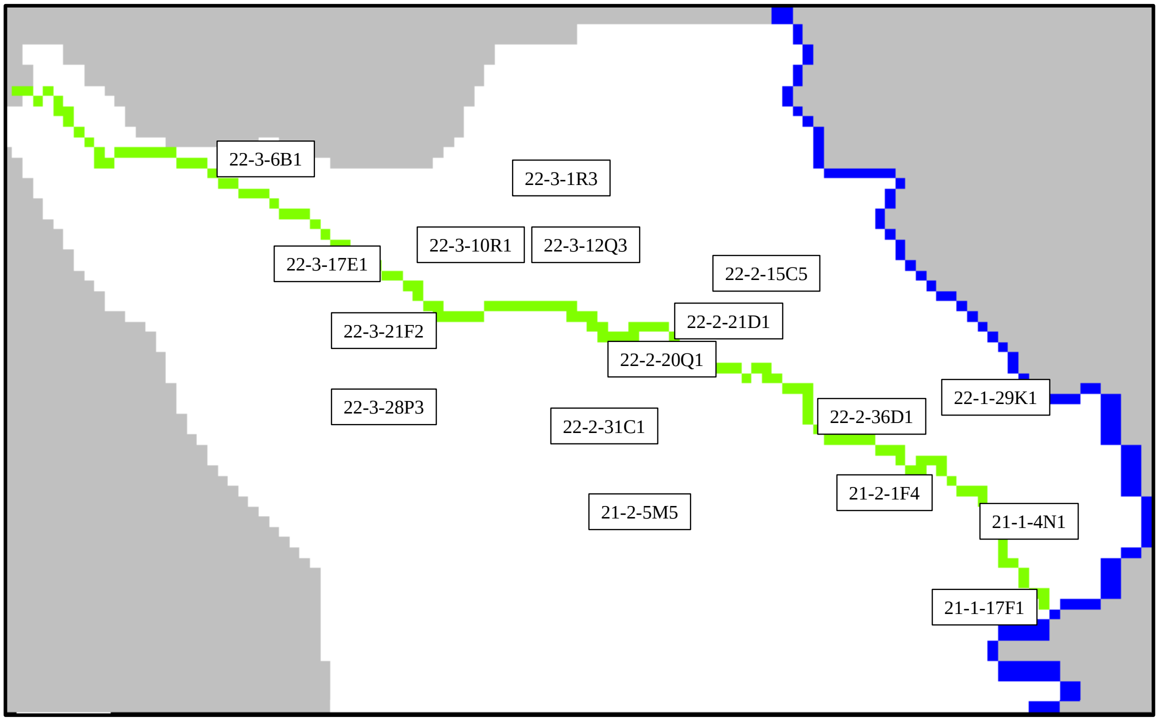

Figure 3.2 Location of calibration wells.

The observed well elevations show trends in certain areas of the fan throughout the model period. For example, the groundwater elevation in ten of the eleven wells south of Stony Creek stayed level or declined during the model period, while those to the north of the

Creek rose. This may indicate that the majority of recharge from the creek flows to the north, or a trend of heterogeneity of aquifer parameters. Many of the observation wells show erratic, short-term spikes and declines in groundwater level. These may be due to pumping in nearby irrigation wells or measurement error.

The range in observed heads is 161 feet. The quantitative calibration goal for the observed versus measured aquifer heads is for the maximum and minimum residuals to be within ten percent of the observed range and the absolute mean residual to be within five percent of the observed head range. Additionally, 95% of all residuals should be within 10% of the observed range. It is recognized that the short time period for calibration allows less opportunity for serious deviations from observed heads. Therefore a qualitative review of the general trend of the observed versus the modeled head is needed to ensure the model is adequately calibrated. Common general calibration statistics including the mean residual, standard deviation of the residuals, sum of the residual squares, and mean of the absolute residuals will be used to evaluate the effect of parameter changes on the entire model.

Calibration Parameters

Limited physical data are available for aquifer parameters and pumping. Model parameters were varied to estimate the model's overall sensitivity to those parameters, while attempting to match the observed groundwater surface elevations and stream fluxes. As mentioned in the previous chapter, though not a true calibration parameter, the model is extremely sensitive to changes in the initial head file.

Hydraulic Conductivity

The initial conductivity estimate of 820 feet/day calculated from the aquifer performance test is likely too high for an average hydraulic conductivity for this aquifer. It is within the range of conductivity for unconsolidated gravels and sands, but the Stony Creek Fan contains layers of clay and other fine material. Additionally, other sources including studies by DWR and modeling by Montgomery Watson Harza (MWH) establish a range of conductivity between 10 and 350 feet/day (DWR, 1979; MWH, 2002). During calibration the conductivity was varied between the range of 1 and 750 feet/day. At higher values of conductivity the water in the higher elevations of the aquifer, the northwest corner, drained quickly down gradient and into the Sacramento River. Without any additional water entering the model through the north or western border the water levels in these sections dropped significantly, though no cells completely dried out. A conductivity of 40 ft/day for the entire model area created the best agreement between modeled and observed heads. However, such a low value created significant groundwater mounding below the stream cells and prevented the model from being able to match estimated stream fluxes. Therefore a final value of 75 ft/day was used to match both the calibration targets for observed heads and stream fluxes.

Specific Yield

Model heads were not very sensitive to changes in specific yield. It was initially estimated that the specific yield was ten percent based on knowledge of the aquifer materials. Specific yield was varied from five to fifteen percent with limited effect on the model heads. Modeled heads improved in some calibration wells while getting worse in most wells. The fluxes across boundaries were sensitive to changes in specific yield. A 5% decrease in Sy resulted in approximately a 5% increase in flux across the stream and river boundaries. A 5% increase in Sy created a slightly larger decrease in flux across the same boundaries. The current value in the model is the original ten percent.

Recharge

During calibration the assumptions made in calculating the cell recharge values were also reviewed. Reviewing head profiles of observed versus modeled heads showed clear points of inflection in the modeled head levels occurring at the time step corresponding to the beginning of a new month, when the recharge values change. It was also noted that most wells showed too strong of a response to recharge values, either gaining or losing too much water depending on the water source. The recharge values were reduced by fifty percent to diminish their effect on model heads. Initial recharge values were likely too high due a combination of high ETAW, higher assumed irrecoverable losses, or too low of an estimated irrigation efficiency. Further research into the recharge values is recommended to improve the model in the future.

A few wells still do not follow the overall trend of the observed heads due to the recharge values in the cells containing and surrounding the well. While it is possible to correct these discrepancies by altering the recharge values, additional research into the land use and water source is required prior to doing so. There have been land use changes since the last DWR survey in 1998 that are not accounted for in the model. Additionally, some areas have both surface and groundwater available to them and may switch between sources depending on the availability of each. Including these land use and water source updates would improve the model for other purposes, but the effect on recharge through the stream is likely limited.

Streambed Conductance

To easily vary the streambed parameters in the model and calculate accurate conductance values a separate Excel spreadsheet and macro were developed to create the MODFLOW stream package files. The spreadsheet and macro provided an easier and more refined method than that offered in Groundwater Vistas.

For model calibration the measured widths and stages were used for each stream reach. The streambed material thickness was assumed to be a constant three ft along the entire length of the creek and the streambed hydraulic conductivity was varied to match the average stream losses from the calibration data. Model stream flows were recorded at the same locations as actual stream measurements on the appropriate time step. The average stream losses throughout the model period were then compared with the calibration goal and adjustments made to the streambed conductivities in each reach. The final results are provided in Tables 3.2 and 3.3.

Model Stream Flows and Percent of Release Lost (Mcf/d)													
Time Step	**Release (Mcf/d)**	**Reach 1**	**% Loss**	**Reach 2**	**% Loss**	**Reach 3**	**% Loss**	**Reach 4**	**% Loss**	**Reach 5**	**% Loss**	**Total Loss**	**Total % Loss**
7	7.00	6.47	7.5%	5.80	9.6%	5.28	7.5%	3.88	20.0%	1.83	29.3%	5.17	73.9%
14	8.64	8.06	6.7%	7.29	8.9%	6.94	4.1%	5.31	18.8%	3.47	21.4%	5.18	59.9%
21	7.86	7.29	7.3%	6.59	8.9%	6.01	7.3%	4.36	21.0%	3.06	16.5%	4.80	61.1%
28	4.58	4.06	11.4%	3.43	13.8%	3.04	8.4%	0.00	66.4%	0.00		4.58	100.0%
35	7.52	7.05	6.3%	6.35	9.3%	5.87	6.4%	4.45	18.9%	3.20	16.7%	4.32	57.5%
42	21.69	20.91	3.6%	19.90	4.7%	19.18	3.3%	16.51	12.3%	15.29	5.6%	6.40	29.5%
49	30.24	29.37	2.9%	28.08	4.3%	26.85	4.1%	24.70	7.1%	23.58	3.7%	6.66	22.0%
56	25.75	25.00	2.9%	23.82	4.6%	22.75	4.2%	20.82	7.5%	19.83	3.8%	5.92	23.0%
63	8.90	8.38	5.9%	7.67	8.0%	6.89	8.7%	5.67	13.8%	4.84	9.3%	4.06	45.6%
70	25.49	24.75	2.9%	23.69	4.2%	22.65	4.1%	20.72	7.6%	19.75	3.8%	5.74	22.5%
77	8.64	8.06	6.7%	7.29	8.9%	6.94	4.1%	5.72	14.1%	5.05	7.8%	3.59	41.6%
84	25.92	25.08	3.2%	23.94	4.4%	22.87	4.1%	21.22	6.4%	20.43	3.0%	5.49	21.2%
91	25.92	25.08	3.2%	24.01	4.1%	22.94	4.1%	21.46	5.7%	20.72	2.9%	5.20	20.1%
98	8.64	8.06	6.7%	7.33	8.5%	6.97	4.1%	5.95	11.9%	5.37	6.6%	3.27	37.8%
105	2.59	2.29	11.8%	1.75	20.7%	1.37	14.8%	0.47	34.5%	0.15	12.3%	2.44	94.2%
112	2.59	2.29	11.8%	1.75	20.8%	1.36	14.8%	0.44	35.6%	0.04	15.4%	2.55	98.4%
119	2.68	2.28	14.8%	1.74	20.0%	1.23	19.2%	0.25	36.5%	0.00	9.5%	2.68	100.0%
Average Modeled Loss			6.8%		9.6%		7.2%		19.9%		10.5%		53.4%
Averaged Observed Loss			6.9%		10.4%		7.3%		20.0%		11.5%		55.7%
Calibrated Streambed K (ft/d)			0.10		1.00		0.45		0.85		3.60		

Table 3.2 Calibrated model stream reach flows and losses.

Observed and Modeled Fluxes as Percent of Release Lost													
Release (Mcf)	**Time-Step (days)**	**Reach 1**		**Reach 2**		**Reach 3**		**Reach 4**		**Reach 5**		**All Reaches**	
		Observed	**Modeled**	**Observed**	**Modeled**	**Observed**	**Modeled**	**Observed**	**Modeled**	**Observed**	**Modeled**	**Observed**	**Modeled**
7.00	7	14.4%	7.5%	22.9%	9.6%	82.0%	7.5%	27.0%	20.0%	10.8%	29.3%	80.3%	73.9%
8.64	14	18.3%	6.7%	N/A	8.9%	N/A	4.1%	22.7%	18.8%	10.9%	21.4%	86.5%	59.9%
7.86	21	27.9%	7.3%	N/A	8.9%	N/A	7.3%	20.0%	21.0%	18.0%	16.5%	70.0%	61.1%
4.58	28	3.8%	11.4%	N/A	13.8%	N/A	8.4%	N/A	66.4%	N/A	N/A	N/A	100.0%
7.52	35	4.9%	6.3%	5.2%	9.3%	12.9%	6.4%	22.4%	18.9%	17.0%	16.7%	61.9%	57.5%
21.69	42	-12.1%	3.6%	7.4%	4.7%	1.6%	3.3%	28.7%	12.3%	21.1%	5.6%	47.9%	29.5%
30.24	49	10.6%	2.9%	4.9%	4.3%	4.4%	4.1%	6.2%	7.1%	3.6%	3.7%	28.8%	22.0%
25.75	56	-2.8%	2.9%	10.4%	4.6%	5.3%	4.2%	6.3%	7.5%	0.3%	3.8%	19.8%	23.0%
9.00	63	6.0%	5.9%	25.1%	8.0%	2.9%	8.7%	15.0%	13.8%	2.8%	9.3%	50.3%	45.6%
25.49	70	-1.8%	2.9%	8.1%	4.2%	-4.8%	4.1%	20.6%	7.6%	0.2%	3.8%	22.4%	22.5%
8.64	77	23.0%	6.7%	17.8%	8.9%	-1.0%	4.1%	12.7%	14.1%	11.4%	7.8%	59.6%	41.6%
25.92	84	5.6%	3.2%	4.8%	4.4%	3.3%	4.1%	9.2%	6.4%	2.7%	3.0%	25.1%	21.2%
25.92	91	2.1%	3.2%	0.2%	4.1%	-5.5%	4.1%	12.5%	5.7%	3.5%	2.9%	12.7%	20.1%
8.64	98	12.1%	6.7%	3.6%	8.5%	10.2%	4.1%	14.3%	11.9%	9.1%	6.6%	47.6%	37.8%
2.59	105	-1.1%	11.8%	45.7%	20.7%	12.0%	14.8%	21.7%	34.5%	12.4%	12.3%	91.3%	94.2%
2.59	112	3.7%	11.8%	-4.4%	20.8%	26.0%	14.8%	38.0%	35.6%	29.3%	15.4%	92.7%	98.4%
2.68	119	7.9%	14.8%	-6.9%	20.0%	26.5%	19.2%	35.3%	36.5%	30.6%	9.5%	93.4%	100.0%
Average Flux		6.9%	6.8%	10.4%	9.6%	7.3%	7.2%	20.0%	19.9%	11.5%	10.5%	55.7%	53.4%

Table 3.3 Observed and modeled fluxes.

The streambed conductivities in some reaches are lower than expected values for gravel and sand streambeds. One possible factor is the presence of clay layers interspersed in the aquifer. Well construction logs at DWR indicate that many wells in the fan have clay layers of from five to twenty feet, interspersed throughout the gravel and sand alluvial deposits. The logs were examined for the presence of these gravel and clay layers and the presence of a substantially thicker clay layer, twenty or more feet thick, which was assumed to be the bottom of the unconfined aquifer.

The limited data in the well construction logs and other sources makes it difficult to estimate the size and location of these clay layers in the unconfined aquifer. In a single layer, unconfined MODFLOW model it is impossible to account for the retardation of downward flow caused by such clay layers because the K_z term is not used. Therefore, the streambed conductance, and more specifically the streambed hydraulic conductivity, is used to approximate the effect of clay layers on infiltration of stream flow from Stony Creek.

The presence of clay layers also may account for some sections of the stream gaining water from the aquifer during the calibration period. It is possible that some of the layers lie below the streambed and create small, perched aquifers that may contribute water back into the stream even though the water surface elevation in surrounding wells is too low to be in contact with the streambed.

An alternative method for calibration is to use the estimated stream flux based on the flow measurements as source terms in the model and then calibrate the aquifer hydraulic conductivity to match observed heads. Once the aquifer parameters are determined then the method for calibrating the streambed parameters described above could be used.

Calibration Results

The parameter values described above met the calibration targets and provided a reasonable representation of stream flux and well water levels. While additional adjustments, particularly to the recharge files for certain cells could improve the overall model agreement, there is insufficient information to justify such changes. Table 3.2 presented the calibration for the stream fluxes. Table 3.4 provides the overall model calibration statistics and the percent of residuals within certain ranges. A scatter plot of all computed and measured heads is provided as Figure 3.3. Appendix A contains plots of the simulated versus observed heads for each of the wells used in calibration. Appendix B contains plots showing residuals and the locations of residuals within the model for each time step with an observed measurement. These plots provide an indication of model agreement in various areas and how the agreement changes as the simulation progresses.

Model Calibration Results (ft)	
Residual Mean	0.642
Res. Std. Dev.	3.920
Sum of Squares	4,401.367
Abs. Res. Mean	3.069
Min. Residual	(10.097)
Max. Residual	15.836
Range	161.000
Std/Range	0.024
Percent of Residuals within 2.5% of Range	69.53%
Percent of Residuals within 5% of Range	94.62%
Percent of Residuals within 7.5% of Range	99.64%
Percent of Residuals within 10% of Range	100.00%

Table 3.4 Model Calibration Results

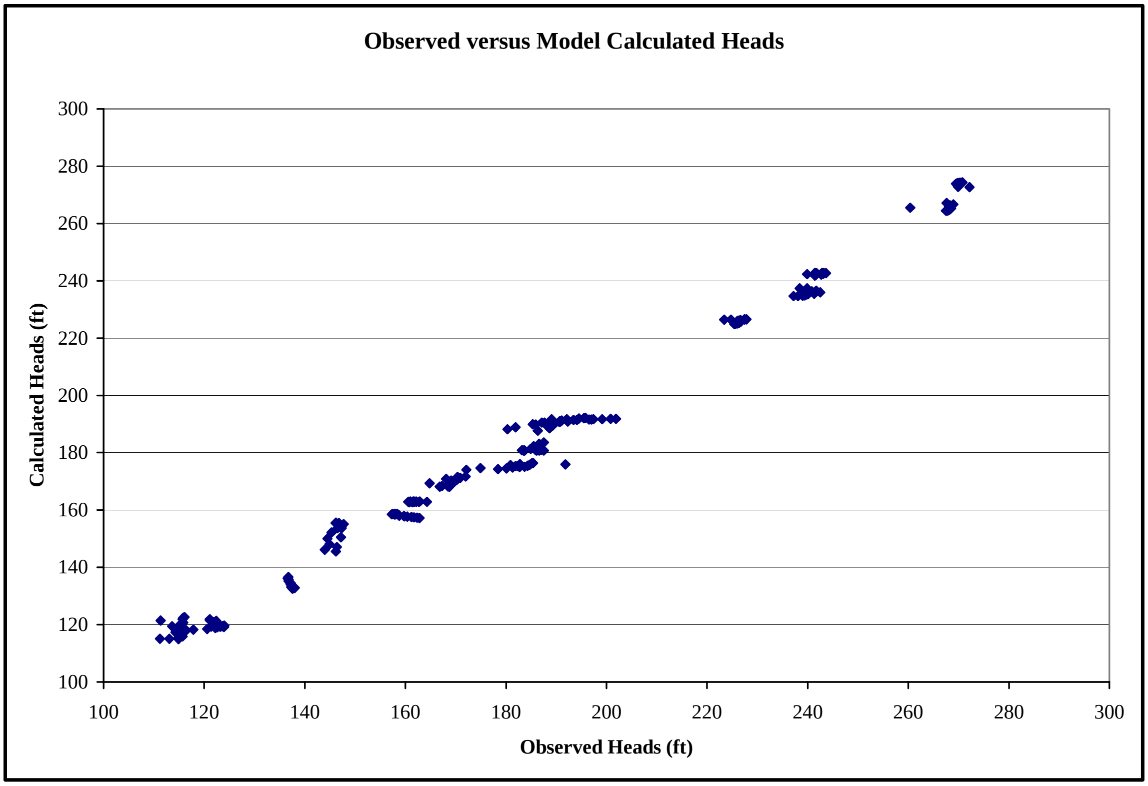

Figure 3.3 Scatter plot of observed and calculated heads.

Sensitivity Analysis

During the calibration process the model's sensitivity to changes in the calibration parameters was discovered and noted. Table 3.5 provides a qualitative discussion of changes to the most of the parameters.

Parameter	Range	Remarks
Aquifer Hydraulic Conductivity	40 – 750 ft/day	Lower values of K result in slightly better agreement between model and observed heads, however, significant mounding occurs below the stream cells and prevents agreement between estimated and computed stream flux. Higher values of K result in significant differences between model and observed heads and drainage from higher elevation model areas.
Specific Yield	5-15 %	Model heads are not sensitive to changes within the probable range of specific yields. Flux across boundaries varies approximately + or – 5% for a 5% reduction or increase respectively in Sy.
Recharge	Original to ½ of ETAW values	The model is sensitive to changes in recharge. Using ½ of the original ETAW values provides good agreement. Additional research and data collection are required to vary the recharge values in specific areas of the model to improve results.

Table 3.5 Model Sensitivity to Calibration Parameters.

A more formal sensitivity analysis on the streambed hydraulic conductivity is warranted because of the emphasis on the stream-aquifer interaction. The streambed K values were varied from the calibrated values by plus and minus one order of magnitude to examine the effect on the total stream flux during the simulation period. The results of this analysis are provided in Table 3.6 and show increasing the streambed K significantly has less of an impact than a significant reduction in streambed K.

Total Stream Recharge during Simulation (Mcf)	
Order of Magnitude Higher	713.8
Calibrated	512.4
Order of Magnitude Lower	93.3

Table 3.6 Model sensitivity to changes in streambed conductivity

CHAPTER FOUR: SIMULATION RESULTS

After the model was developed and calibrated, model runs were made using different reservoir releases to test the effect of various release magnitudes, durations, and frequencies. The end goal of the model runs is to estimate the optimal release pattern for recharging the aquifer. Black Butte Reservoir is typically drawn down prior to the start of the flood control season. The volume of water that must be evacuated varies with the hydrology of the year and the demands. In dry years there is no additional water to release while in wet years there can be as much as 50 TAF (Kibby, 2004). This chapter discusses the types of release patterns tested and the results.

Release Magnitude

The first model runs were to simulate a constant release rate for the entire simulation period. Constant release rates range from 25 to 350 cfs, which represent total volumes of 6 to 83 TAF released from the reservoir over the 119-day simulation period. Table 4.1 and Figure 4.1 present the results of different magnitudes of release.

Release Rate (cfs)	Release Volume (af)	Recharge Volume (af)	Spill to River (af)	Recharge Efficiency
25	5,901	5,901	0	100.0%
50	11,802	10,434	1,368	88.4%
75	17,703	10,932	6,771	61.8%
100	23,604	12,219	11,384	51.8%
125	29,505	13,063	16,442	44.3%
150	35,405	13,510	21,896	38.2%
175	41,306	13,916	27,390	33.7%
200	47,207	14,294	32,913	30.3%
225	53,108	14,653	38,455	27.6%
250	59,009	14,998	44,011	25.4%
275	64,910	15,339	49,571	23.6%
300	70,811	16,344	54,467	23.1%
325	76,712	16,736	59,976	21.8%
350	82,613	16,915	65,698	20.5%

Table 4.1 Recharge volumes and efficiency for various constant release rates.

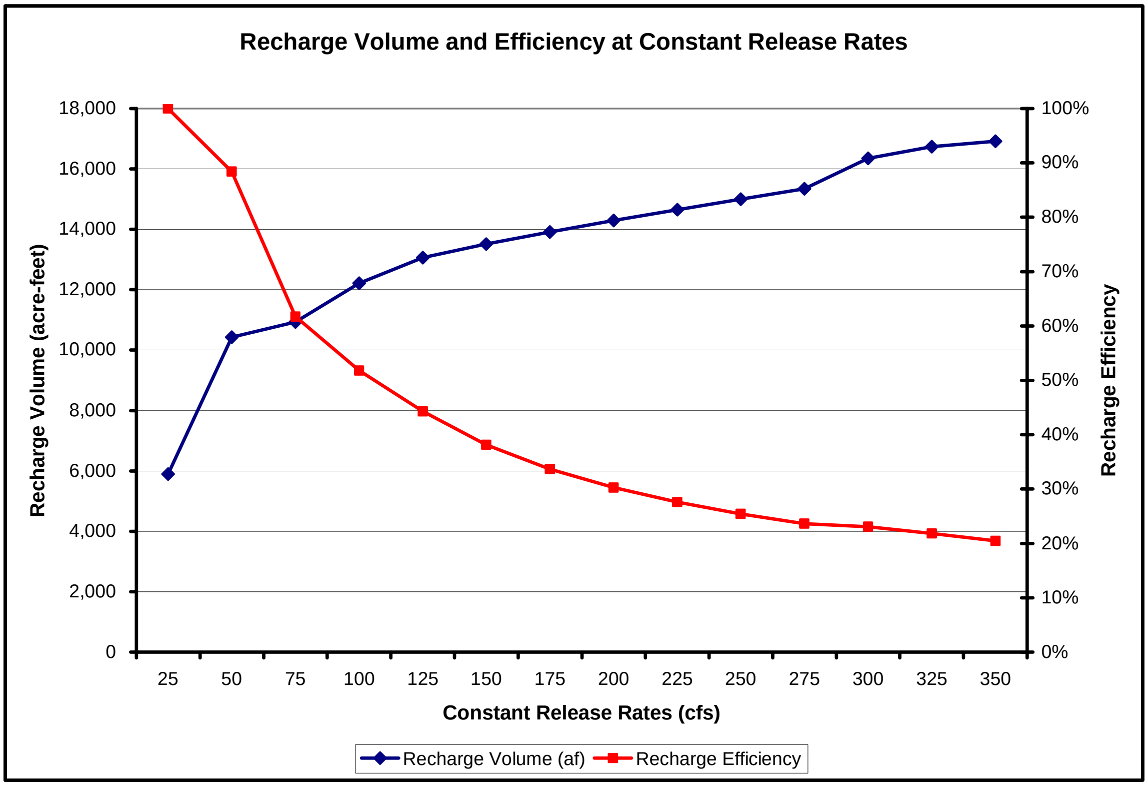

Figure 4.1 Recharge volumes and efficiency for various constant release rates.

These results show that it is possible to continue to increase the total volume of recharge to the aquifer by continuing to increase the release rate, however, the recharge efficiency, recharge volume/release volume, continues to decline at higher releases. The results in Figure 4.1 show the trade off between recharge and efficiency and that high release rates should be avoided, when possible.

The sensitivity of the results to changes in the aquifer hydraulic conductivity was also examined to provide a range of potential recharge volumes. The aquifer conductivity varies spatially across the fan, and 75 ft/day is estimated to be representative of the average conductivity. To provide a better understanding of the recharge potential, the aquifer K was varied by plus and minus one order of magnitude from 7.5 to 750 feet per day. Figure 4.2 shows a range of recharge volume, at each constant release rate that would be expected depending on the true aquifer K value.

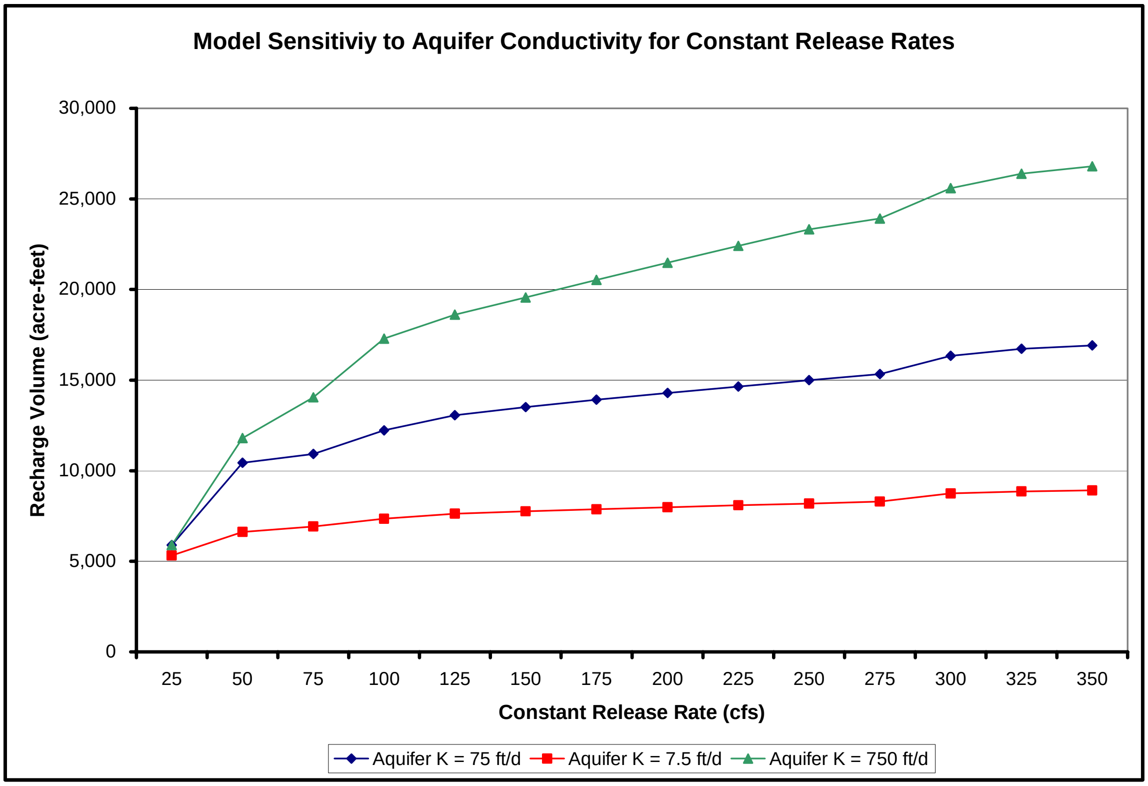

Figure 4.2 Sensitivity of recharge volume to aquifer hydraulic conductivity.

Pulses at a Set Release Rate

In addition to selecting the correct magnitude for release, there may be benefit in analyzing release patterns that send pulses of water down Stony Creek. Based on the simulations at various magnitudes, pulses of varying duration but a constant release rate of 50, 75, 100, and 125 cfs were simulated.

Initial estimates for the optimal release duration were made based on heads in the stream cells from the simulations for different magnitudes. Plots of the head levels over time were reviewed to determine the point when heads began to flatten out. Figure 4.3 is a plot of aquifer head versus time for one cell with a stream boundary condition. It shows the head increases quickly from day one to day 25 and increases slowly for the remainder of the simulation period.

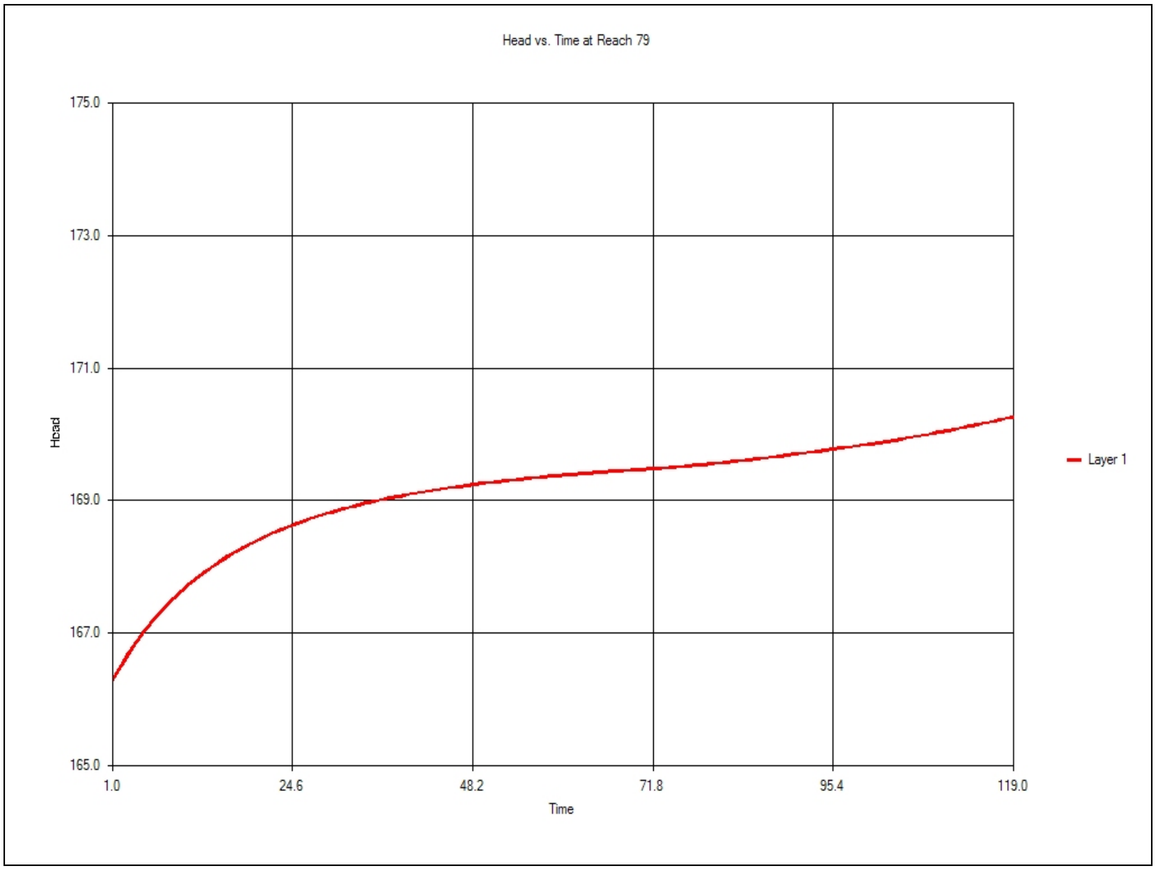

Figure 4.3 Stream cell model head with time for a constant release rate of 100 cfs.

At higher flow rates the heads flatten out more quickly than at lower flow rates. This information was used as a starting point when experimenting with different durations of release. Heads in ten different stream cells, dispersed down the model stream segment, were reviewed at several different release rates. Plots of the heads over time indicated in most cells the heads increased quickest during the first 25 days of the simulation. Therefore, initial model runs for duration sent pulses of water down the creek for 15, 20, 25, 30, and 35 days. A 7-day recovery period between pulses was initially selected to allow the aquifer to recover and for the groundwater mound in the stream cells to flow to adjacent cells. The results of these model runs are presented in Table 4.2 and Figures 4.4 and 4.5.

Release Rate (cfs)	Days On	Days Off	Total Days On	Release Volume (af)	Recharge Volume (af)	Spill to River (af)	Recharge Efficiency
50	15	7	84	8,331	7,973	357	95.7%
	20	7	91	9,025	8,506	518	94.3%
	25	7	98	9,719	9,010	709	92.7%
	30	7	98	9,719	9,017	702	92.8%
	35	7	105	10,413	9,507	906	91.3%
75	15	7	84	12,496	8,438	4,058	67.5%
	20	7	91	13,537	8,966	4,572	66.2%
	25	7	98	14,579	9,476	5,103	65.0%
	30	7	98	14,579	9,471	5,108	65.0%
	35	7	105	15,620	9,973	5,647	63.8%
100	15	7	84	16,661	9,581	7,081	57.5%
	20	7	91	18,050	10,148	7,901	56.2%
	25	7	98	19,438	10,698	8,740	55.0%
	30	7	98	19,438	10,693	8,745	55.0%
	35	7	105	20,826	11,230	9,597	53.9%
125	15	7	84	20,826	10,357	10,469	49.7%
	20	7	91	22,562	10,963	11,599	48.6%
	25	7	98	24,298	11,531	12,766	47.5%
	30	7	98	24,298	11,529	12,769	47.4%
	35	7	105	26,033	12,071	13,962	46.4%

Table 4.2 Recharge volumes and efficiency for various release durations and magnitudes.

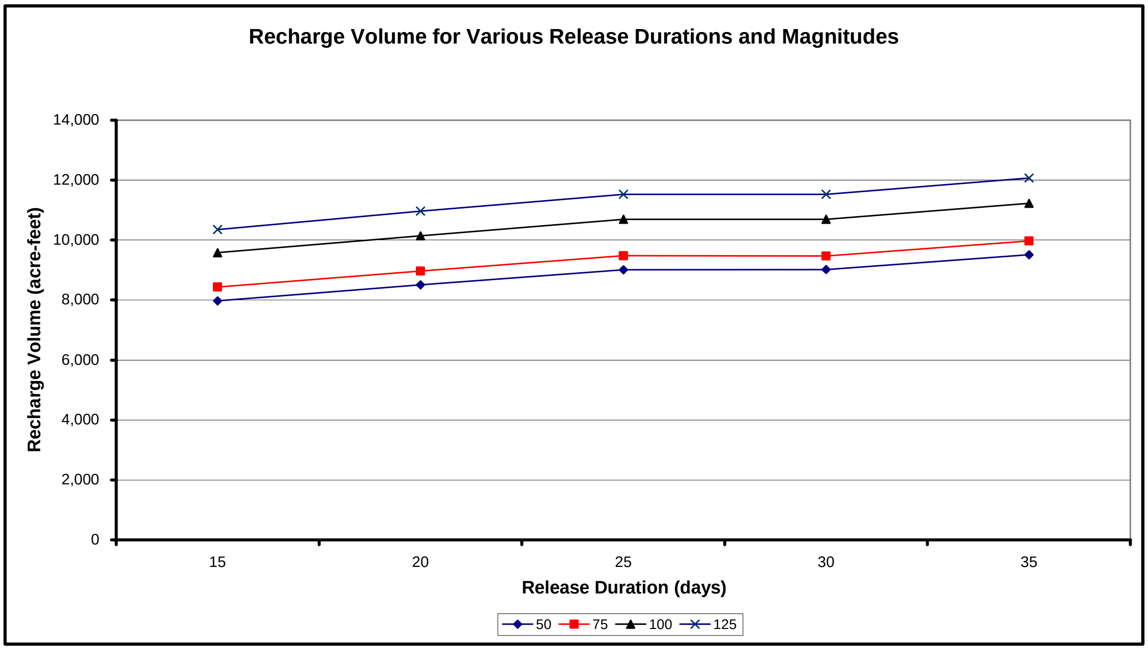

Figure 4.4 Recharge volume for various release durations and magnitudes.

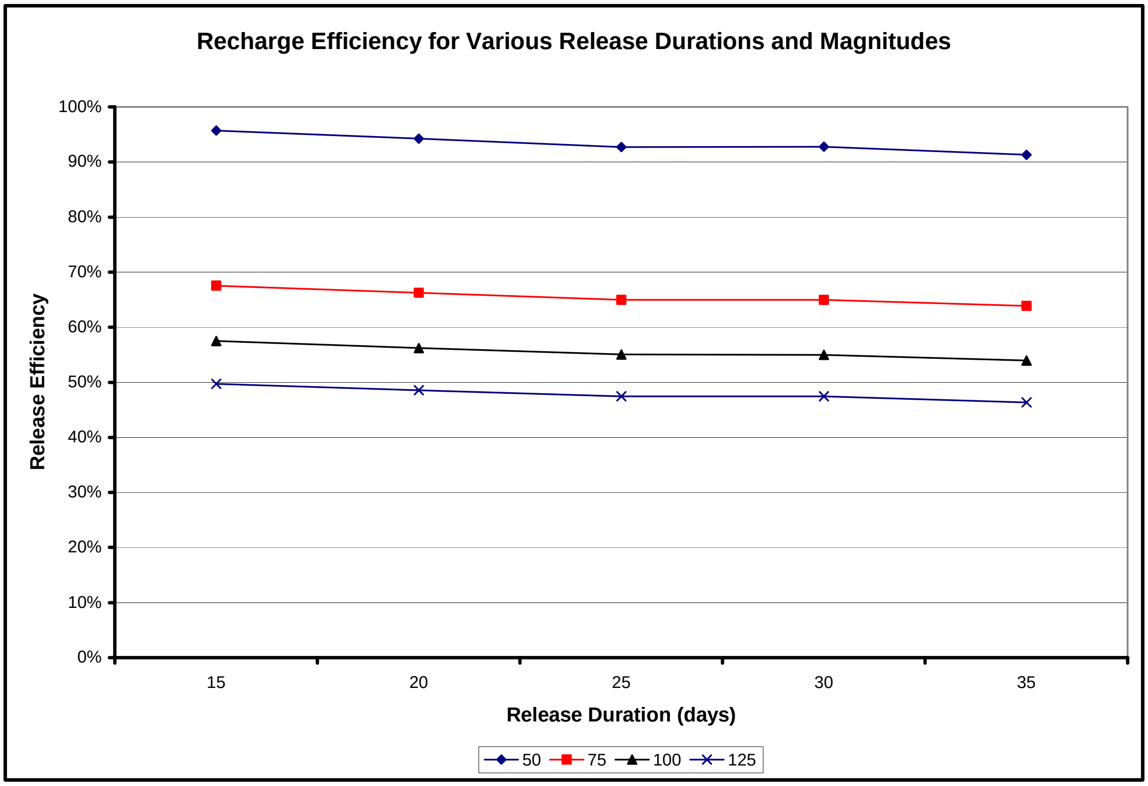

Figure 4.5 Recharge efficiency for various release durations and magnitudes.

These results indicate that for a constant release rate, it is better to use shorter duration releases to achieve a higher efficiency. However, using a shorter release duration results in less water being released during the simulation period. Operationally a set volume of water must be evacuating from the reservoir prior to the flood season, and releasing less water may not be an option. Additionally, a model run was made to evacuate the same volume of water as released during the scenarios of 35 days on and 7 days off at 100 cfs, and 15 days on and 7 days off at 125 cfs (20,826 acre-feet) at a constant release rate. A release rate of 88 cfs for the entire 119-day model period was required to release this volume of water and resulted in 11,634 acre-feet of recharge and an efficiency of 55.9%.

Pulses to Evacuate a Set Volume

A second set of model runs at different durations was made to evacuate the maximum anticipated volume of 50 TAF from the reservoir during the model period. For these runs the release rate was varied based on the number of days the reservoir was releasing water during the model period. Higher numbers of days allowed for lower release rates to release a total of 50 TAF over the 119-day period. Initial runs were made with a one-day recovery period when there were no flows. After the first series of runs, the duration of the recovery period was also increased until a trend in the recharge volumes was determined. The results of these runs are presented in Table 4.3 and Figures 4.6 and 4.7.

Release Rate (cfs)	Days On	Days Off	Total Days On	Release Volume (af)	Recharge Volume (af)	Spill to River (af)	Recharge Efficiency
420.13	1	1	60	49,999	12,244	37,755	24.5%
315.10	2	1	80	49,999	13,640	36,359	27.3%
280.09	3	1	90	50,000	13,370	36,629	26.7%
262.58	4	1	96	49,999	13,602	36,396	27.2%
252.08	5	1	100	49,999	13,754	36,245	27.5%
247.14	6	1	102	50,000	13,805	36,195	27.6%
240.08	7	1	105	50,000	13,948	36,052	27.9%
237.81	8	1	106	49,999	13,974	36,025	27.9%
233.41	9	1	108	50,000	14,063	35,937	28.1%
231.27	10	1	109	50,000	14,101	35,899	28.2%
229.16	11	1	110	49,999	14,138	35,860	28.3%
229.16	12	1	110	49,999	14,125	35,874	28.3%
227.10	13	1	111	50,000	14,175	35,825	28.3%
225.07	14	1	112	49,999	14,214	35,785	28.4%
240.08	14	2	105	50,000	13,943	36,057	27.9%
257.22	14	3	98	49,998	13,591	36,407	27.2%
265.35	14	4	95	50,000	13,549	36,451	27.1%
283.24	14	5	89	50,000	13,284	36,716	26.6%
300.09	14	6	84	49,998	13,540	36,459	27.1%
300.09	14	7	84	49,998	13,654	36,344	27.3%
319.09	14	8	79	50,000	13,654	36,345	27.3%
340.65	14	9	74	50,000	13,099	36,900	26.2%
360.11	14	10	70	49,999	12,641	37,357	25.3%
211.83	119	0	119	49,999	14,466	35,533	28.9%

Table 4.3 Recharge volume and efficiency for release patterns to evacuate 50 TAF.

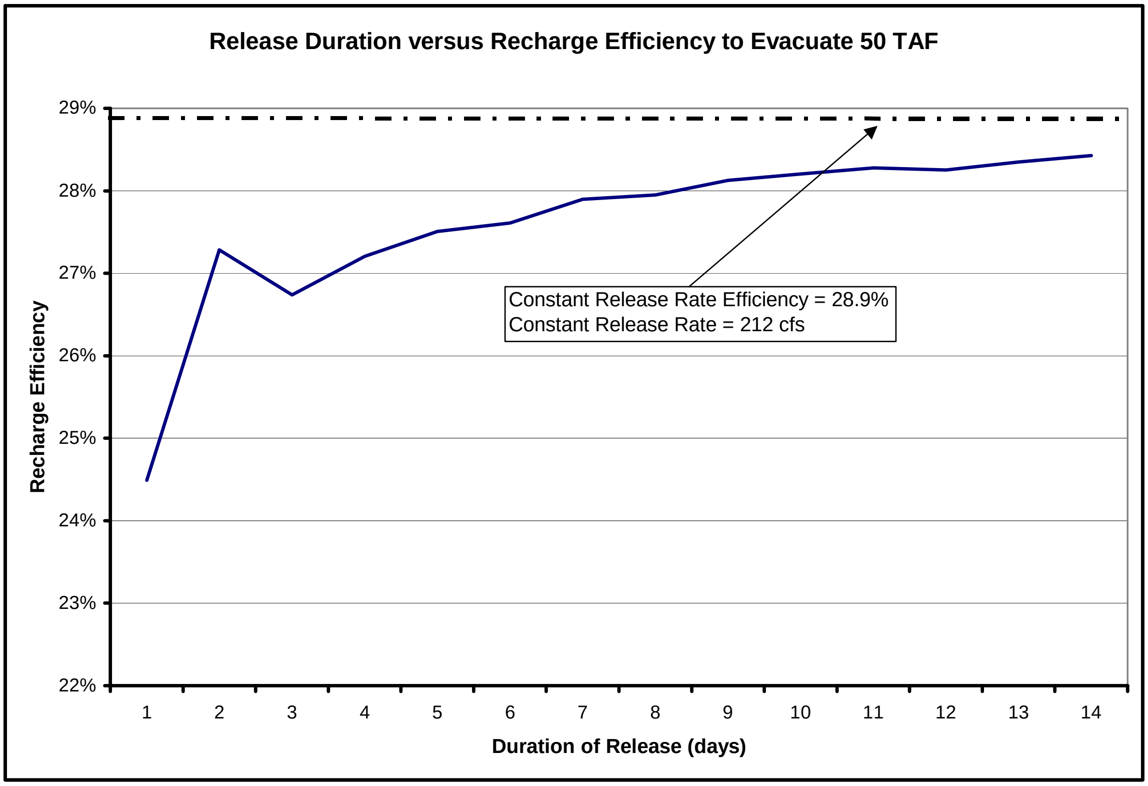

Figure 4.6 Recharge efficiency for various release durations when evacuating 50 TAF.

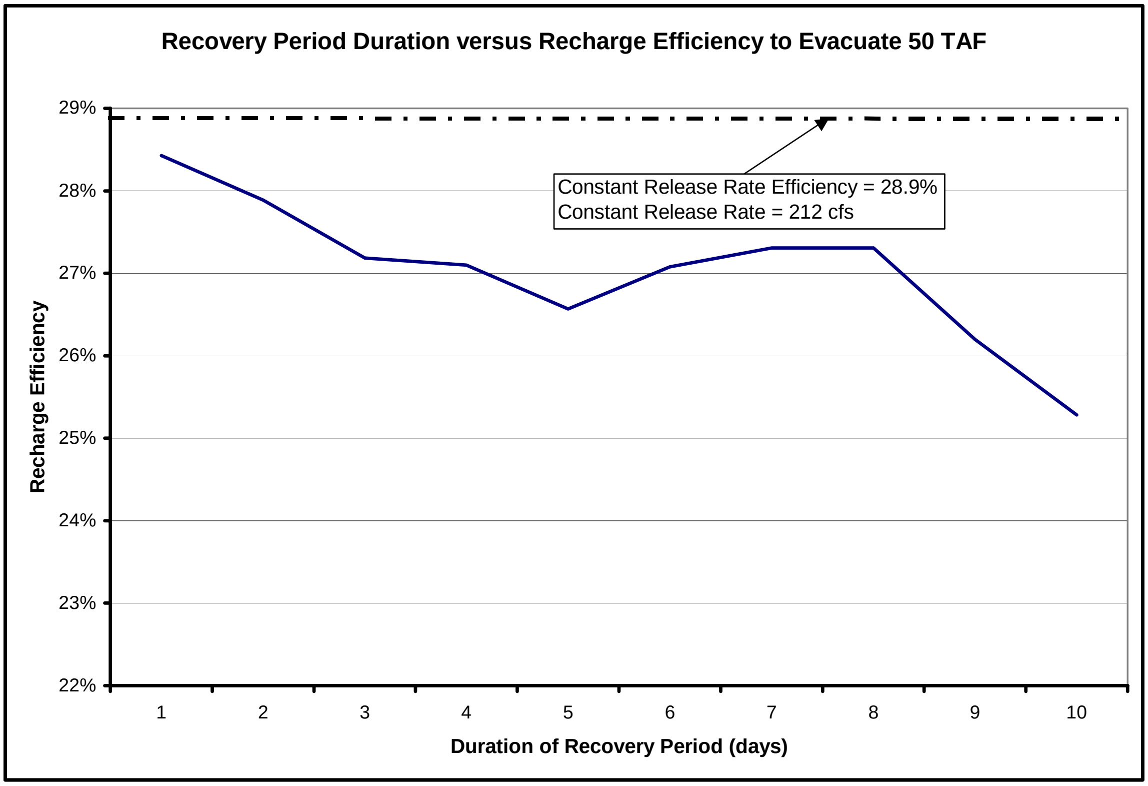

Figure 4.7 Recharge efficiency for various recovery period durations when evacuating 50 TAF.

This set of model runs confirms that a constant release rate is more efficient than a pulsed release pattern when attempting to evacuate a defined volume of water in a limited amount of time. Figure 4.6 shows the general increase in efficiency as the duration of the release pattern increases. As the release duration increases, the release rate is reduced. A duration of 14 days results in releasing water on 112 of the 119 days being modeled. Continuing this series would result in a release on all 119 days, with the lowest possible release rate and the highest efficiency.

Similarly, increasing the duration of the recovery period decreases the recharge efficiency as shown in Figure 4.7. As the recovery period increases, the release rate must increase to evacuate 50 TAF and the recharge efficiency declines.

Pulses with a Decreasing Release Rate

A set of model runs was made to evacuate a set volume from the reservoir with a pulsed, decreasing release rate. Several patterns of pulses were used that began at a high release rate and were reduced over a series of days and then repeated throughout the model period. The slope of the decrease was varied, as well as the duration of the pulse until a trend was established for the data. Examples of two such release patterns are provided in Figure 4.8.

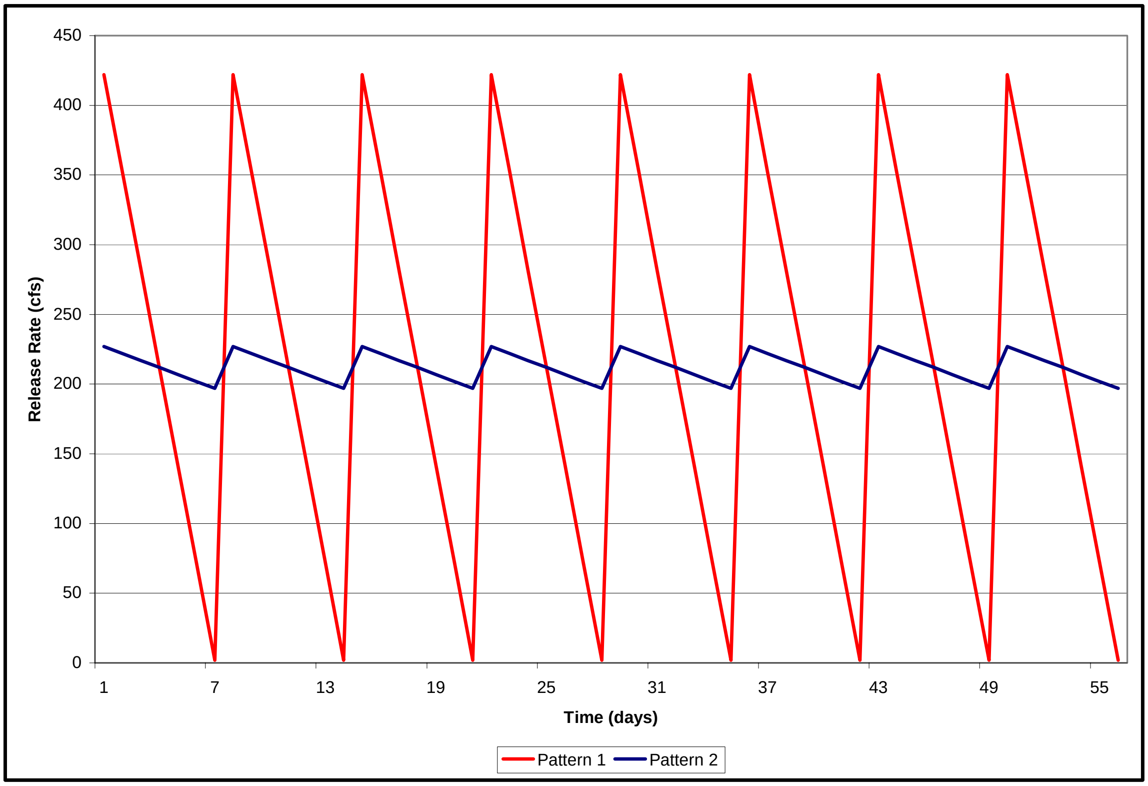

Figure 4.8 Example pulses with decreasing release rates.

The decreasing release pulse patterns produced efficiencies at or slightly above those of a constant release rate for evacuating 50 TAF from the reservoir over a 119-day period. The results are presented in Table 4.4.

Period (days)	Slope (cfs)	Release Volume (af)	Recharge Volume (af)	Spill to River (af)	Recharge Efficiency
7	5	49,999	14,466	35,533	28.9%
7	10	49,999	14,466	35,533	28.9%
7	15	49,999	14,467	35,532	28.9%
7	20	49,999	14,469	35,530	28.9%
7	25	49,999	14,471	35,528	28.9%
7	30	49,999	14,604	35,395	29.2%
7	35	49,999	14,605	35,394	29.2%
7	40	49,999	14,539	35,460	29.1%
7	45	49,999	14,625	35,374	29.3%
7	50	49,999	14,621	35,378	29.2%
7	55	49,999	14,582	35,417	29.2%
7	60	49,999	14,507	35,492	29.0%
7	65	49,999	14,155	35,844	28.3%
21	5	49,999	14,472	35,527	28.9%
21	10	49,999	14,560	35,439	29.1%
21	15	49,999	14,591	35,408	29.2%
21	20	49,999	14,410	35,588	28.8%
3	30	49,999	14,469	35,530	28.9%
3	35	49,999	14,469	35,530	28.9%
3	40	49,999	14,471	35,528	28.9%
3	45	49,999	14,472	35,527	28.9%
3	50	49,999	14,474	35,525	28.9%
3	55	49,999	14,475	35,524	29.0%
3	60	49,999	14,476	35,523	29.0%
3	65	49,999	14,478	35,520	29.0%
3	70	49,999	14,480	35,519	29.0%
119	0	49,999	14,466	35,533	28.9%

Table 4.4 Results of pulses with decreasing release rates.

As seen in Table 4.4 the release efficiency was slightly higher when using some of these patterns, but not high enough to be significant. The results are provided here to demonstrate it is possible to achieve a similar efficiency with other than a constant release rate. Additionally, from an operational perspective a release rate that varies on a daily basis would be significantly more difficult to implement.

Release Rate to Mirror Efficiency

A final model run was made after determining how the release efficiency varied with time. The model run attempted to evacuate 50 TAF during the 119-day period, and attempted to mirror the change in recharge efficiency over time when using a constant release rate. Recharge data for each time step was consolidated for the simulation of a constant release of 212 cfs to see how recharge efficiency varied with time. A plot of this comparison is provided as Figure 4.9.

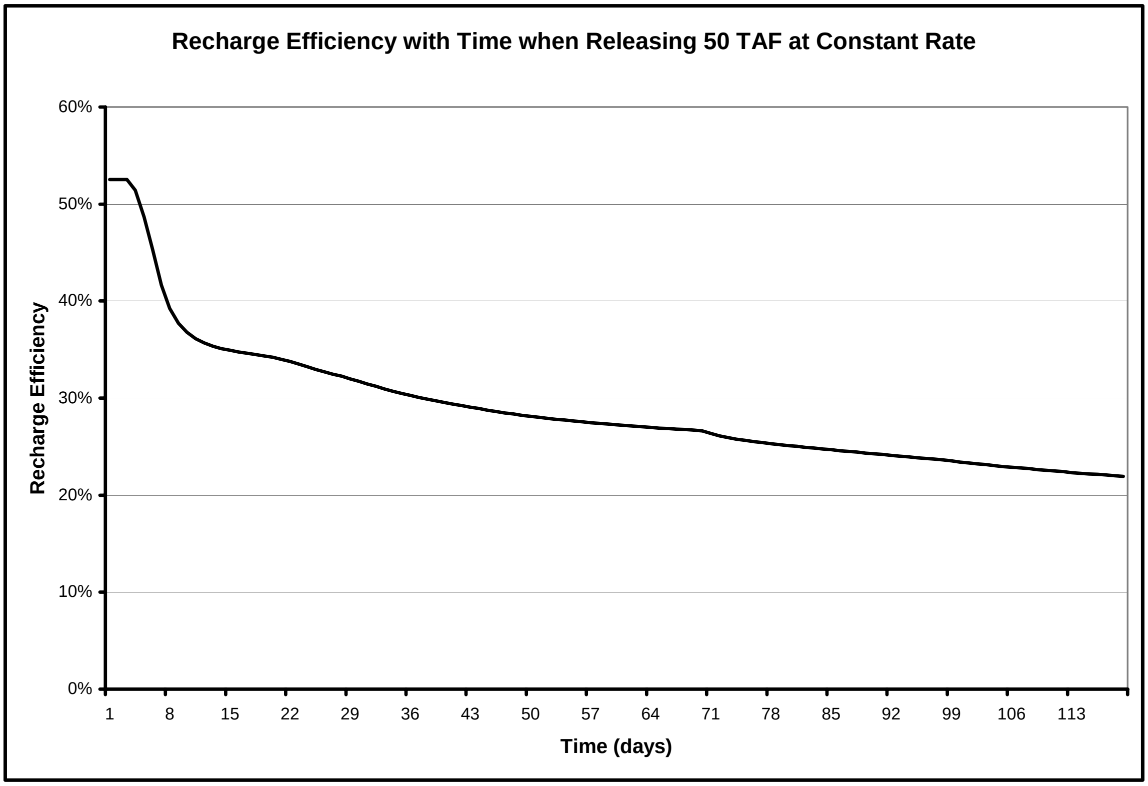

Figure 4.9 Recharge efficiency versus time for a constant release rate of 212 cfs.

Using the change in recharge efficiency per time step it was possible to create a release pattern that mirrored the curve in Figure 4.8 while also ensuring a total release of 50 TAF. The range of release rates for this pattern was from 268 to 197 cfs. A simulation using this pattern resulted in an overall recharge efficiency of 29.0%, a slight, but not significant, increase. This type of release pattern also would be difficult to implement operationally as it requires almost daily adjustment to the release rate.

Based on these model runs it appears the best release strategy for recharge is to release at a constant rate throughout the draw-down period. Operationally this results in the simplest method for determining the release by dividing the volume that must be released by the number of days available to release it. To achieve the highest recharge efficiency, the earliest possible determination of excess water that must be evacuated prior to flood season is needed.

These results are also influenced by the limitations of this simple model. Errors and factors not considered in the model will affect results. For instance, if the model over estimates heads near the stream, the error reduces the stream fluxes. The model does not consider the effects of capillarity. Sections of the Stony Creek streambed are sandy and may dry out quickly during the summer and fall. The model does not consider the storage potential in this sandy material if it dries out significantly between pulsed releases. This effect could significantly increase the recharge efficiencies of pulsed releases, but the effect is dependent on many factors and is difficult to simulate with such a coarse model.

CHAPTER FIVE: ECONOMIC ANALYSIS

Stony Creek Development

The mean annual flow of Stony Creek is approximately 350 TAF, based on USGS gage data at various locations on the creek. Three surface water storage reservoirs were developed to regulate this flow. The two upstream reservoirs of East Park (51 TAF) and Stony Gorge (50 TAF) were constructed and managed by the Orland Unit Water User's Association (OUWUA) for irrigation supplies. The US Army Corps of Engineers constructed Black Butte Reservoir (354 TAF) in 1963 for the purposes of flood control, irrigation, recreation, and future hydropower. The Corps operates the dam for flood control in the winter and early spring, and the US Bureau of Reclamation (USBR) operates for irrigation in the late spring, summer and fall. Additionally, the City of Santa Clara installed a hydropower facility at the dam that became operational in 1996.

Proposed Conjunctive Use Operations

The proposed conjunctive use operations are primarily between Black Butte Reservoir and the Stony Creek Fan aquifer. Reservoir releases for aquifer recharge would percolate into the aquifer from Stony Creek. Recharge releases would likely be made in the fall to empty the reservoir's flood storage space before the wet season. In 2003, approximately 37 TAF were released for this purpose (GCWAC 2004). Releases also may continue into the wet season, if additional water is available, to avoid spills from the reservoir. A second option for making releases would be in the spring when better estimates of the year's surface water supply are available.

Potential Economic Benefits

The economic benefits of conjunctive use include new yield, greater supply reliability, storing water closer to users, and increased flood control benefits and are well documented (Basagaoglu and Marino 1999, Coe 1990, Pulido-Velasquez 2004). The Stony Creek project potentially incorporates many of these benefits as described below.

Potential for New Yield

Conjunctive use operations may allow the capture or use of additional yield from existing surface and groundwater supplies. New yield can be made available primarily from increased capture of high winter flows that typically spill from the reservoir, down Stony Creek and into the Sacramento River. This spilled water eventually passes through the San Francisco Bay-Delta and reaches the Pacific Ocean. Because it occurs in the winter, when water quality concerns in the Delta are typically low, capturing this water would mostly contribute new yield.

The economic benefits of the new yield depend entirely upon how the additional water is used. Currently the area is largely agricultural and additional water supplies may be used to irrigate additional acreage, improve reliability, or for transfer out of the area. However, the area's population and level of development will continue to increase in the future and new yield also may become a source for municipal or industrial supply.

Additionally, as water marketing continues to develop and water transfers and exchanges become more frequent and accepted, new yield may become a direct source of revenue to the region. Because Glenn County is located north of the Delta it will be more difficult to transfer water to the areas of higher demand south of the Delta, but new yield may still prove to be a valuable revenue source.

Flood Control Benefits

Conjunctive use operations can also increase the flood control benefits provided by Black Butte Reservoir. Historically the reservoir is drawn down to approximately 20 TAF of storage prior to the start of each flood season (USACE 1987). Additional flood protection could be gained by drawing down the reservoir to the top of its inactive pool at 6.7 TAF. By releasing water at the proper rates during the draw down period, a significant portion of this 13.3 TAF could be stored in the aquifer for use in the subsequent irrigation seasons. This operation would provide additional flood control storage in the reservoir and also reduce spills, thereby increasing system yield. This operation would create a CU pool as described in a draft report on flood control benefits of conjunctive use from the USACE’s Hydrologic Engineering Center (USACE 2002). In this report, additional new yield and increases in flood storage in six different reservoirs in the Northern and Central Valley are estimated. However, the expected reduction in annual damages for these reservoirs operating under CU rules was not calculated.

Reduced Water Supply Variability

A primary purpose of most conjunctive use operations is to reduce the variability of water supplies to users. Tsur and Graham-Tomasi show that this “buffer” value of groundwater can be quite significant (1991). This is particularly beneficial for areas with significant agricultural and industrial water demands. The buffer value is more important in agricultural areas with permanent crops because of the high costs of establishing permanent crops.

Potential Economic Costs

Fixed Costs

One advantage of using the Stony Creek Fan for conjunctive use is to avoid some of the higher capital costs associated with dedicated recharge areas. However, there are likely to be significant fixed costs incurred to establish additional wells to ensure areas previously irrigated with surface water can receive adequate groundwater supplies in years of reduced surface water. Likewise, additional surface conveyance facilities may be required to service areas traditionally on groundwater during years with excess surface supplies.

Pumping Costs

Most conjunctive use operations incur additional pumping costs for water users. The exception is when “in-lieu” recharge is the sole method of recharge and water that would normally be pumped is left in the aquifer as credit when additional surface water supplies are available. This method is also a possibility in the Stony Creek Fan. However, the additional surface water is not likely to be available during times of high demand. Therefore, there will be additional pumping costs with CU operations.

Hydropower

The City of Santa Clara has generated hydropower on releases from Black Butte Dam since 1996. Power is only generated incidentally when releases are made for other purposes such as flood control or irrigation (Hancock 2004). The plant operates under minimum and maximum release rates and heads for power generation. A release rate of 200 cfs with 45 feet of head is required to begin generating power. There will be impacts to hydropower generation under CU operations because the ideal release rate for recharge will likely be less than 200 cfs. Additionally, releases for recharge will reduce reservoir elevations, thereby decreasing the head available for power generation.

Recreation

Black Butte reservoir’s recreational opportunities have been developed to include fishing, picnicking, camping, pleasure boating, water skiing, swimming, and sightseeing (USACE 1987). As of 1983 there were four boat launching ramps, three picnic sites, and two campsites. The water control manual states that, to the extent possible, a minimum storage of 40 TAF should be maintained until Labor Day and 20 TAF maintained through the fall and into the next flood season for recreation.

The impact of conjunctive use on recreation at Black Butte Reservoir largely depends on when CU operations occur. Releases for aquifer recharge could be made during the spring season when a more reliable estimate of surface water supplies is made available. This type of operation would more severely affect recreational benefits. Recharge releases made in the fall using excess surface water from the previous irrigation season reduce the effect on recreation since water levels are maintained throughout the high summer recreation season. Operations aimed at drawing the reservoir down to the top of the inactive pool would impact recreation in the fall and early winter.

Flood Damages

While conjunctive use operations may provide increased surface water storage for flood protection, operations may simultaneously increase flooding by raising groundwater levels and reducing aquifer storage space for rain percolation (Foley-Gannon 1999-2000). However, the amount of deep percolation occurring during storms is likely a small amount of the total flood volume and therefore additional flood damages can be ignored.

Externalities

Conjunctive use operations have the potential to affect others not involved in the direct economic exchange. These externalities can take the form of environmental damage, flooding of overlying lands, reduced groundwater quality, damage to the aquifer through subsidence and compactions, and impacts to overlying wells (Foley-Gannon 1999-2000). In the Stony Creek Fan the most likely and significant of this list is effects on other overlying wells. It is assumed that the two main water agencies in the area, OUWUA and the Glenn-Colusa Irrigation District, in conjunction with the USACE and USBR, would undertake a conjunctive use operation. However, many residential groundwater users in the area have wells, which may be affected. Conjunctive use operations often result in a larger range of groundwater elevation changes than what typically occurs without conjunctive use (McClurg 1996). This effect can be particularly damaging in severe droughts when increased reliance on groundwater can draw the water table down below the depth of residential wells. For the purpose of this initial analysis it is assumed that these externalities are minimal and are balanced by the positive externality of reduced pumping costs for these same third party users when groundwater elevations are higher than normal during periods of increased recharge. Further study of the expected range of groundwater levels would test the validity of this assumption and indicate if any third-party well would need to be deepened. In some cases conjunctive use programs include the deepening of third-party wells.

Conjunctive use may also create environmental externalities, mostly due to the variability of the groundwater levels. High levels during recharge may create ephemeral wetland areas, while during drought, levels may drop below tree root zones. Estimating and assigning a cost or benefit to environmental externalities is extremely difficult and beyond the scope of this analysis.

Cost-Benefit Analysis

It is possible to perform a preliminary cost-benefit analysis based on estimated or assumed values for new yield, water and crop prices, power costs, recreation, etc. The following section details the assumptions made to estimate benefits and costs and provides a preliminary analysis.

Benefit of New Yield

It is difficult to quantify the new yield from conjunctive use operations. However, the primary purpose of this analysis is to define the method and the required data. For this purpose it will be assumed that the excess water used in the 2003 study, 37 TAF, approximates the average annual excess that is released at the start of the flood control season. The actual volume of water available in any one year varies with hydrology and water demand and is known to range from zero to 50 TAF (Kibby, 2004). However, not all of the 37 TAF is new yield. There are losses involved in the recharge process as water is intercepted in the root zone, evaporates from the creek, or flows all the way to the Sacramento River. A commonly used estimate for recharge losses is 15% (USACE 2002). Additionally, some of this water would have previously recharged the aquifer while flowing to the Sacramento River, so it is only the additional volume that percolates to the aquifer under the CU release pattern that actually represents new yield. Because Stony Creek is hydraulically connected to the aquifer there is likely to be significant recharge even at high flow rates. Therefore, it is assumed that 50% of the water that reaches the aquifer is new yield, the other 50% having previously percolated during non-CU releases. The total new yield is then:

$$37 \text{ TAF} * (0.85 \text{ for losses}) * (0.5 \text{ for historical recharge}) = 16 \text{ TAF}. \qquad (5.1)$$

This value is also close to the 13.3 TAF that could be captured by drawing down the reservoir to the top of the inactive pool. Benefits derived from this new yield can take many forms. It is unlikely that additional yield would be used to irrigate additional acreage in this region, as water supply is not typically the limiting constraint to agriculture. The buffer or stabilizing value of groundwater and conjunctive use operations can sometime be significant (Tsur 1990, and Tsur and Graham-Tomasi 1991). However, even without the benefit of conjunctive use, there is sufficient groundwater to in the area to limit the impact of drought on most crops. Therefore, the additional yield from CU operations is not likely to have a significant impact during a severe drought. The highest value for any new yield captured through CU is likely to be realized through water marketing.

To estimate the possible benefits from the new yield through water marketing it is necessary to assume a price other users would be willing to pay. For this analysis, the average price of $75/ac-ft paid by the State during operation of the Drought Water Bank in 1991, 1992, and 1994 is used as a lower bound (DWR 1998). A more recent value was agreed to in a water transfer between GCID and the Metropolitan Water District of Southern California (MWD). MWD paid $10/ac-ft for options on 80 TAF in January of 2005 (Kasler 2005). The option reserves the water until April 1st and if it is bought at that time the price is $125/ac-ft, or purchase can be delayed until May and made for $145/ac-ft. Using $145 as an upper bound, the potential benefits from the sale of the new yield may range between $1.2 and $2.3 M.

Flood Damage Reduction

There may be some additional benefits from reduced flood damages. It is possible to make estimates of the expected reductions in flood damages from conjunctive use operations. However, these estimates require significant data and modeling effort. For the purpose of this preliminary estimate it will be assumed that the damage reduction benefit is approximately equal to the damage increase that may be seen because of raised groundwater levels. Additionally, the increase in flood storage due to CU operations is a relatively small volume. Therefore, there is no net benefit or cost from flood damages.

Fixed Capital Costs

To transfer the new yield to other users by pumping the water out of storage and into the Sacramento River one or more well fields are required, preferably located near the river, to extract the water. The major costs to develop these well fields include land purchases or long-term leases, well drilling, and pumps.

Assuming wells capable of pumping continually at 2,000 gpm, and that it may be required to deliver the 16 TAF of new yield in as little as one month approximately 60 wells are required. Well drilling costs can be estimated in price per foot drilled. Values differ based on location, well diameter, and requirements for casings and screening. Approximate values for the Glenn County area are $95/foot (Dudley 2004). Based on well depths of approximately 120 feet, to the bottom of the existing unconfined aquifer, this results in a total drilling cost $684,000. Purchase and installation of a pump is also required and estimated at approximately $60,000 per pump, or $3.6 million in pumps.

The additional cost for 30 acres of land at $5,000 per acre, needed for two well fields is an additional $150,000 for a total project initial cost of approximately $4.5 million.

The total fixed capital costs can be discounted and annualized over the expected life of the well to provide an annual cost in present value for both end uses. Assuming a 50-year well-life, and a discount rate of 3%, the annual cost is calculated as:

$$\text{Annual Payment} = \text{Present Value Cost} * (i*(1+i)^n) / [(1+i)^n-1] \qquad (5.2)$$

where *i* is the discount rate and *n* is the well life. This provides an annual cost of $175,000 for the well fields. The choice of a discount rate is very important in this process and depends largely on the type of financing expected. For instance a 1% reduction in the discount rate reduces the annual cost by approximately $32,000. A similar reduction in the annual cost could be achieved by reducing the present value by $800,000 with a grant from the government. Some financing options are provided in the following section.

Pumping Costs

Average annual pumping costs can be estimated as the cost to recover the new yield. This method ignores the cost to recover any additional water stored in the aquifer that would historically be delivered by surface conveyance, but it is difficult to estimate this volume with presently available data.

Pumping costs have been estimated for numerous studies and models with a typical value being around \$0.13/ac-ft*ft (Knapp and Olson 1995). An average value for pumping heads of wells in the fan during July of 2003 was approximately 41.6 feet (DWR 2004). Therefore, to recover the 16 TAF of new yield over that head would cost approximately \$87,000. It is recognized that this cost would not be incurred every year and that when surface supplies are reduced it will be higher. However, this estimate should provide the average annual additional pumping cost created by CU operations.

Costs to Hydropower Generation

Unfortunately historical generation data are not available, so estimates will be made using historical release and storage data from USACE. Average monthly releases and storage from September through October will be used in the standard hydropower equation to estimate potential generation during this period of CU releases. The standard power equation is:

$$Kw = N*Q*H/11.8 \tag{5.3}$$

Where Kw = power generated in kilowatts

N = efficiency of the turbine and generator

Q = flow rate in cfs

H = head difference between water surface elevation and tail water - head losses

Based on an interview with the hydropower plant operator, the average plant efficiency is 86% with an average tail water elevation of 390 feet (Hancock 2004). Table 5.1 provides the average releases, storage, elevations and revenues potentially generated during the three-month period impacted by CU operations. A value of $72 per megawatt hour is assumed based on a recent power contract in Northern California (SAIC, 2003). Based on the historic average release and head being less than the minimums required, there is little hydropower generated in November.

Variables	September	October	November
Average Release (cfs)	331	185	101
Average Storage (ac-ft)	42,882	29,215	26,247
Average Elevation (ft)	443	435	432
Head (ft)	53	45	42
Power Generation (MWH)	912	438	-
Revenue ($1,000/month)	66	32	-

Table 5.1 Calculated historic hydropower revenue.

All of this revenue may be lost due to CU operations because of the release rate being less than the minimum required to generate power. Additional revenue will also be lost in the following months as reservoir storage is refilled, resulting in lower heads and releases. However, at this time it is assumed that the annual cost in hydropower revenue is approximately $100,000.

Costs to Recreation

The Black Butte Lake Water Control Manual states the average annual attendance in recreation days from 1964 to 1984 was 210,000 days (USACE 1987). It also states that 80% of the recreation takes place during a peak season from 15 March to 15 August.

Using this information it is possible to estimate current recreational value in the late summer and fall period when CU operations may affect water levels.

Assuming that increases in recreation days roughly paralleled population growth in Glenn County from 1980 to 2000, a 24% increase in the average number of days is estimated to give a current annual average of 260,000 (USCB 2004). Assuming the same percentage of use occurs in the high recreation period the potential number of visitor days that may be affected by CU operations is 70,000. An estimate of 50% of these recreational days being cancelled due to low lake elevations combined with an average value per recreation day provides a total cost to recreation. The value of the recreation can be estimated with a travel cost analysis. It is assumed that most users live within 100 miles of Black Butte reservoir, because there are other lakes, offering similar amenities, in the surrounding area. For most visitors, the largest costs to visit the lake are gasoline and wear on a vehicle, estimated at approximately $30. There is no entrance fee and most activities are free of charge, so an additional $10 is assumed to cover any other miscellaneous costs. This provides a very simplified estimate of $1.4 million cost to recreation on an annual basis.

Numerous studies present much more detailed analysis of estimating the recreational value of water. Walsh, Aukerman, and Rud presented a study that used surveys to estimate recreational users willingness-to-pay (WTP) to visit Colorado reservoirs at different water levels (1979). Users reported a marked decrease in WTP to visit reservoirs when water levels drops from 50% to 25% of the maximum level, from

$43.24/trip at 50% water level to $13.41/trip at 25% water level compared to a change from $57.54 to $43.24 when going from 75% to 50% water levels. This may indicate a more severe impact to recreation at Black Butte reservoir if water levels are drawn down significantly such as in operations using a conjunctive use pool and bring reservoir levels down to the inactive pool.

Cost-Benefit Summary

Table 5.2 provides a summary of the benefits and costs for the new yield.

Yield Used in Water Transfer	
Benefits	**Annual Value**
New Yield	1,200-2,300
Total Benefits	1,200-2,300
Costs	
Fixed Capitol	(175)
Pumping and Operation	(87)
Hydropower	(100)
Recreation	(1,400)
Total Costs	(1,762)
Project Total	**(562)-538**

Values in thousands of dollars

Table 5.2 Cost-benefit summary.

Table 5.2 shows the project is beneficial if the new yield is sold in a water transfer at the more recent rates of $125 or $145 per ac-ft, at $75/ac-ft it is not beneficial because of the significant impact to recreation. This analysis is preliminary and could be improved with additional information and more accurate estimates. However, it does provide some order of magnitude estimates and insight into the more important benefits and costs. The recreational impacts are potentially significant and require further study to more accurately determine, while pumping costs are not.

Financing Options

Conjunctive use in the Stony Creek Fan is attractive because of the natural recharge opportunity afforded by Stony Creek. Use of the streambed for recharge eliminates the need for dedicated recharge ponds or injection wells both of which incur capital costs. However, a complete CU operation may still have capital costs associated with additional wells or surface conveyance facilities, or payment to alleviate externality costs such as deepening an existing domestic well.

Based on the cost benefit analysis, it is unlikely that the local water agencies can finance these costs without government assistance. Additional funding options are available through state grants. Glenn County has been successful in securing Local Groundwater Management Assistance (AB303) Grants from the state in previous years to expand their groundwater monitoring and management plans, receiving over $750,000 thus far (GCWAC 2004). Continuing through AB303 grants or even Proposition 13 Grants for increased Agricultural Efficiency are both strong possibilities (DWR 2004).

If these funding sources are not available, it is still possible to implement conjunctive management with individual farmers drilling the needed wells over time (especially to ensure supplies for permanent crops), though this plan may meet with local opposition. The analysis assumes the need to drill 500 new wells at the start of CU operations, which provides an upper bound on potential capital costs for new wells. In reality the new wells could be drilled over a period of years, thereby reducing the money needed to begin operations and reducing the overall project costs.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

The primary purpose of this study was to better understand the interaction between Stony Creek and the Stony Creek Fan aquifer and investigate release strategies for improving aquifer recharge. A better understanding of the stream-aquifer interaction is necessary for developing conjunctive use operations in the Stony Creek Fan. Additionally, a preliminary economic analysis of conjunctive use operations is provided to assist in understanding the potential economic benefits of any new yield derived as part of CU.

The groundwater modeling results indicate the highest recharge efficiency is obtained by releasing water at the lowest possible release rate from Black Butte Reservoir. This preliminary model suggests no significant benefit from using a pulse release pattern. The actual benefits of pulsing should be studied through the use of an enhanced model that better represents the near-stream groundwater environment and/or through field experiments involving constant and pulsed releases. Whether the releases are pulsed or not, the model clearly shows that moderate release rates over longer times provide the greatest recharge efficiency. Therefore, to maximize the volume of water reaching the aquifer through the streambed it is necessary to identify the total volume of water available for conjunctive use releases as early as possible. This allows the reservoir to be drawn down over a longer period and at a lower release rate.

The groundwater model would benefit from additional verification and refinement. A second set of stream flows and well water surface elevations collected over the same time of year in the future could be used to verify the aquifer and streambed hydraulic conductivities. The recharge values could be updated with the most recent land use survey and ETAW values and the constant head boundary of the Sacramento River would be updated for the period being modeled.

A method to account for capillarity would be a significant improvement to the model. A more detailed streambed survey would be useful in estimating sandy areas that may dry quickly and provide more opportunity for recharge using a pulsed release pattern.

Additional streambed cross sections would also improve the model. The calculated conductance term between the stream and aquifer is determined by the stream length, width, and stage. Stream stage-discharge-width data at additional locations along the streambed could be incorporated into the stream package spreadsheet to provide a better physical representation of the stream. Additional stream flow measurements for releases between 125 cfs and 225 cfs would better define the existing stage-discharge-width tables.

Another strategy to increase recharge would be to construct natural weirs or install temporary weirs to slow the flow of Stony Creek. The Orange County Water district has used this technique successfully for many years in the Santa Ana River (OCWD 2005). The model may be useful in estimating the expected recharge of the stream with these modifications or in investigating potential locations for the weirs.

The benefits of the potential new yield depend on how that yield is used. At this time the value for increasing agricultural production is likely to be small compared to the large capital costs for numerous new wells. Greater benefit and decreased costs might be realized by transferring the water to users with a higher willingness-to-pay. If the project were to be implemented, it would most likely serve a combination of these uses and perhaps others such as municipal supply or environmental stream flow.

Additional Model Improvements

Refining certain assumptions and modeling methods may improve the model's ability to simulate real-world conditions. Some improvements such as replacing the northern and western no-flow boundary conditions with general-head boundaries and better estimates of the initial head file have been mentioned. Additional areas for study and refinement include the interaction between the upper, unconfined Stony Creek Fan and the underlying Tehama aquifer, using multiple layers to simulate the upper aquifer, and extending the model period.

The model is currently two dimensional with a single layer and no leakage from the bottom of the layer. The short modeling period and the focus on the stream-aquifer interaction allow this assumption, even though there is likely some water movement between the Stony Creek Fan and the underlying Tehama aquifer. The well construction logs indicate a clay layer twenty to sixty feet thick separates the two formations. Therefore, the interaction is not likely to be significant over short time periods. If the model were to be extended over a greater temporal range, this assumption may require further research.

A second possible improvement involves creating two layers to model the Stony Creek Fan. The top layer would contain Stony Creek, and the underlying layer the aquifer. One of the assumptions inherent in the MODFLOW stream package is that the stream is fully penetrating the top model layer. This assumption prevents any groundwater flow under the stream between cells on either side of the stream. This is not an accurate representation of the Stony Creek Fan system.

Extending the modeling period would also be useful for improving simulations. Extending the period requires a significant effort to gather additional land use and precipitation data. Running the model for a longer period may indicate which assumptions require additional research.

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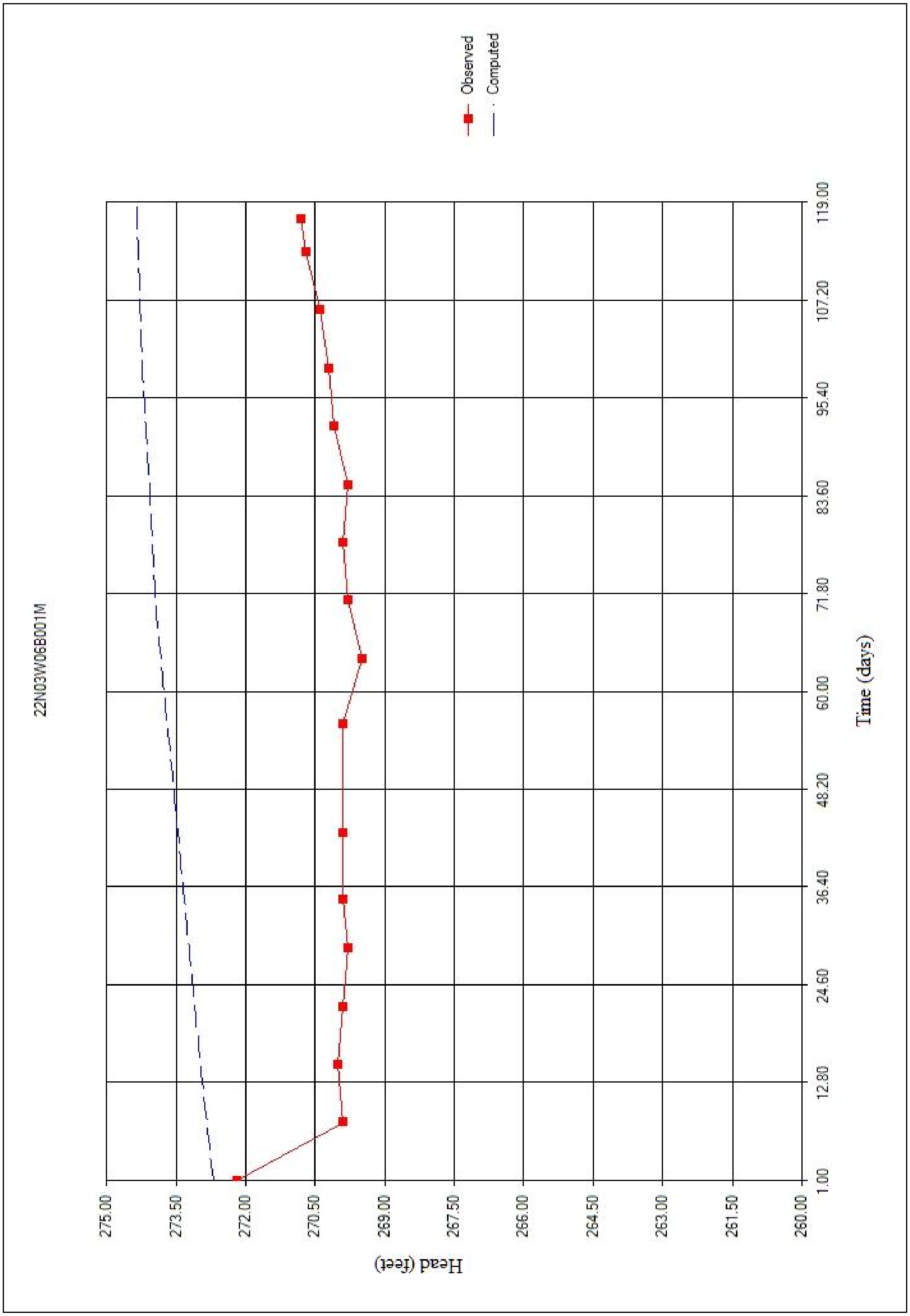
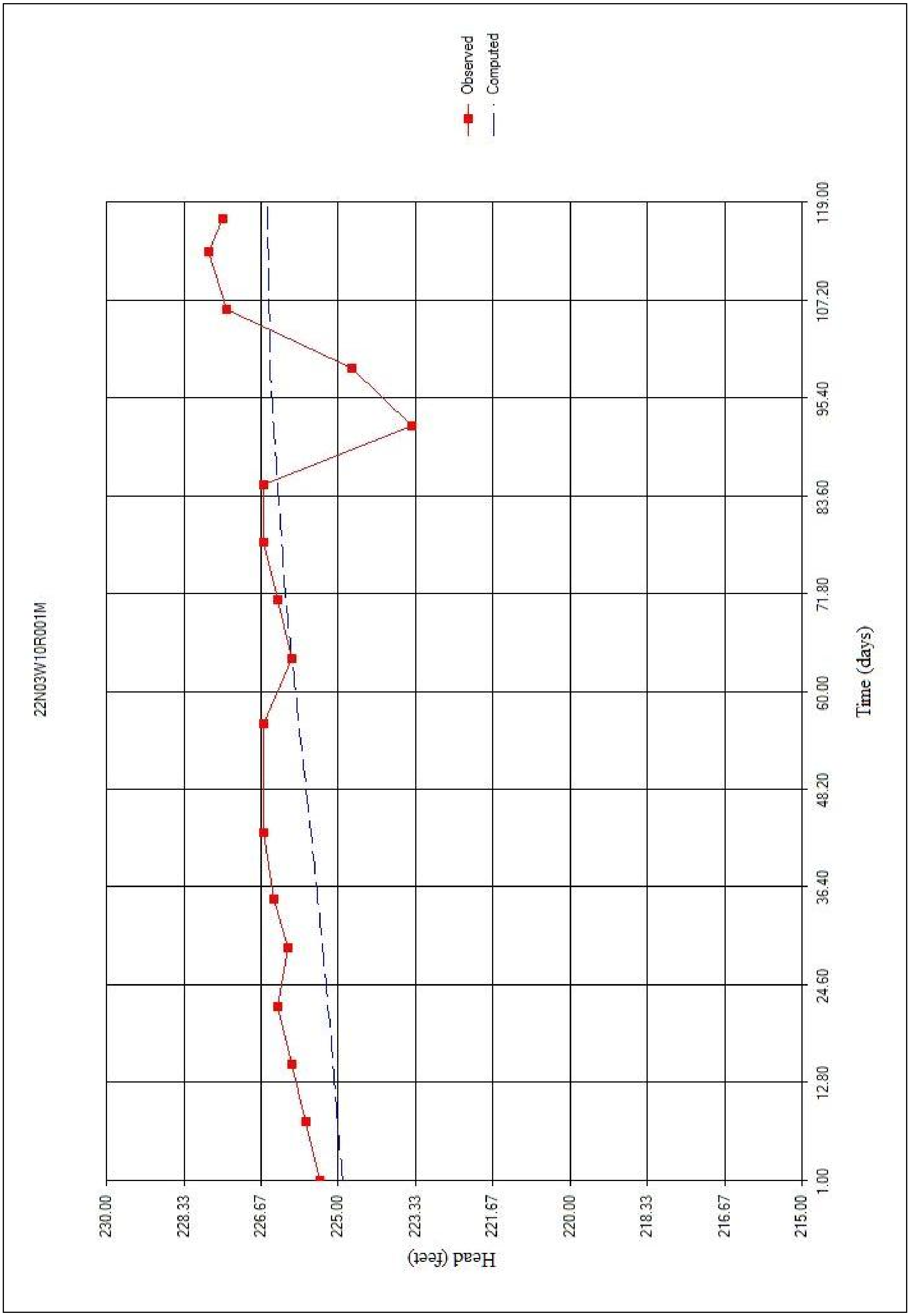
APPENDIX A: OBSERVED AND MODELED HYDRAULIC HEAD VALUES

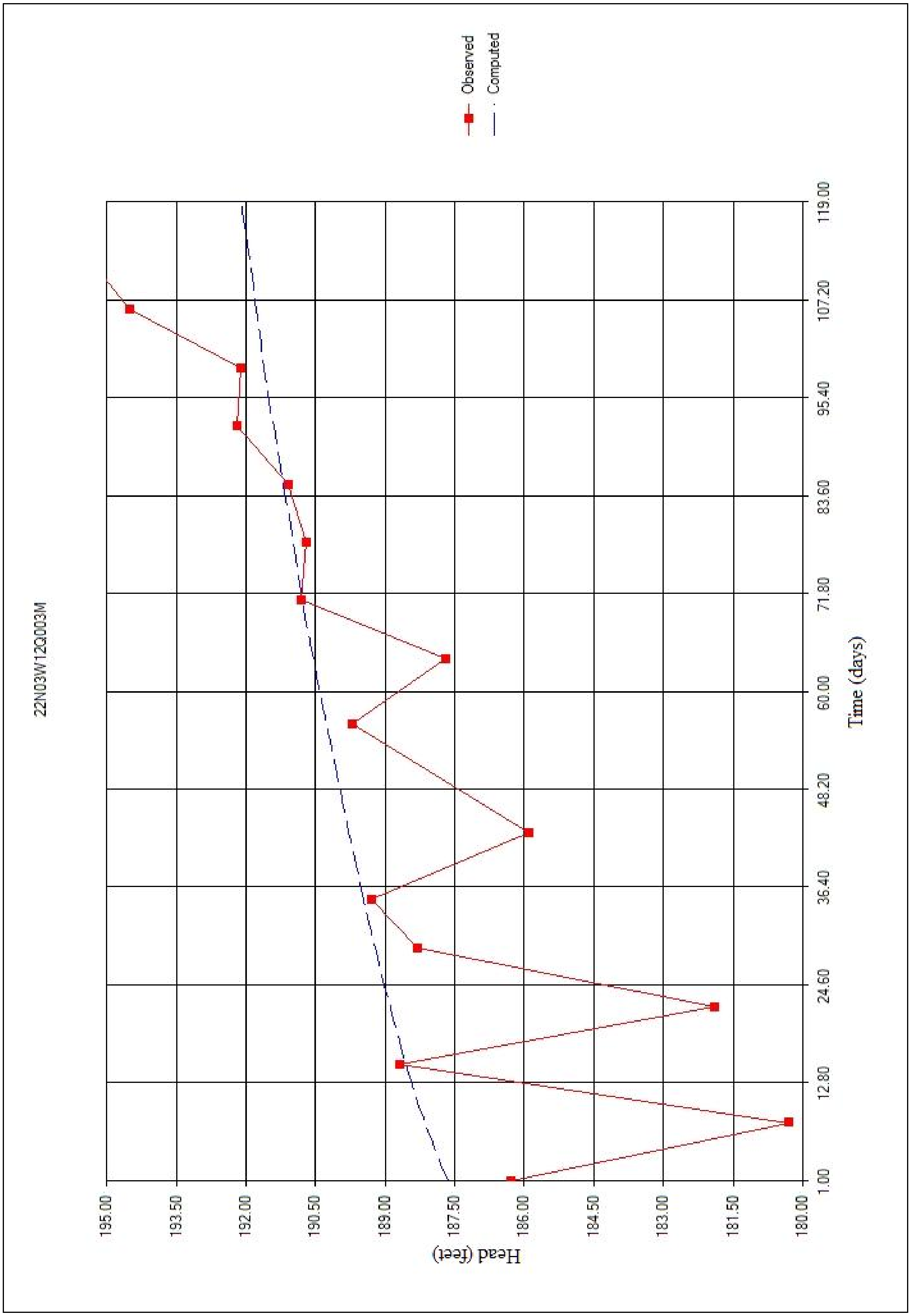
This appendix contains plots of the 17 different wells used in calibration. Water level measurements were taken on a weekly basis during the calibration period and are plotted against heads computed by the model. These wells are screened only in the upper, unconfined aquifer. The appendix is organized as shown in Table A.1. Please reference Figure 3.2 on page 37 for more exact well locations based on the state well number.

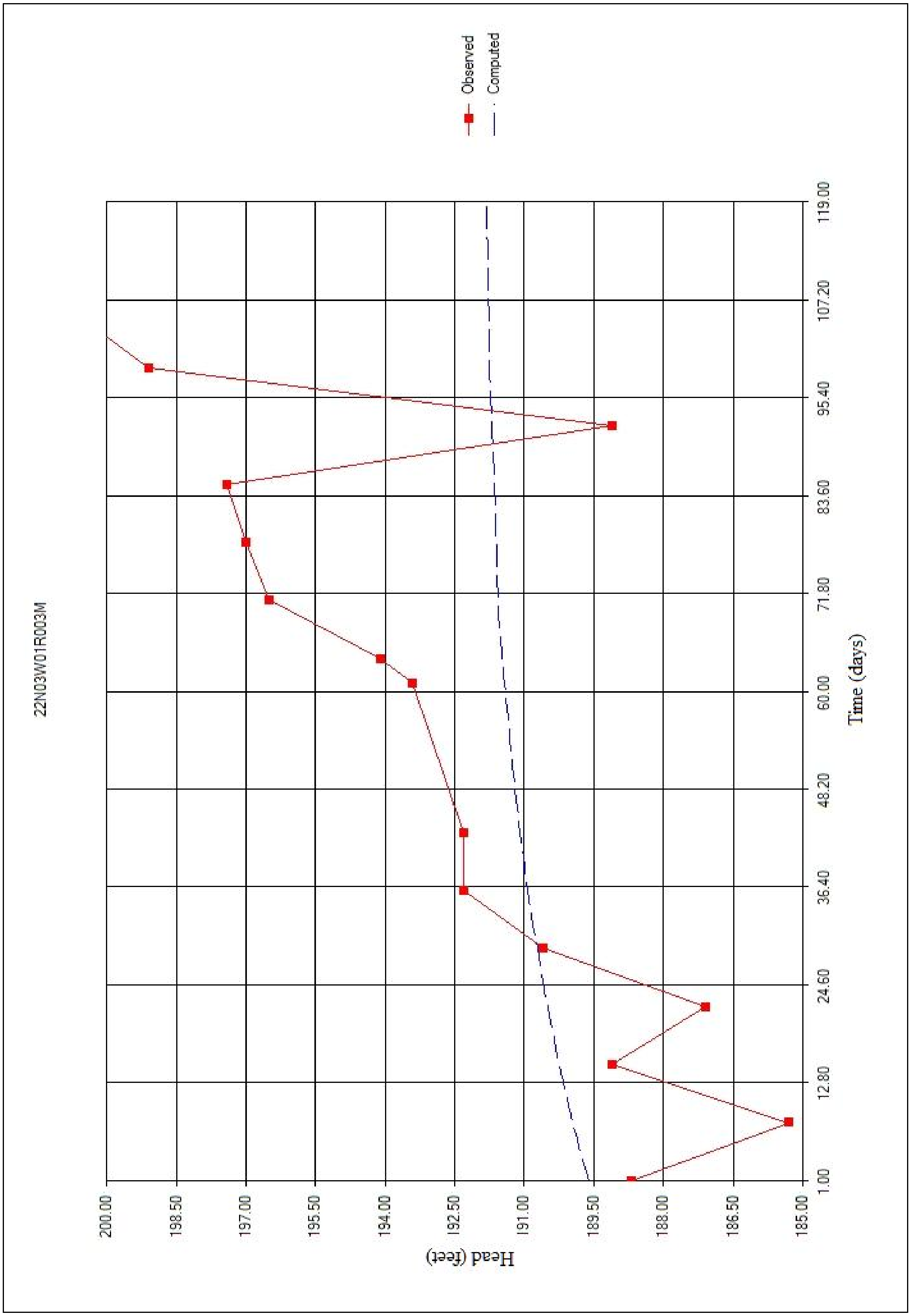
Location to Stony	Page	State Well Number	Location West or
North of Creek	84	22N03W06B001M	Furthest West
	85	22N03W10R001M	
	86	22N03W12Q003M	
	87	22N03W01R003M	
	88	22N02W21D001M	
	89	22N02W15C005M	
	90	22N02W36D001M	
	91	22N01W29K001M	
	92	21N01W04N001M	Furthest East
South of Creek	93	22N03W17E001M	Furthest West
	94	22N03W21F002M	
	95	22N03W28P003M	
	96	22N02W31C001M	
	97	21N02W05M005M	
	98	22N02W20Q001M	
	99	21N02W01F004M	
	100	21N01W17F001M	Furthest East

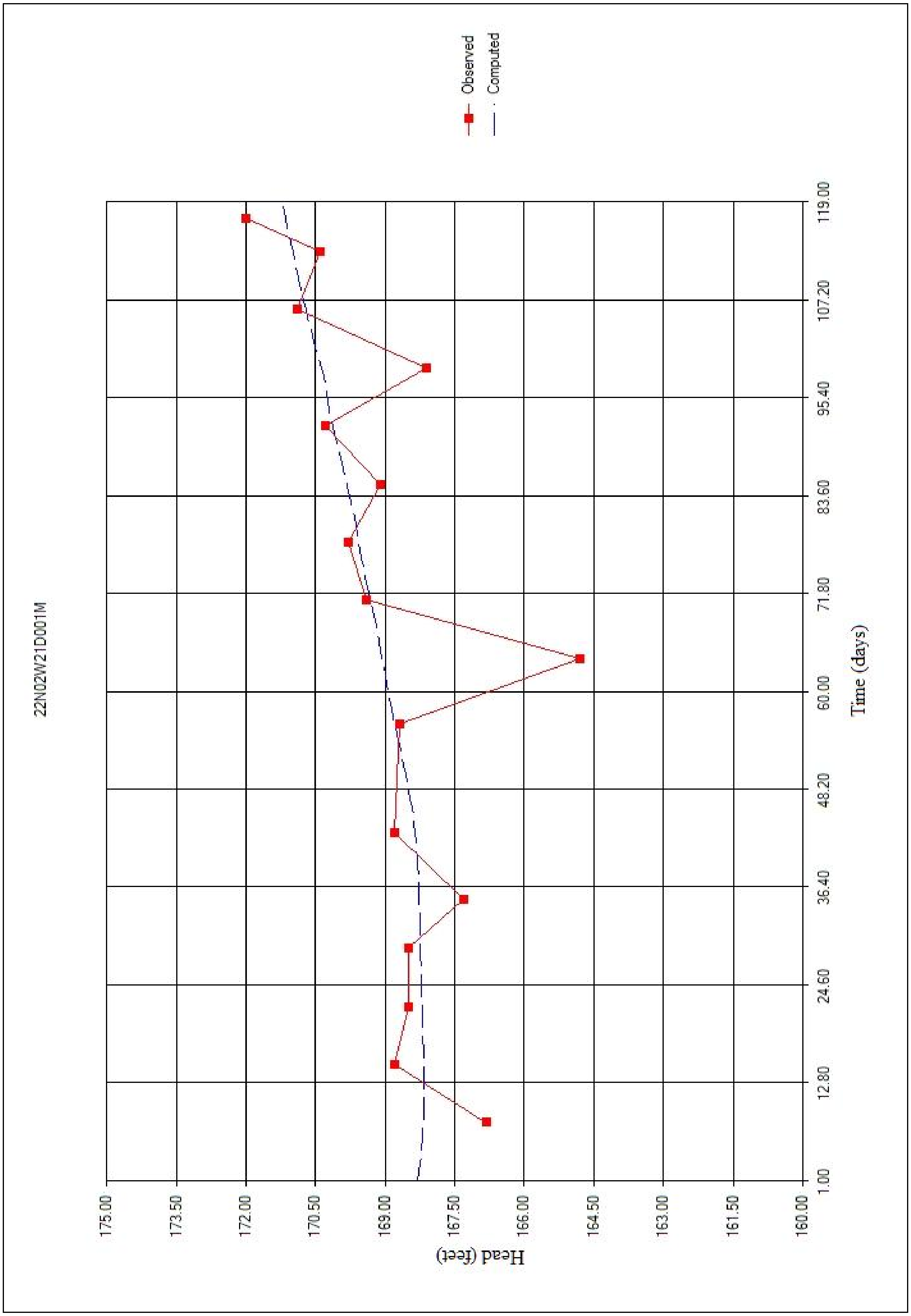
Table A.1 Location of Observation Wells

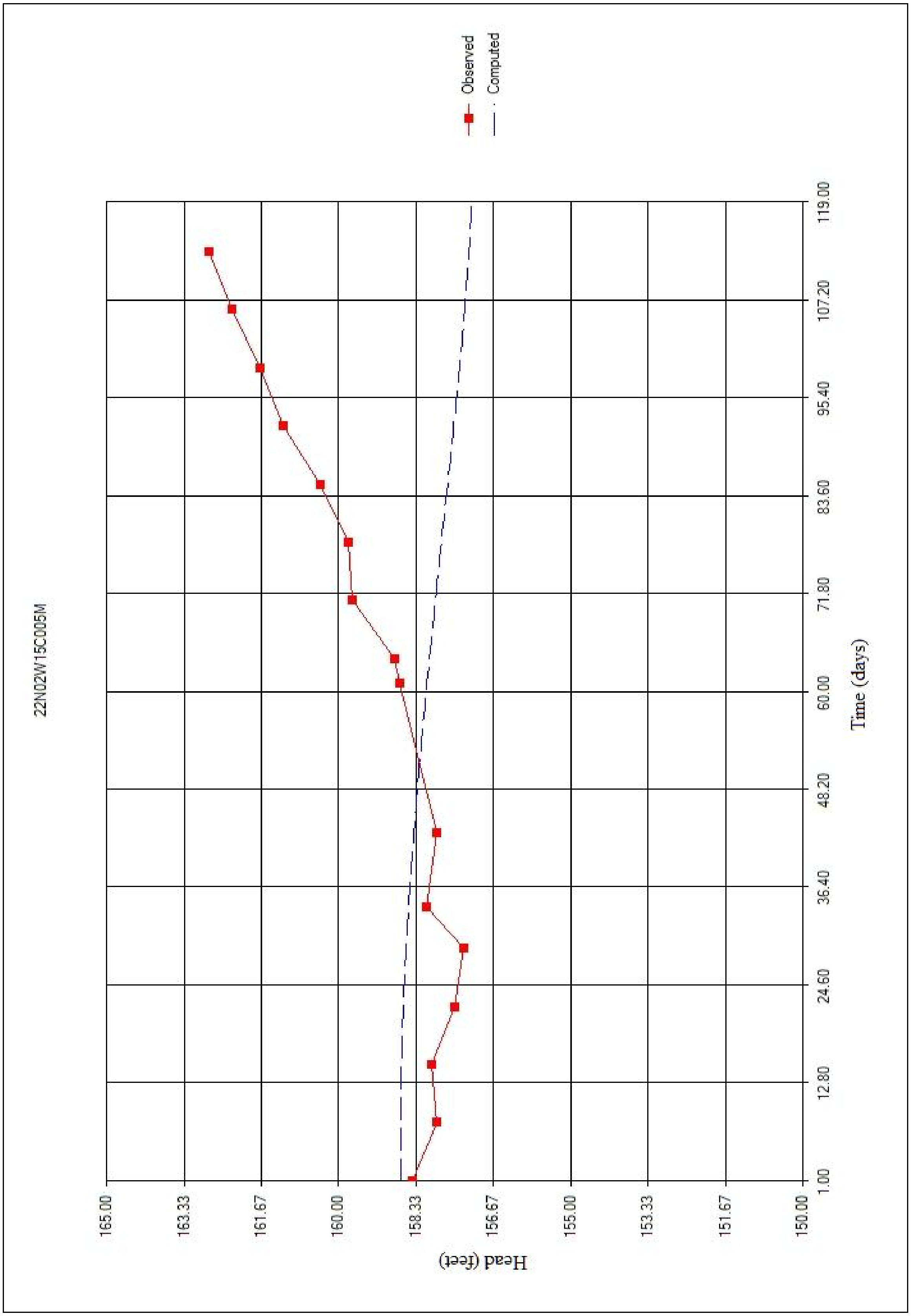

22N03W06B001M
Head (feet)
275.00
273.50
272.00
270.50
269.00
267.50
266.00
264.50
263.00
261.50
260.00
Time (days)
1.00
12.80
24.60
36.40
48.20
60.00
71.80
83.60
95.40
107.20
119.00
Observed
Computed

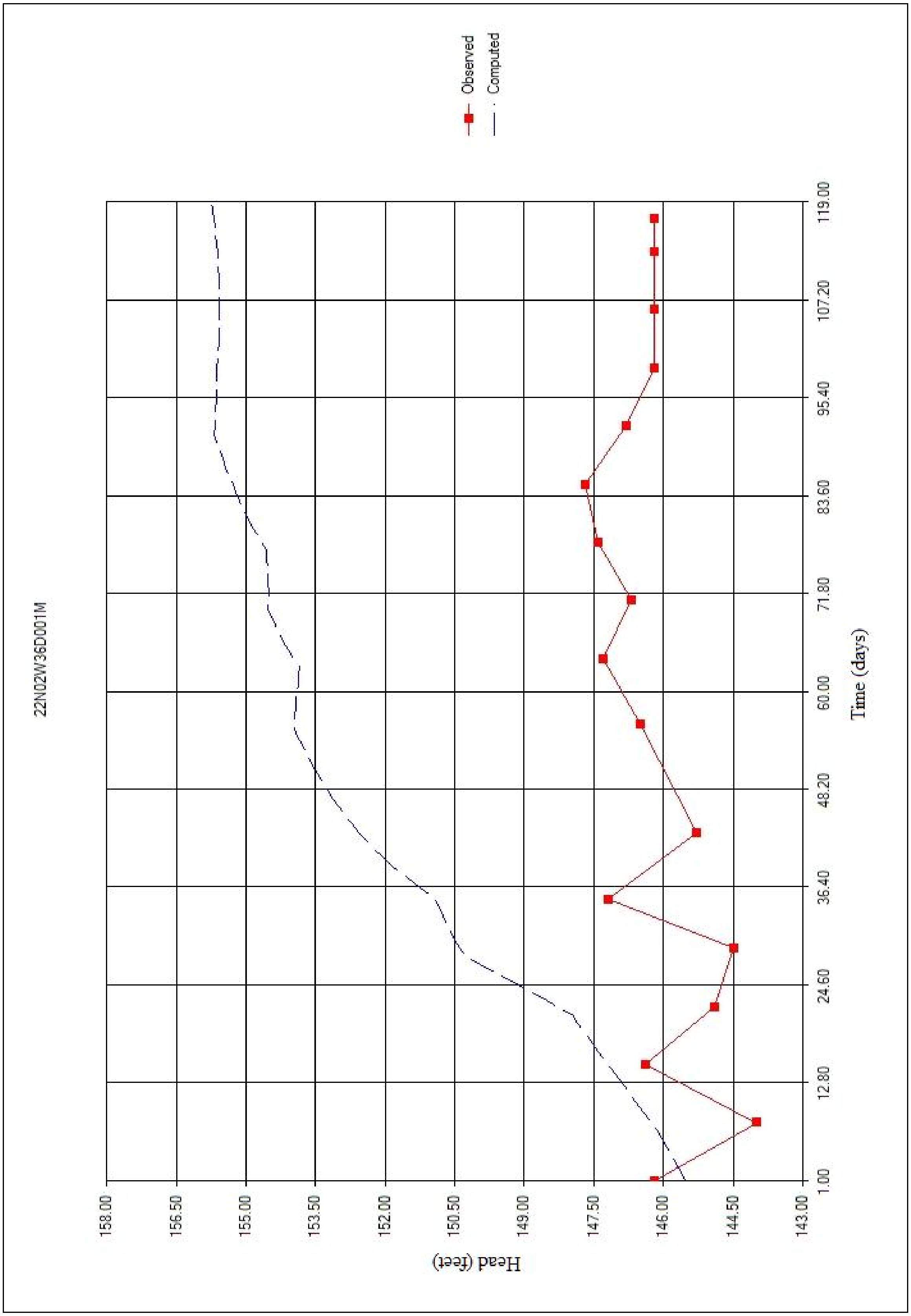

22N03W10R001M
Head (feet)
230.00
228.33
226.67
225.00
223.33
221.67
220.00
218.33
216.67
215.00
1.00
12.80
24.60
36.40
48.20
60.00
71.80
83.60
95.40
107.20
119.00
Time (days)
Observed
Computed

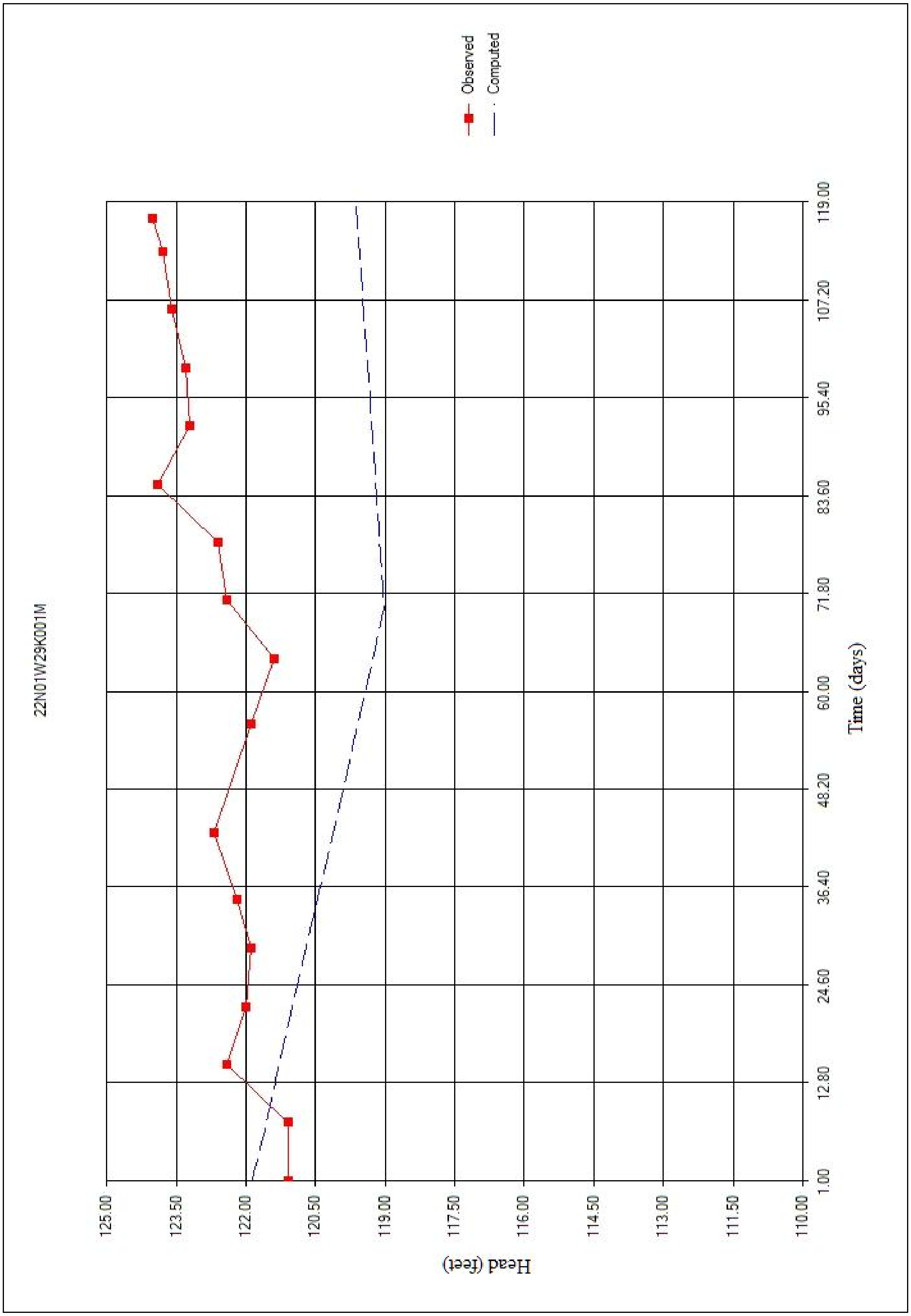

22N03W12Q003M
Observed
Computed
Head (feet)
195.00
193.50
192.00
190.50
189.00
187.50
186.00
184.50
183.00
181.50
180.00
Time (days)
1.00
12.80
24.60
36.40
48.20
60.00
71.80
83.60
95.40
107.20
119.00

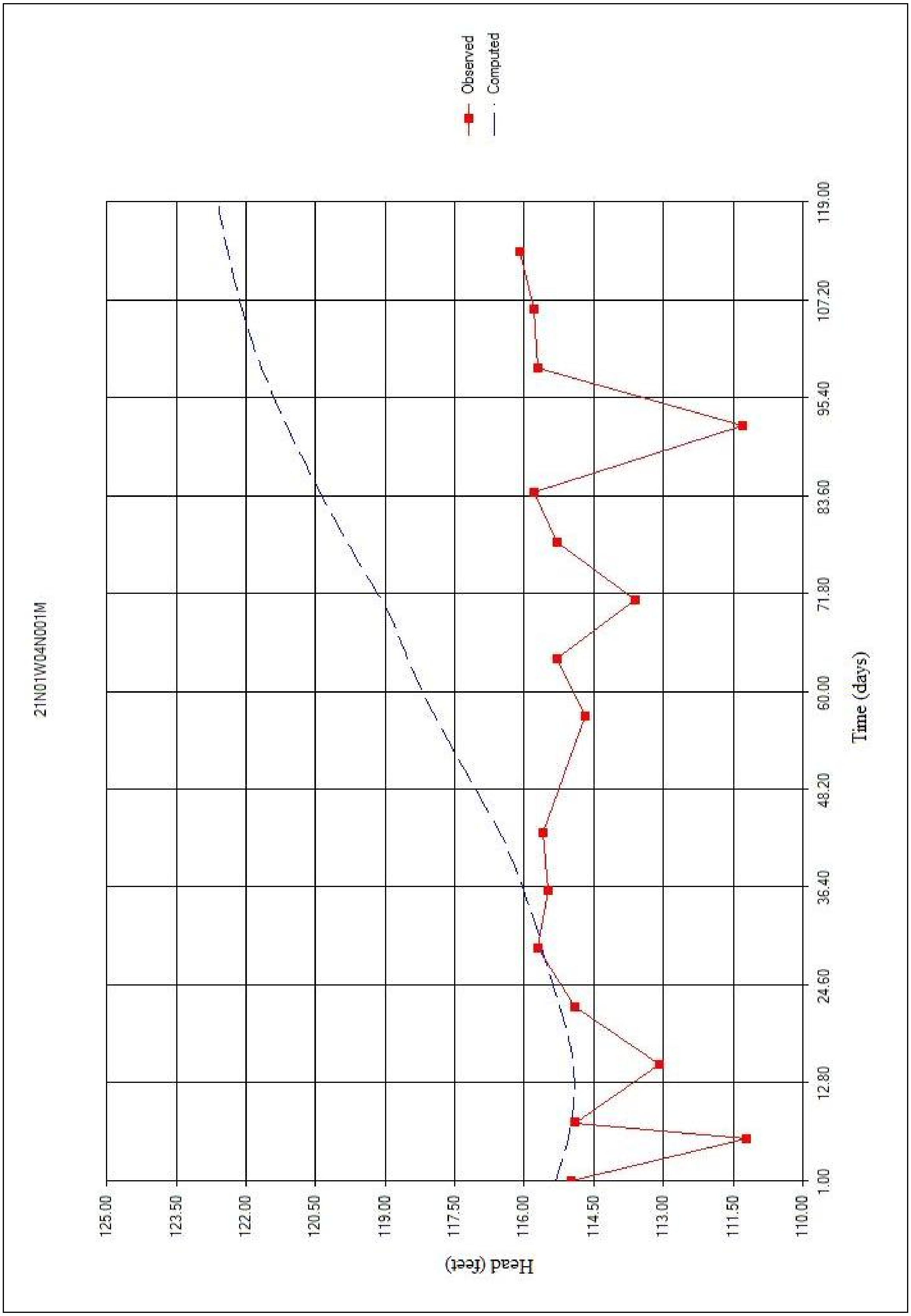

22N03W01R003M
Observed
Computed
Head (feet)
200.00
198.50
197.00
195.50
194.00
192.50
191.00
189.50
188.00
186.50
185.00
Time (days)
1.00
12.80
24.60
36.40
48.20
60.00
71.80
83.60
95.40
107.20
119.00

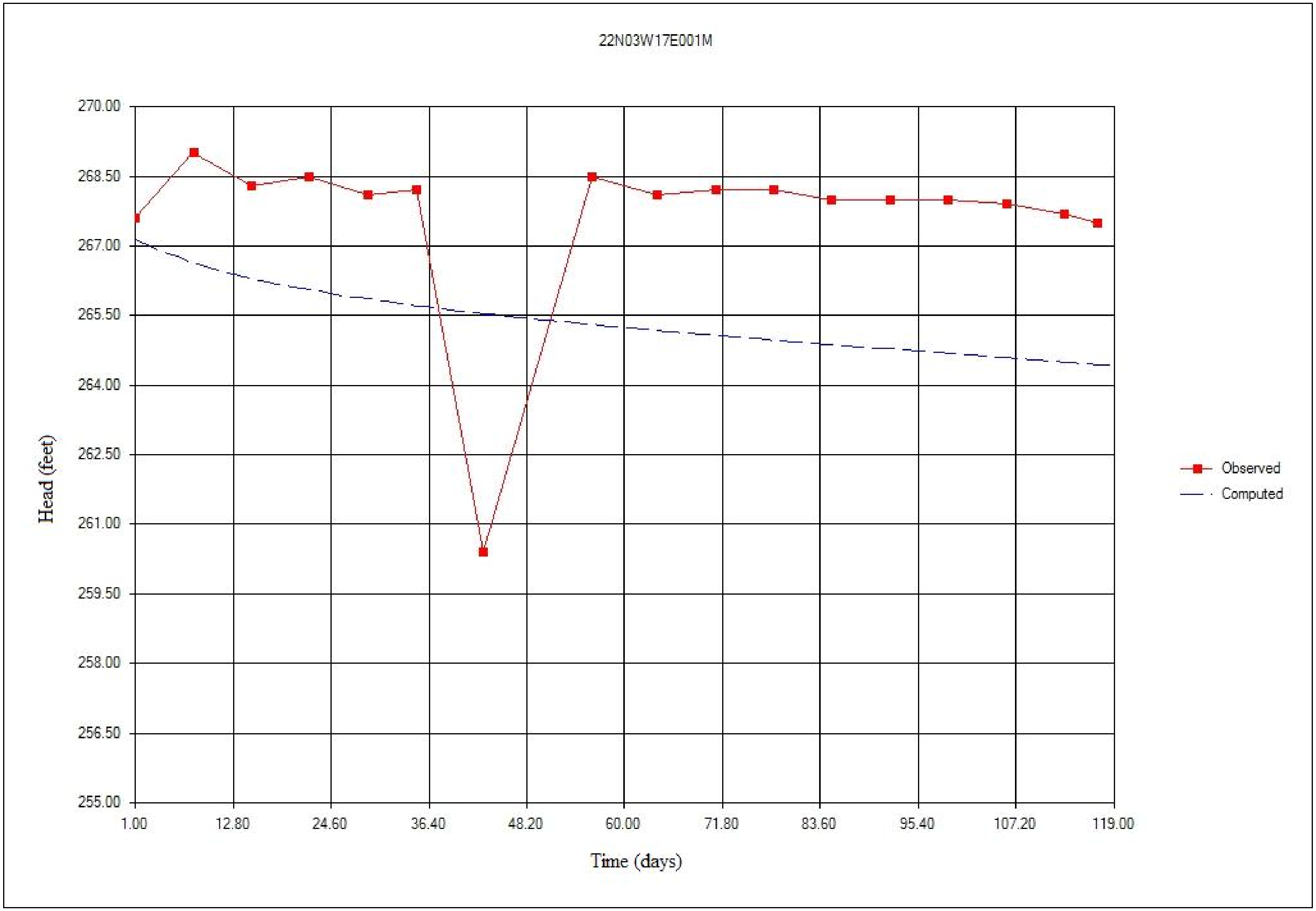

22N02W21D001M
Observed
Computed
Head (feet)
175.00
173.50
172.00
170.50
169.00
167.50
166.00
164.50
163.00
161.50
160.00
1.00
12.80
24.60
36.40
48.20
60.00
71.80
83.60
95.40
107.20
119.00
Time (days)

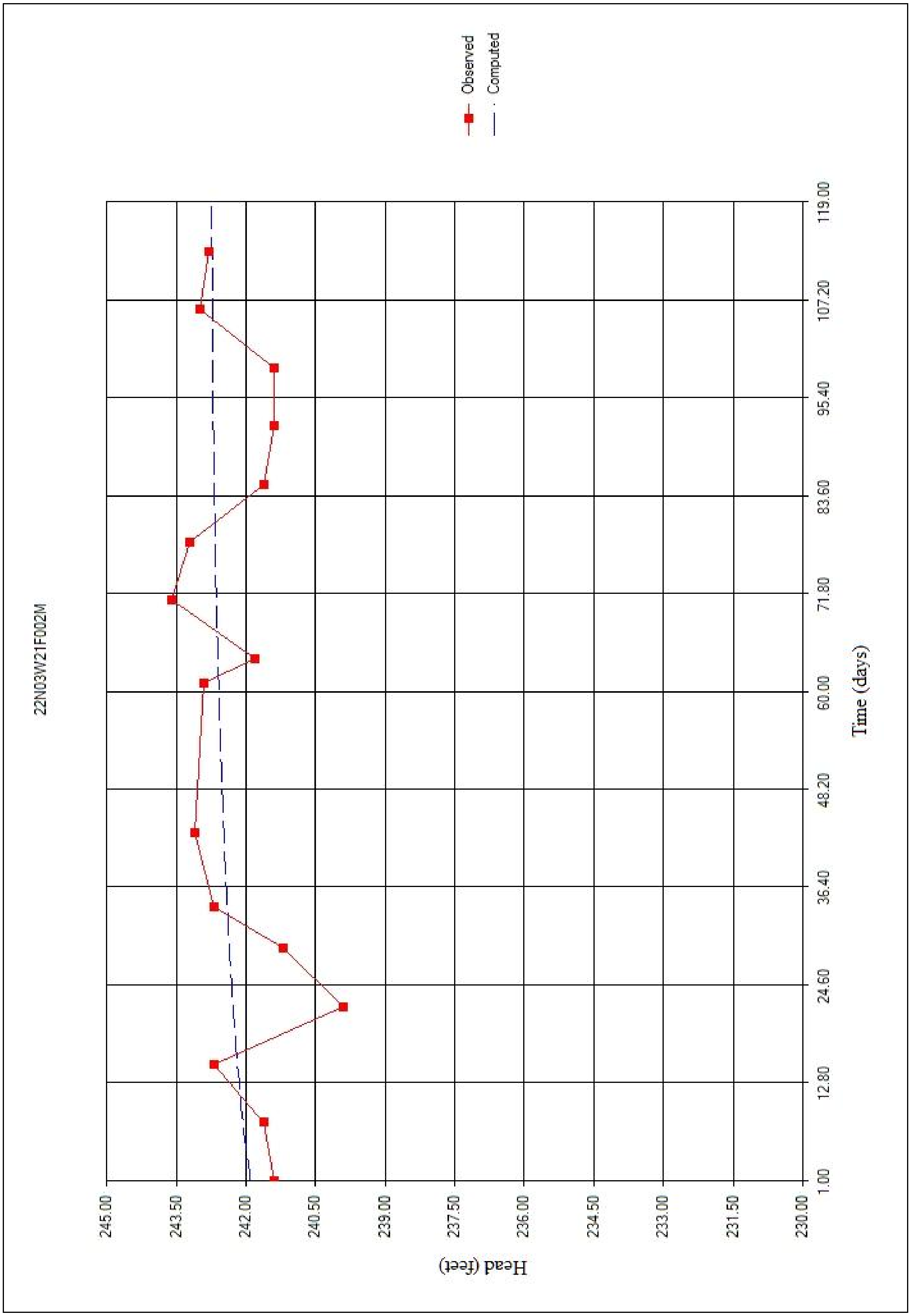

22N02W15C005M
Head (feet)
165.00
163.33
161.67
160.00
158.33
156.67
155.00
153.33
151.67
150.00
Time (days)
1.00
12.80
24.60
36.40
48.20
60.00
71.80
83.60
95.40
107.20
119.00
Observed
Computed

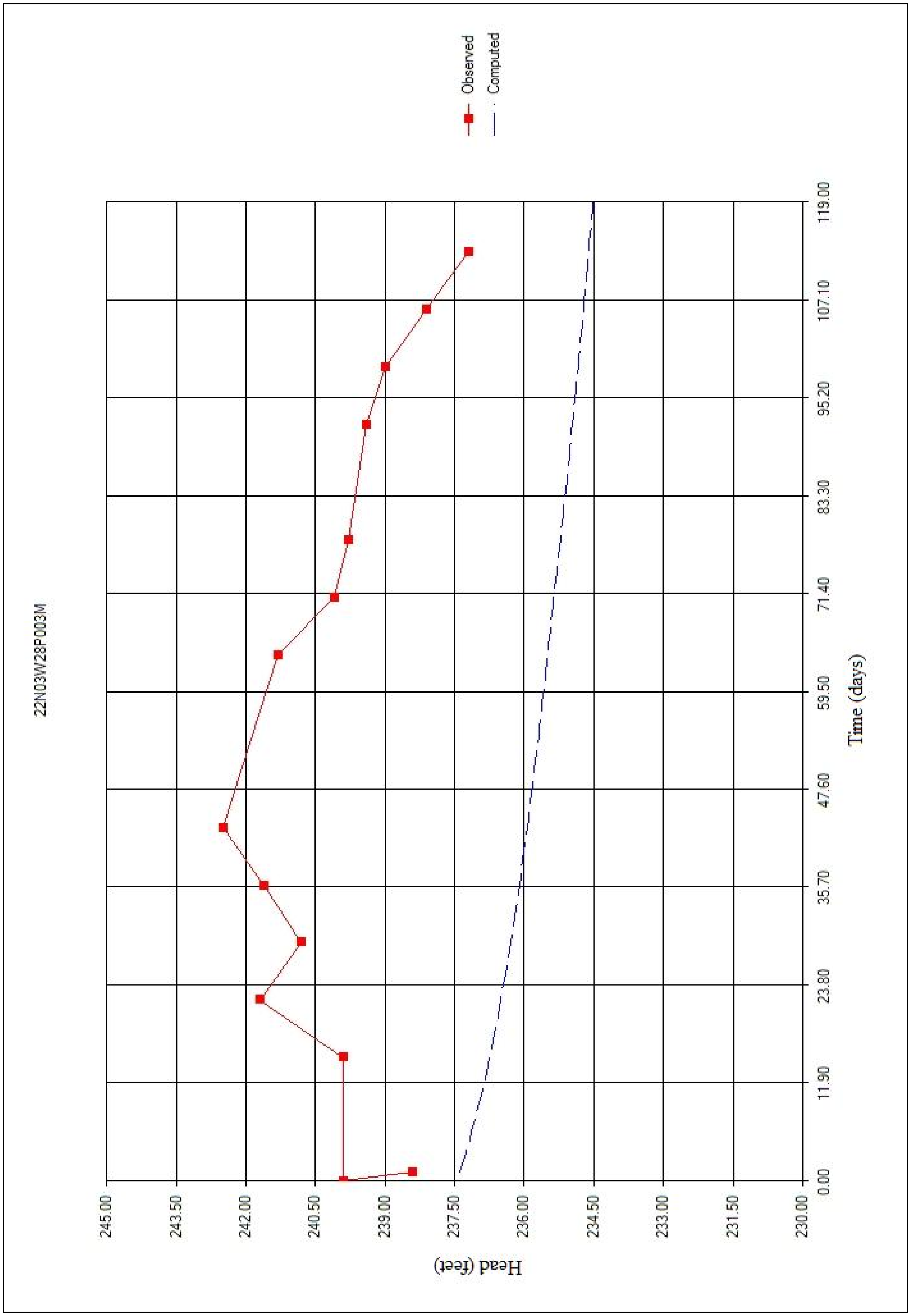

22N02W36D001M
Observed
Computed
Head (feet)
158.00
156.50
155.00
153.50
152.00
150.50
149.00
147.50
146.00
144.50
143.00
Time (days)
1.00
12.80
24.60
36.40
48.20
60.00
71.80
83.60
95.40
107.20
119.00

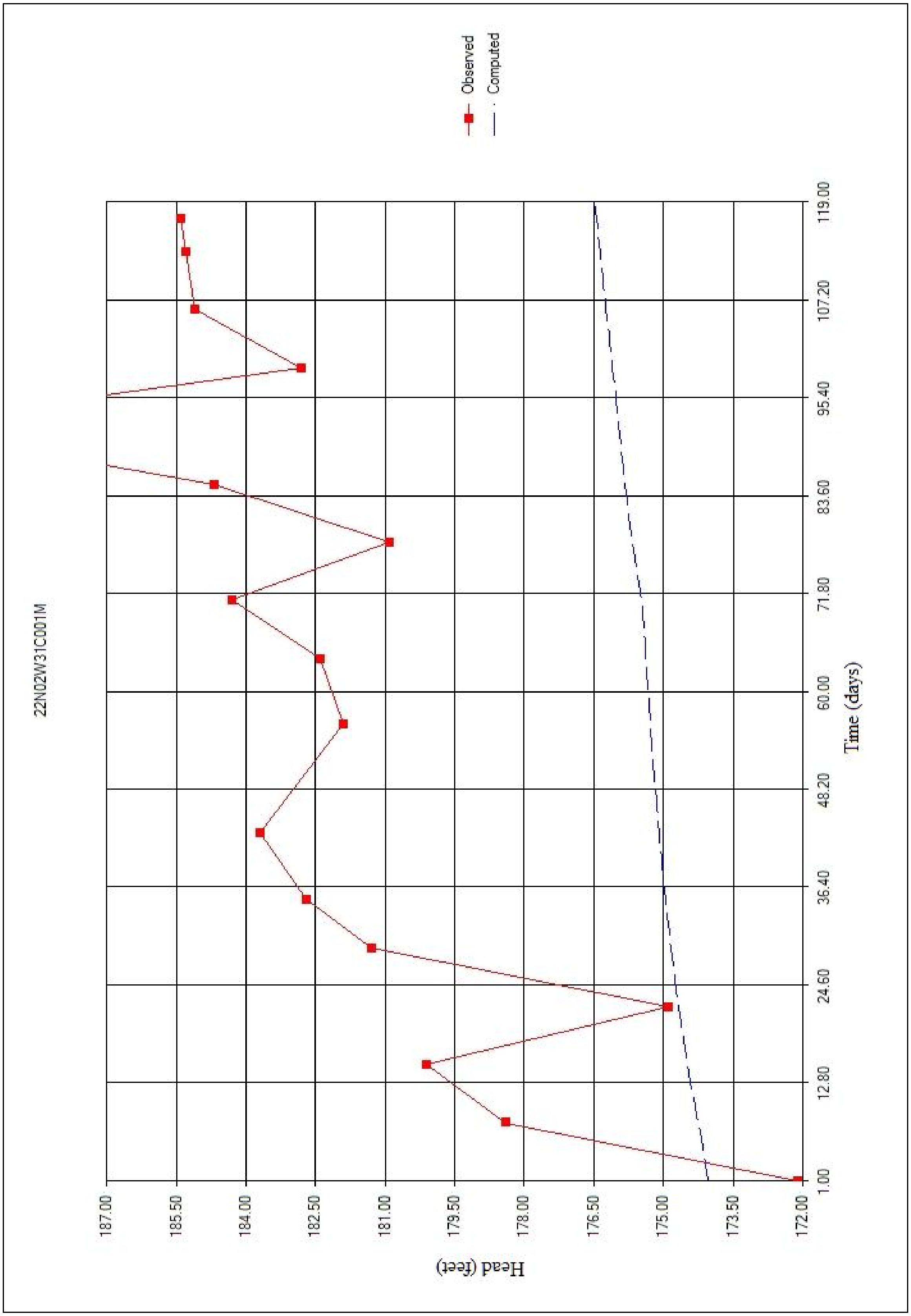

22N01W29K001M
Head (feet)
125.00
123.50
122.00
120.50
119.00
117.50
116.00
114.50
113.00
111.50
110.00
Time (days)
1.00
12.80
24.60
36.40
48.20
60.00
71.80
83.60
95.40
107.20
119.00
Observed
Computed

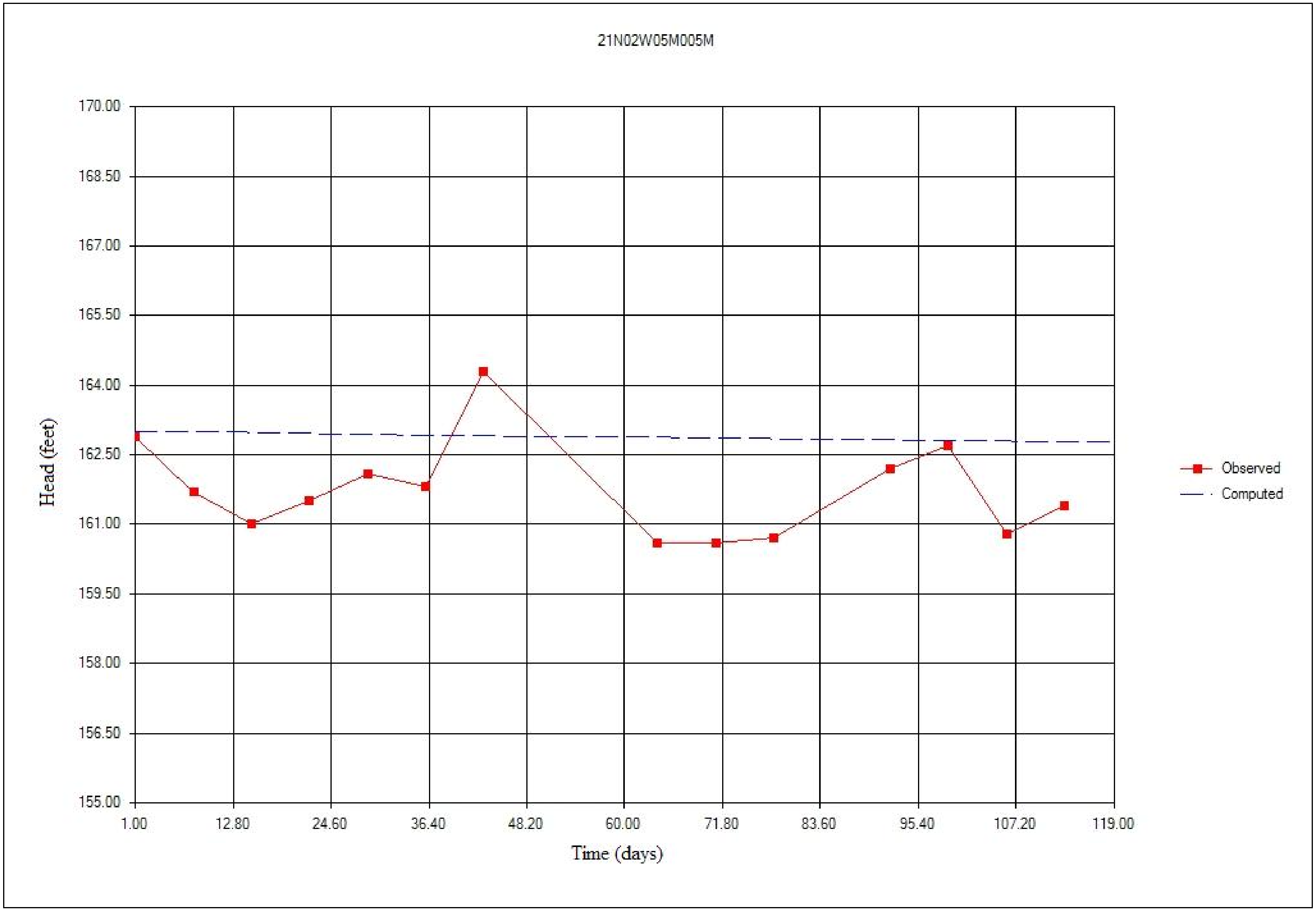

21N01W04N001M
Observed
Computed
Head (feet)
125.00
123.50
122.00
120.50
119.00
117.50
116.00
114.50
113.00
111.50
110.00
Time (days)
1.00
12.80
24.60
36.40
48.20
60.00
71.80
83.60
95.40
107.20
119.00

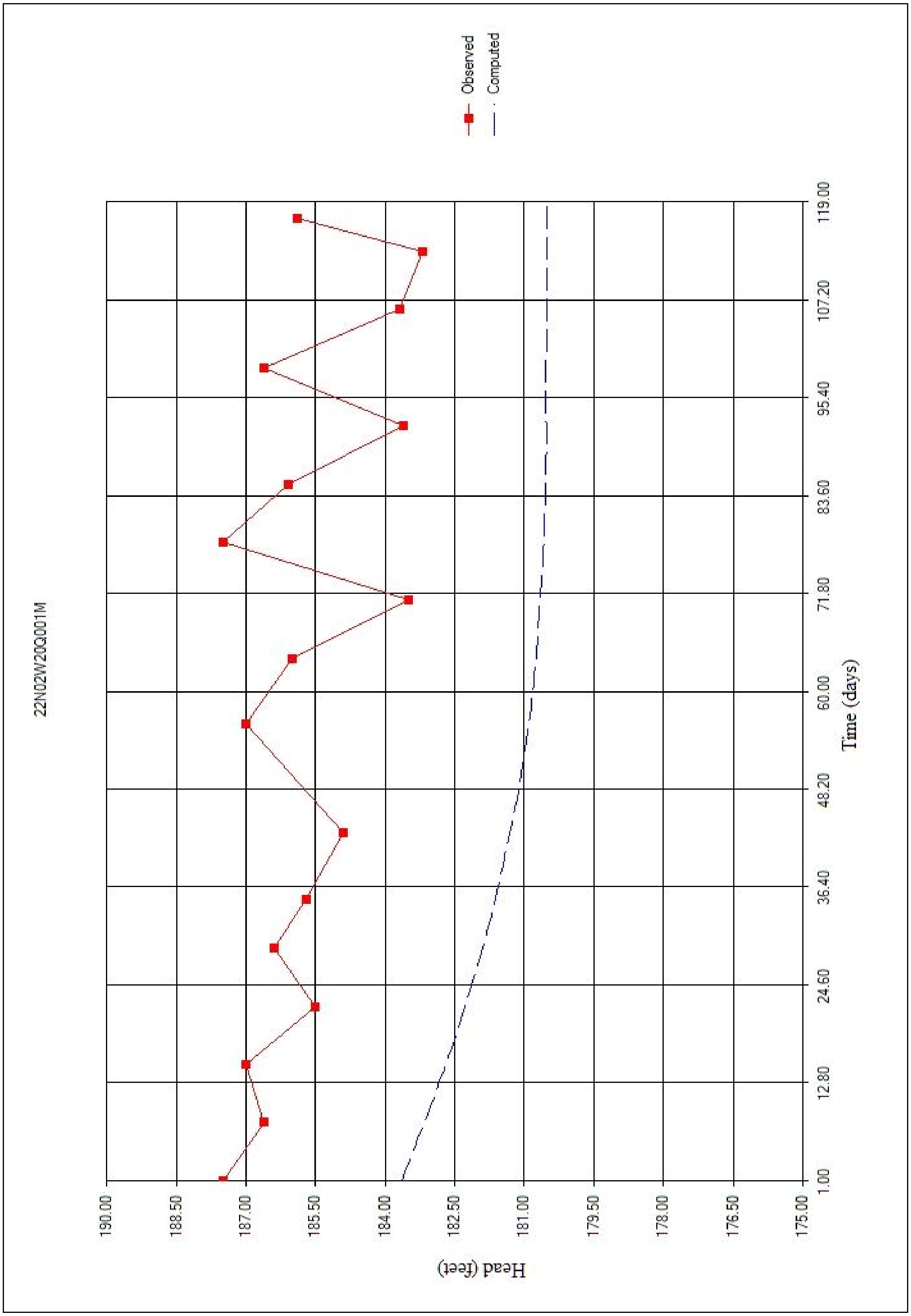

22N03W17E001M
Head (feet)
270.00
268.50
267.00
265.50
264.00
262.50
261.00
259.50
258.00
256.50
255.00
1.00
12.80
24.60
36.40
48.20
60.00
71.80
83.60
95.40
107.20
119.00
Time (days)
Observed
Computed

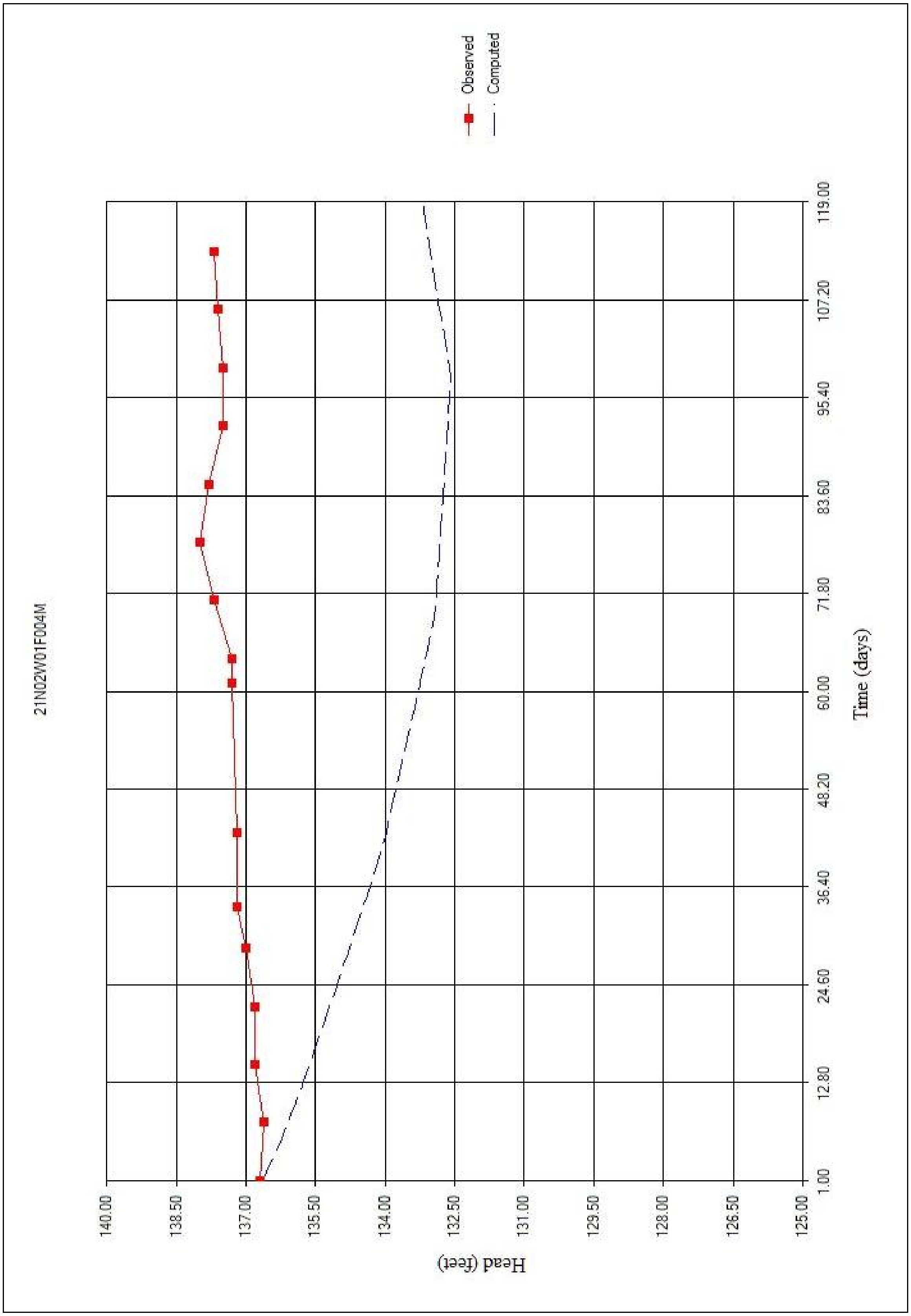

22N03W21F002M
Head (feet)
245.00
243.50
242.00
240.50
239.00
237.50
236.00
234.50
233.00
231.50
230.00
Time (days)
1.00
12.80
24.60
36.40
48.20
60.00
71.80
83.60
95.40
107.20
119.00
Observed
Computed

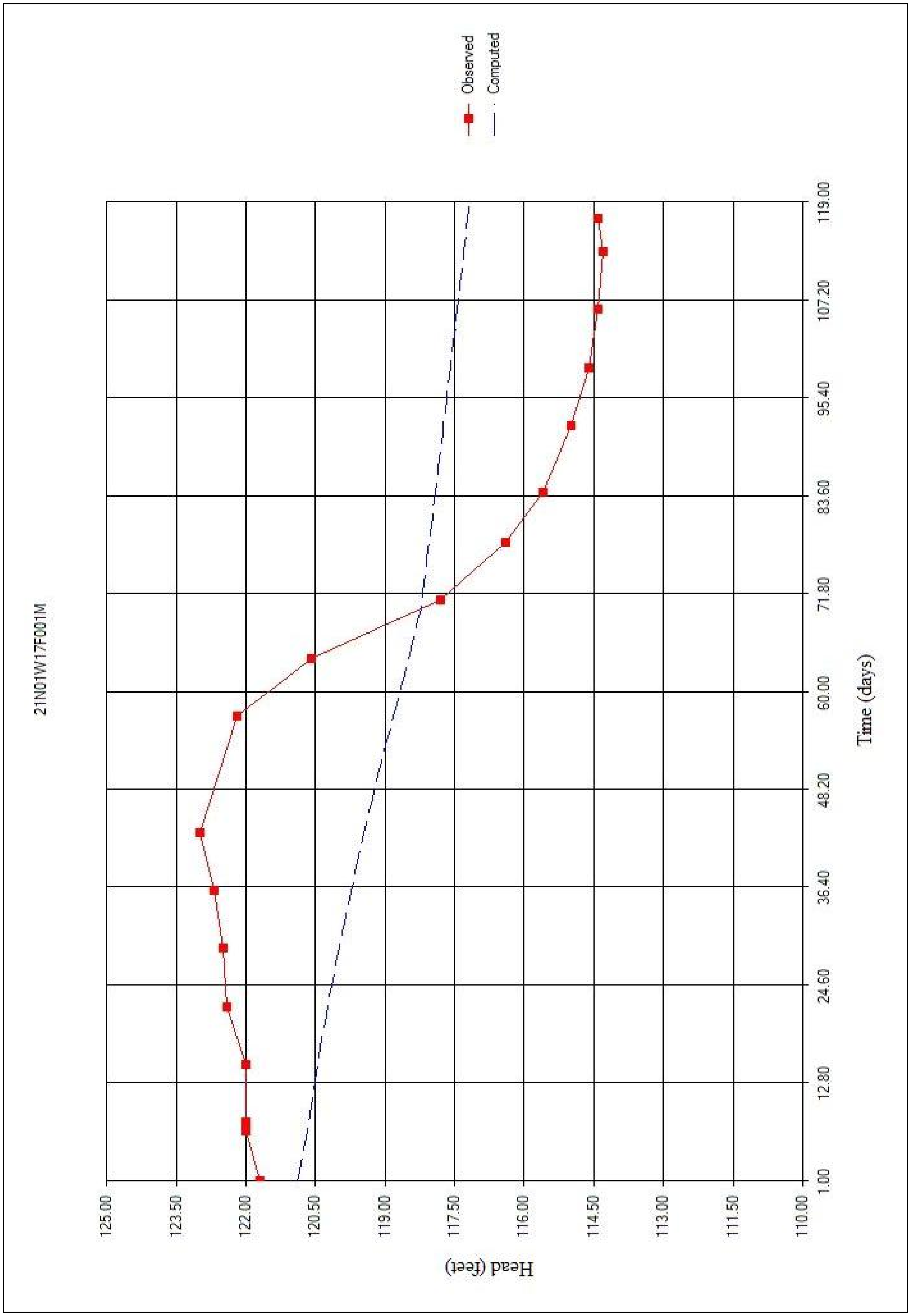

22N03W28P003M
Head (feet)
245.00
243.50
242.00
240.50
239.00
237.50
236.00
234.50
233.00
231.50
230.00
Time (days)
0.00
11.90
23.80
35.70
47.60
59.50
71.40
83.30
95.20
107.10
119.00
Observed
Computed


22N02W31C001M
Head (feet)
187.00
185.50
184.00
182.50
181.00
179.50
178.00
176.50
175.00
173.50
172.00
Time (days)
1.00
12.80
24.60
36.40
48.20
60.00
71.80
83.60
95.40
107.20
119.00
Observed
Computed

21N02W05M005M
Head (feet)
170.00
168.50
167.00
165.50
164.00
162.50
161.00
159.50
158.00
156.50
155.00
1.00
12.80
24.60
36.40
48.20
60.00
71.80
83.60
95.40
107.20
119.00
Time (days)
Observed
Computed


22N02W20Q001M
Observed
Computed
Head (feet)
190.00
188.50
187.00
185.50
184.00
182.50
181.00
179.50
178.00
176.50
175.00
Time (days)
1.00
12.80
24.60
36.40
48.20
60.00
71.80
83.60
95.40
107.20
119.00

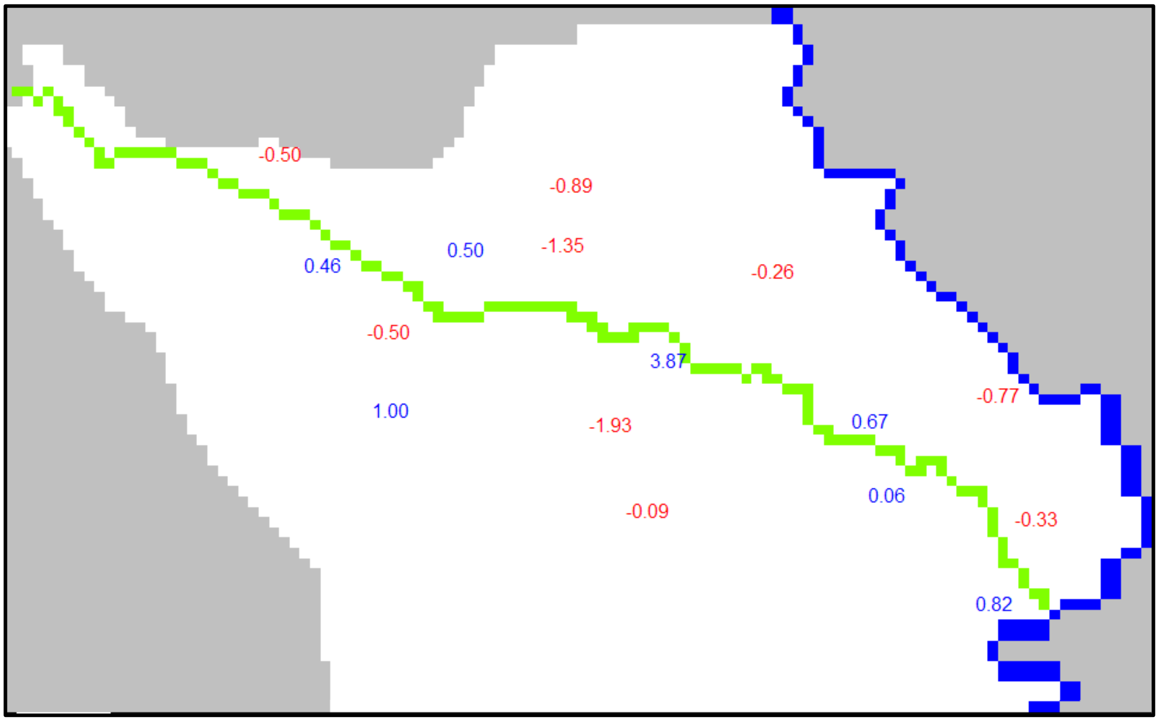

21N02W01F004M
Observed
Computed
Head (feet)
140.00
138.50
137.00
135.50
134.00
132.50
131.00
129.50
128.00
126.50
125.00
Time (days)
1.00
12.80
24.60
36.40
48.20
60.00
71.80
83.60
95.40
107.20
119.00


21N01W17F001M
Observed
Computed
Head (feet)
125.00
123.50
122.00
120.50
119.00
117.50
116.00
114.50
113.00
111.50
110.00
Time (days)
1.00
12.80
24.60
36.40
48.20
60.00
71.80
83.60
95.40
107.20
119.00

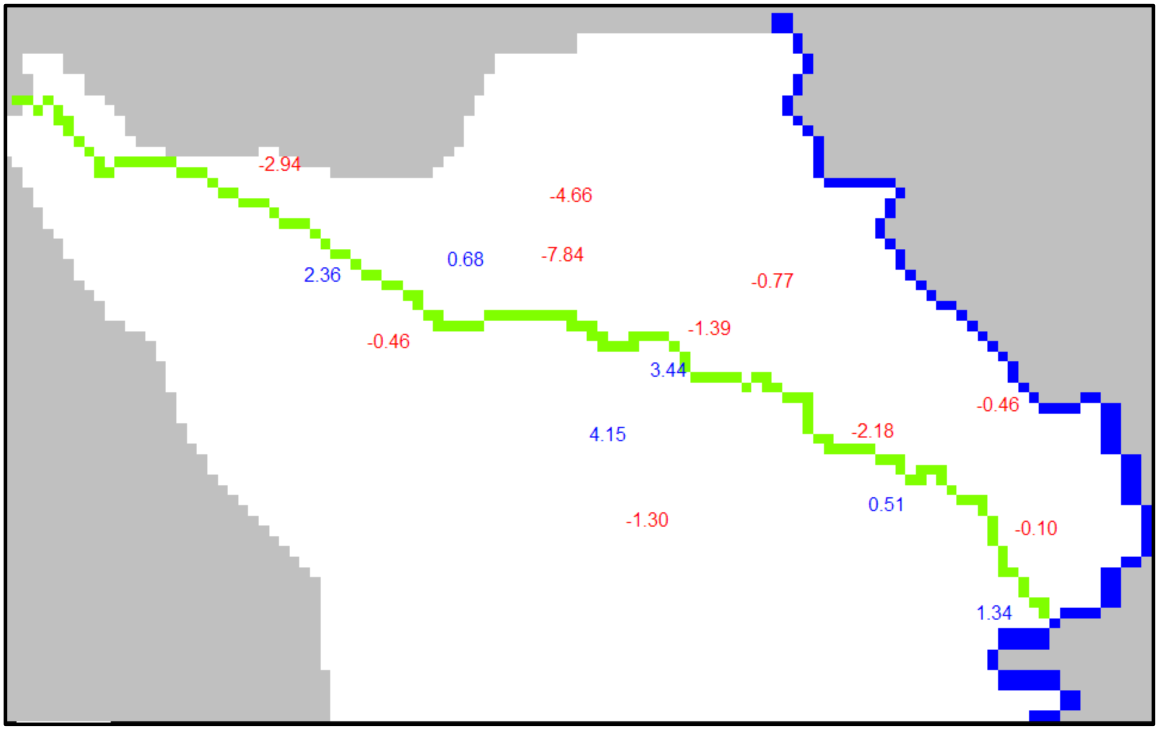
APPENDIX B: HEAD RESIDUALS AT SELECTED TIME STEPS

Appendix B presents differences between the model heads and observed heads at selected time steps during the calibration period. Residuals values are both positive (model > observed) and negative (model < observed) and provide an indication of the level of calibration in specific model areas and how it changes during the model period.

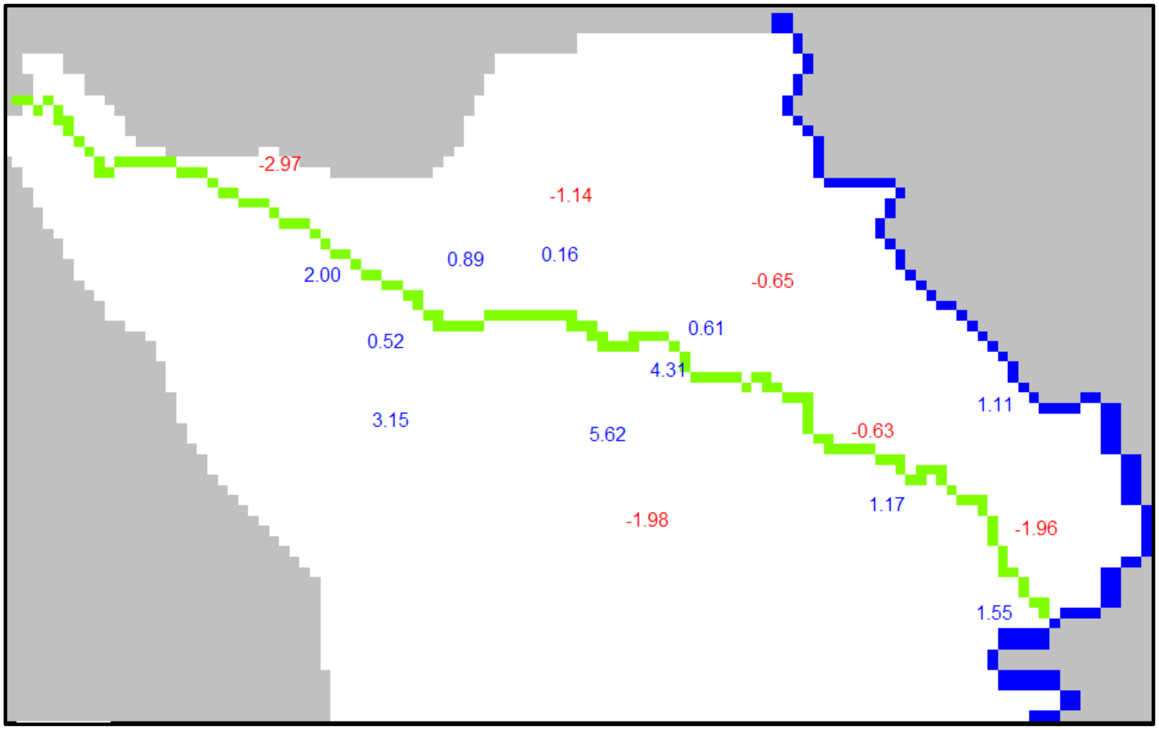
Model Head Residuals (in feet) for Time Step = 1



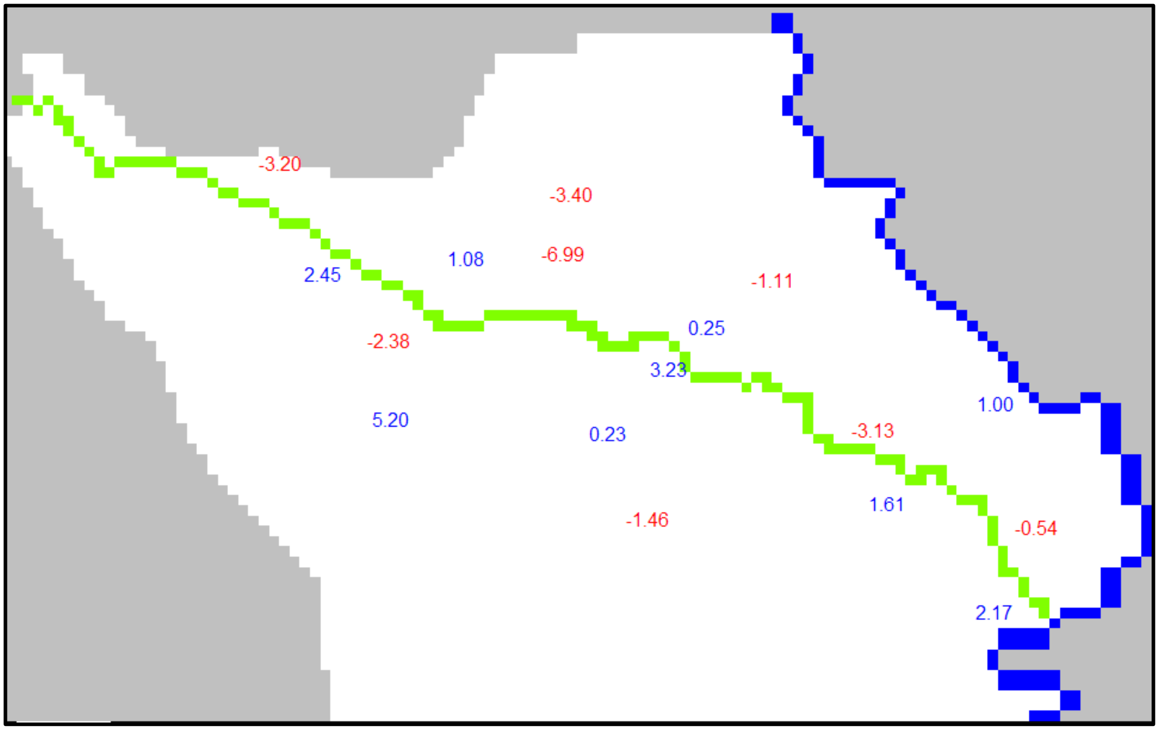
Model Head Residuals (in feet) for Time Step = 8



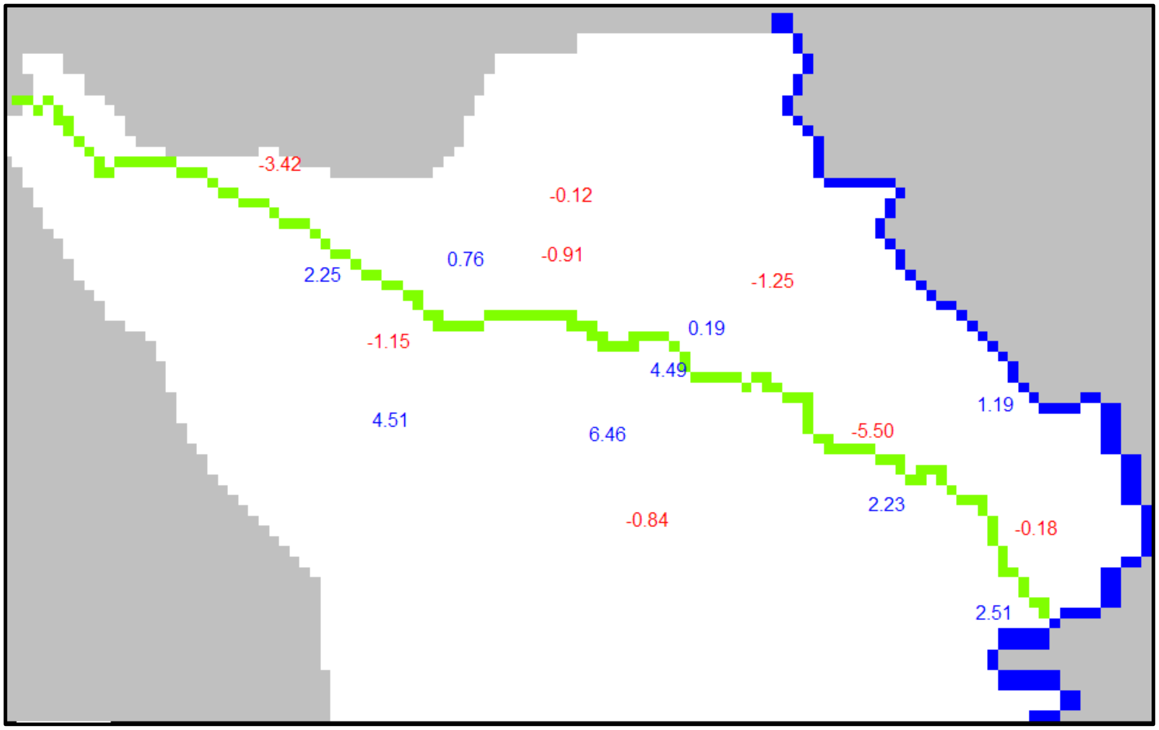
Model Head Residuals (in feet) for Time Step = 15



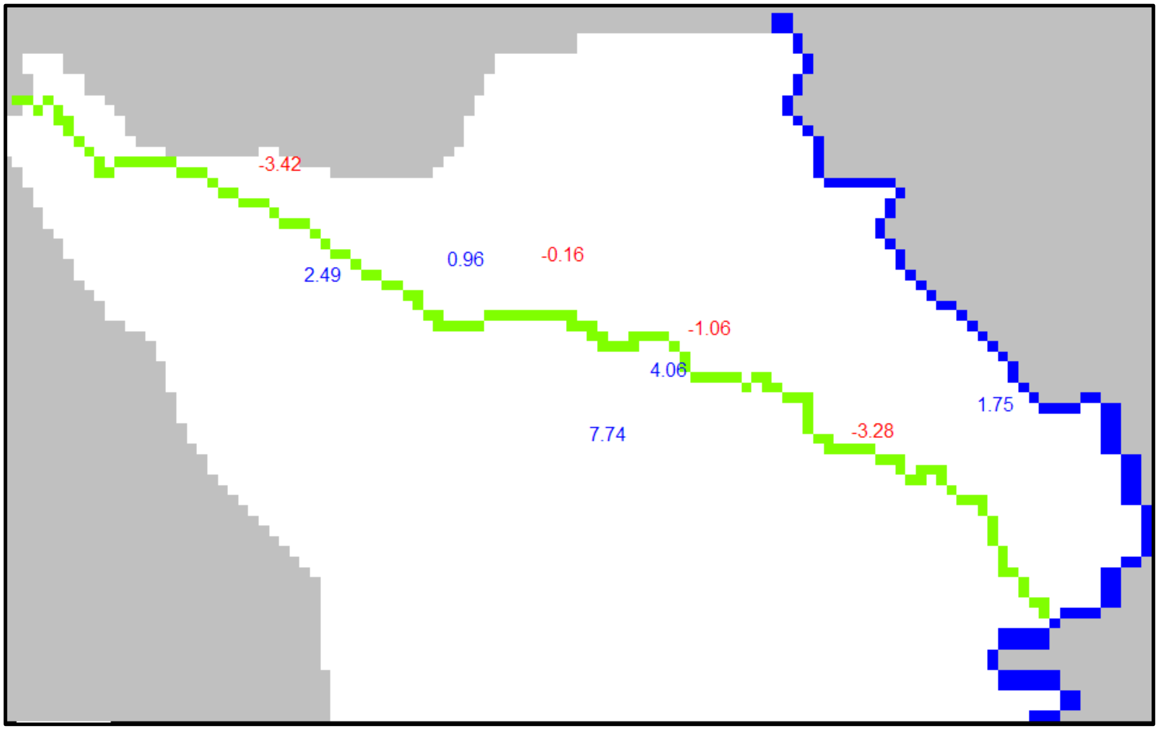
Model Head Residuals (in feet) for Time Step = 22



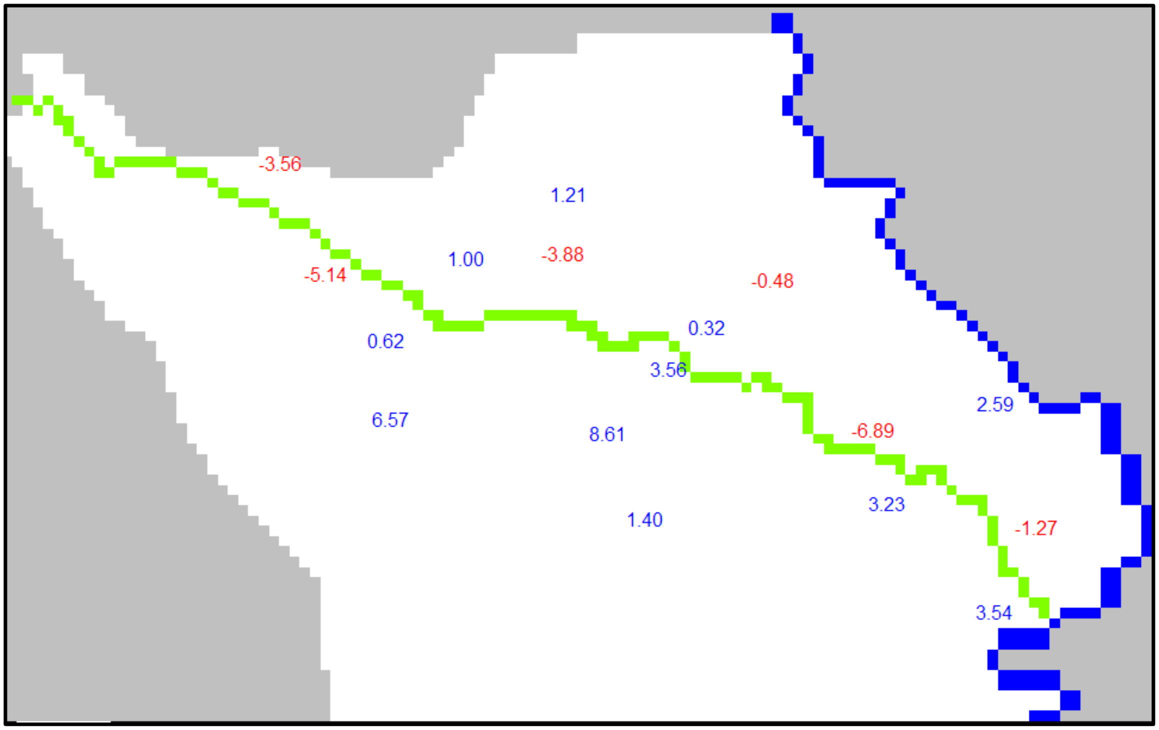
Model Head Residuals (in feet) for Time Step = 29



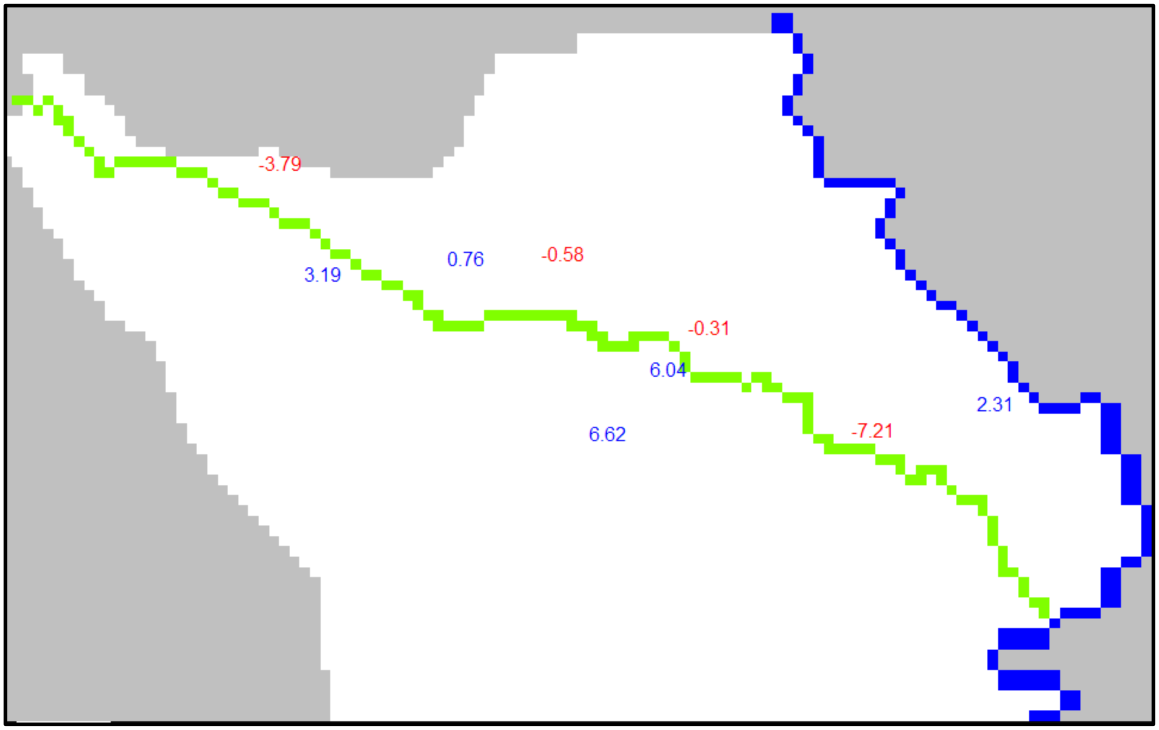
Model Head Residuals (in feet) for Time Step = 35



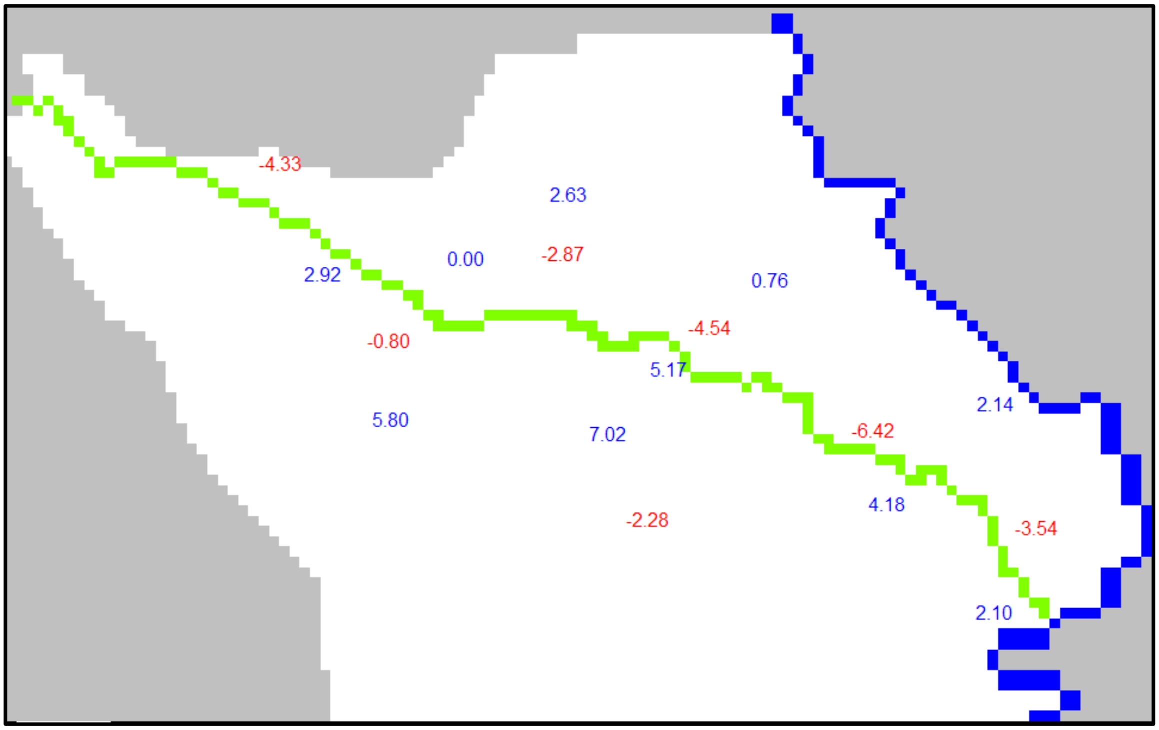
Model Head Residuals (in feet) for Time Step = 43



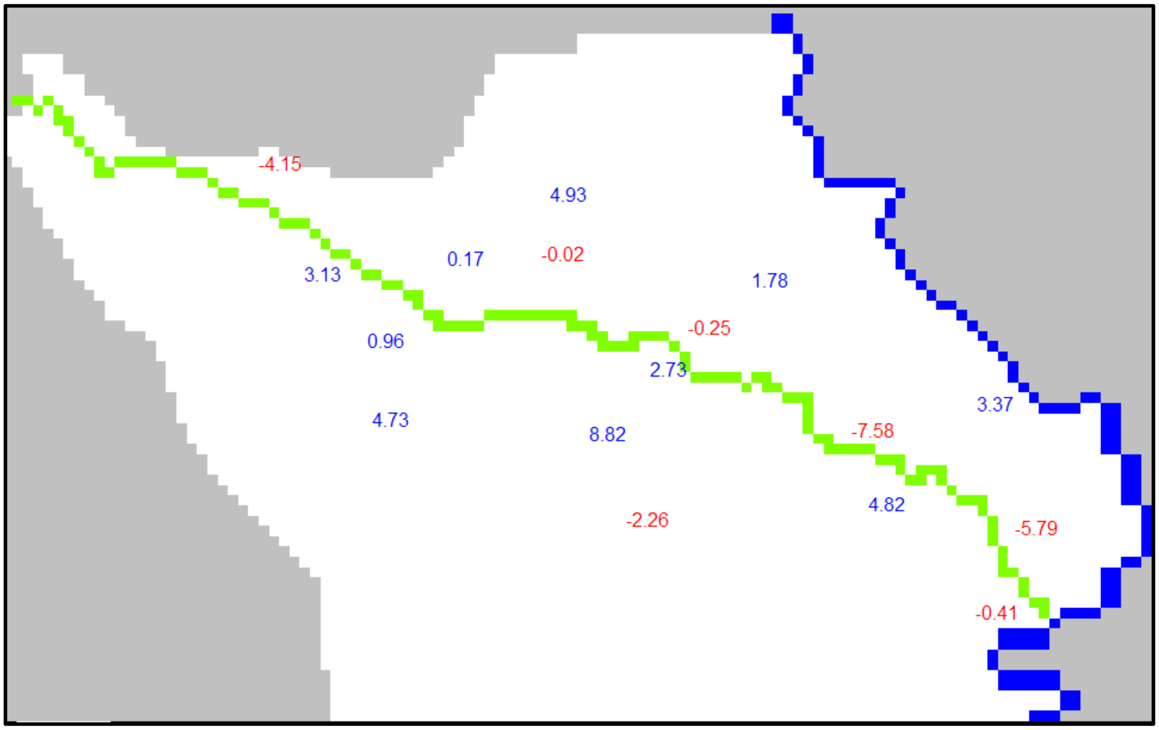
Model Head Residuals (in feet) for Time Step = 56



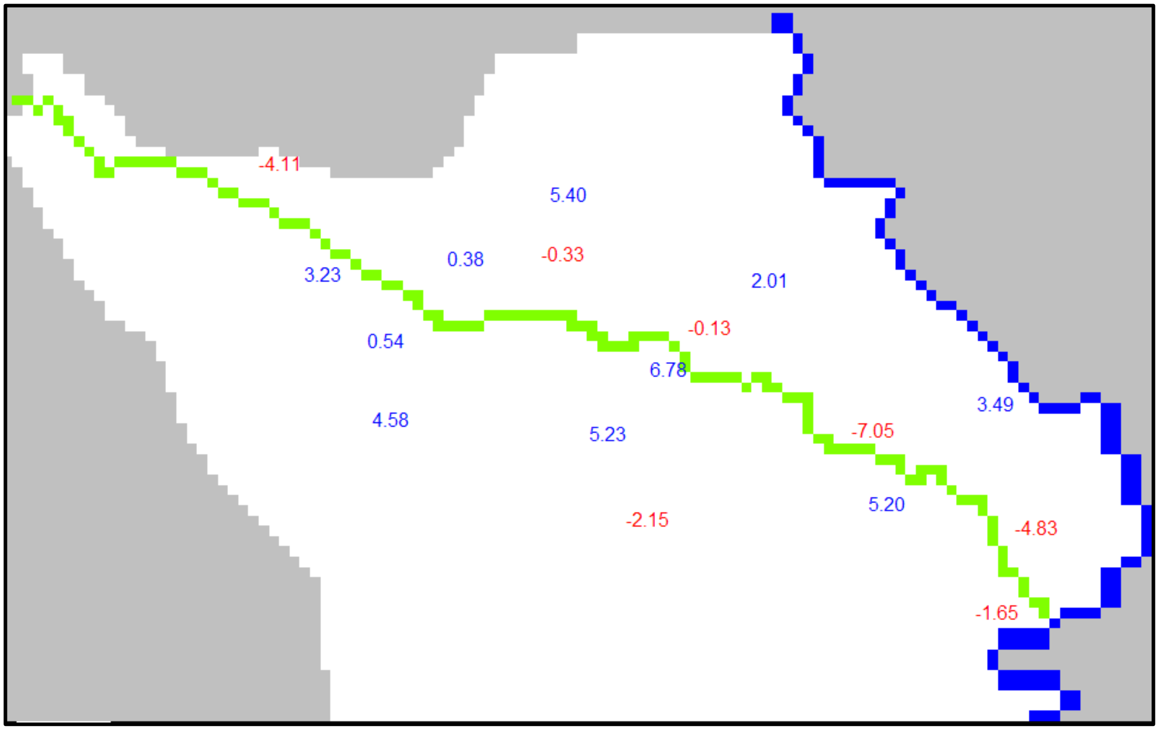
Model Head Residuals (in feet) for Time Step = 64



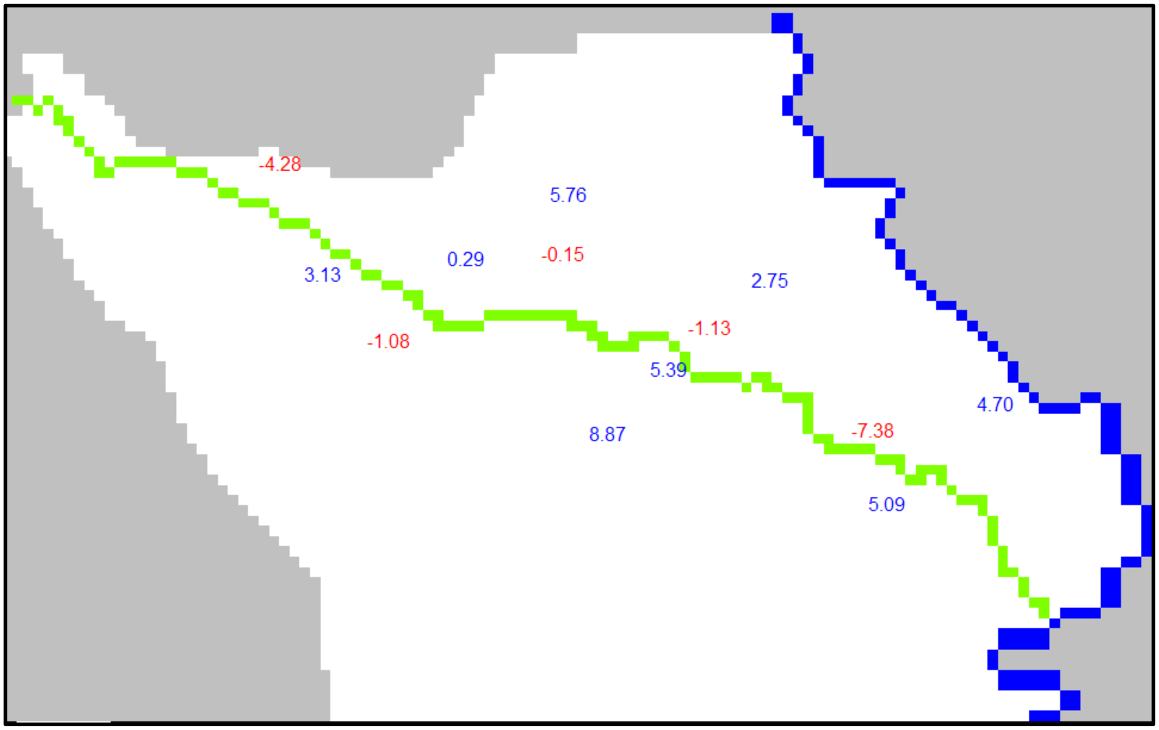
Model Head Residuals (in feet) for Time Step = 71



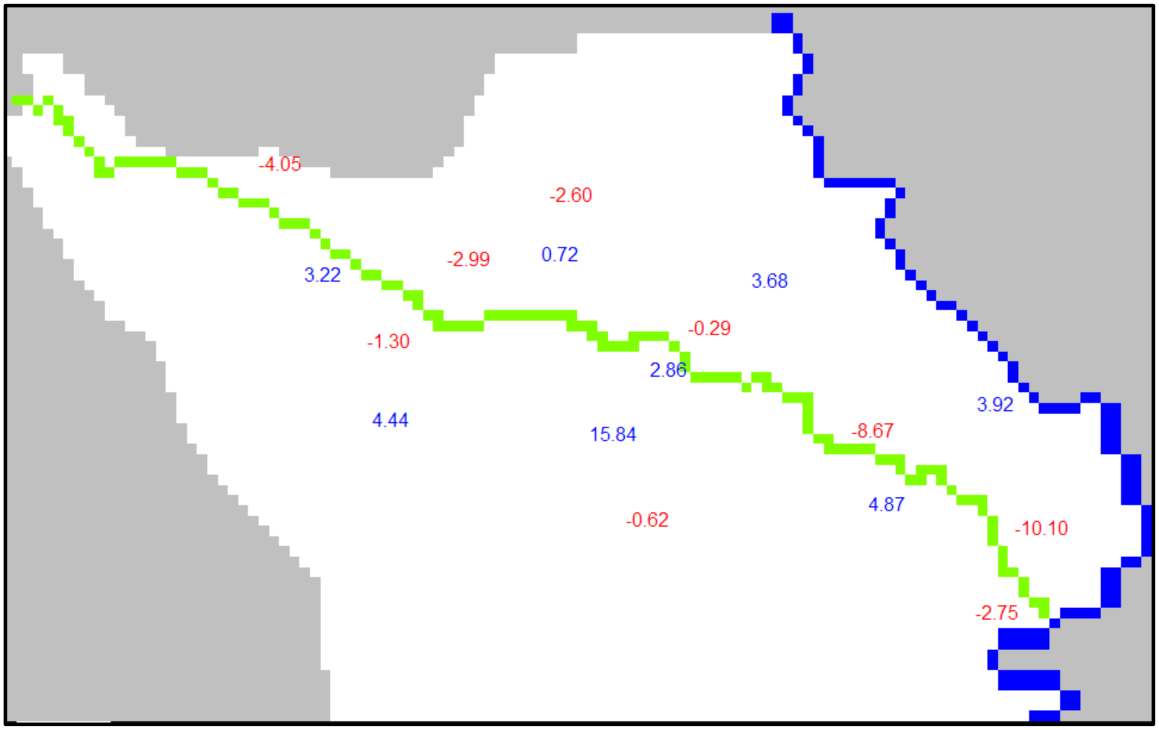
Model Head Residuals (in feet) for Time Step = 78



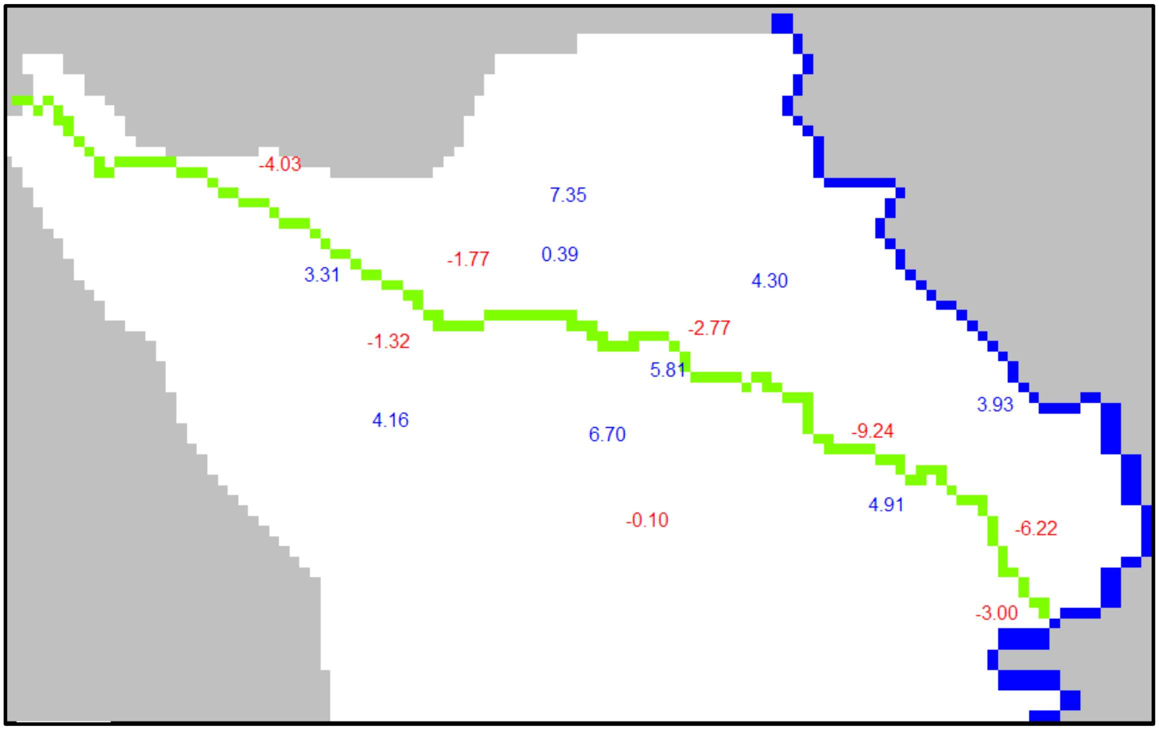
Model Head Residuals (in feet) for Time Step = 85



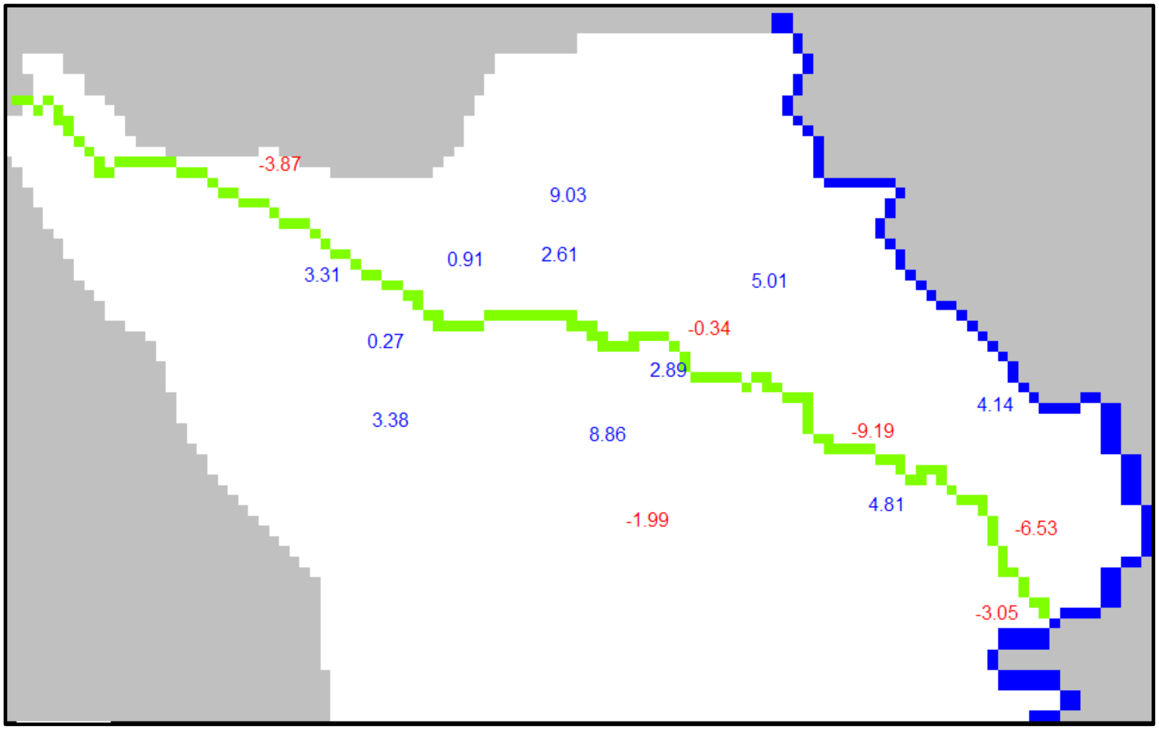
Model Head Residuals (in feet) for Time Step = 92



Model Head Residuals (in feet) for Time Step = 99



Model Head Residuals (in feet) for Time Step = 106



Model Head Residuals (in feet) for Time Step = 113