Susitna-Watana Hydroelectric Project
(FERC No. 14241)

Groundwater Study
Study Plan Section 7.5

2014-2015 Study Implementation Report

Appendix B

Preliminary MODFLOW Three Dimensional Groundwater Model for FA-128 (Slough 8A)

Prepared for

Alaska Energy Authority

SUSITNA-WATANA HYDRO
Clean, reliable energy for the next 100 years.

Prepared by

Pacific Groundwater Group

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LIST OF ACRONYMS AND SCIENTIFIC LABELS

Abbreviation	Definition
1-D	One-dimensional
3-D	Three-dimensional
AEA	Alaska Energy Authority
ASTM	American Society for Testing and Materials
Cfs	cubic feet per second
DPM	Deep Percolation Model
FERC	Federal Energy Regulatory Commission
Ft	Foot
GHB	General Head Boundary
GIS	Geographic Information System
GUI	Graphic User Interface
GW/SW	Groundwater / Surface Water
ISR	Initial Study Report
LiDAR	Light Detection and Ranging
OWFRM	Open-water Flow Routing Model
PHABSIM	Physical Habitat Simulation
PRM	Project River Mile
Project	Susitna-Watana Hydroelectric Project, FERC No. 14241
QC	Quality Control
RMSE	Root-Mean-Square Error
RSP	Revised Study Plan
SP	Stress Periods
USGS	United States Geological Survey

1. INTRODUCTION

On December 14, 2012, Alaska Energy Authority (AEA) filed with the Federal Energy Regulatory Commission (FERC) its Revised Study Plan (RSP) to support the federal licensing process of the Susitna-Watana Hydroelectric Project (FERC No. 14241). The RSP included 58 individual study plans (AEA 2012). Included within the RSP was the Groundwater Study, Section 7.5. RSP Section 7.5 focuses on providing an overall understanding of groundwater/surface water (GW/SW) interactions at both the watershed - and local - scales. This understanding will be used in evaluating Project operational effects on GW/SW interactions and resulting effects on riparian and aquatic habitats.

Operation of the Susitna-Watana Hydroelectric Project (Project) is expected to change the hydrologic characteristics of the riverine portion of the drainage downstream of the proposed Dam and the mainstem Susitna River reach inundated by the Project reservoir. Project operations will cause seasonal, daily, and hourly changes in Susitna River flows compared to existing conditions. The potential alteration in flows will influence downstream resources/processes, including fish and aquatic biota and their habitats, channel form and function including sediment transport, water quality, GW/SW interactions, ice dynamics, and riparian and wildlife communities.

Development of a groundwater flow model (MODFLOW) was specified as part of the Groundwater Study (7.5) as described in the FERC-approved Study Plan. Groundwater modeling will be used and integrated with other groundwater analyses and existing aquatic studies for evaluating potential impacts to both fish and aquatic habitats, as well as riparian habitats associated with future operations of the Project. Seasonal changes during project operation may include lower discharges during the summer reservoir refill period, higher discharges during the winter, and hourly load-following operations to meet energy demands.

Studies have documented the importance of groundwater upwelling in the selection of spawning areas within the Middle River Segment of the Susitna River by sockeye and chum salmon (Summary Review of Susitna River Aquatic and Instream Flow Studies Conducted in the 1980s with Relevance to Proposed Susitna – Watana Dam Project – 2012: A Compendium of Technical Memoranda submitted to the FERC March 25, 2013 [R2 2013]; Evaluation of Relationships between Fish Abundance and Specific Microhabitat Variables submitted to the FERC September 17, 2014 [R2 2014a]; SIR Study 8.5, Appendix D, Habitat Suitability Criteria Development submitted to the FERC November 2015 [R2 2015a]). In addition, groundwater upwelling plays an important role in maintaining suitable surface water temperatures for egg incubation, fry development and juvenile salmonid rearing during the winter months (R2 2013; Lorenz and Filer 1998; Douglas 2006; Durst 2000). Groundwater may also play an important role in the sustainability of riparian communities within the system. The amount of groundwater upwelling is dependent on the magnitude, direction, and duration of the vertical hydraulic gradient between the river surface water stage and groundwater in the underlying aquifer. Groundwater upwelling in lateral habitats can be generated from small scale features within the hyporheic zone of a stream system or from large scale recharge/discharge features within a groundwater basin.

2. STUDY OBJECTIVES

This appendix (Appendix B) is specific to objectives 5 and 6 of the Groundwater Study (Study 7.5) as specified in RSP Section 7.5.1. These two objectives are focused on evaluation of groundwater-influenced floodplain, and aquatic habitats (i.e., groundwater upwelling/downwelling areas), respectively. The specific objective of the work described in this appendix was to develop a preliminary three-dimensional (3-D) MODFLOW groundwater model for Focus Area 128 (FA-128 [Slough 8A]) to better understand the relationship between surface water and groundwater and that can be used to evaluate potential impacts on groundwater upwelling associated with future project operations. The model was developed over a two month period and relied on existing site data reviewed at Quality Control (QC) Level 3. The model presented in this report is therefore considered "preliminary" and serves as a "Proof of Concept" to demonstrate how the groundwater flow model can be used as a tool for evaluating upwelling processes and how it can be integrated with other studies to assess potential impacts that could be imposed by project operations. This is consistent with other resource studies who similarly demonstrated model integration and ability to evaluate potential project impacts during Proof of Concept meetings held on April 15-17, 2014, as described in Initial Study Report (ISR) Study 8.5, Part C, Appendix N, Middle River Fish Habitat and Riverine Modeling Proof of Concept submitted to the FERC June 3, 2014 (R2 2014b). Additional model calibration and refinement will be needed before project predictive simulations are performed.

3. STUDY AREA

As established by RSP Section 7.5.3, the overall study area related to groundwater processes includes primarily the Middle River Segment of the Susitna River extending from Project River Mile (PRM) 102.4 to PRM 187.1, portions of the Lower River Segment associated with domestic wells and riparian transect locations in the Lower River, and the lowest portion of the Upper River Segment near the proposed Dam Site associated with potential groundwater changes relative to reservoir construction and operations. Figure 3-1 shows these river segments and the general watershed boundary of the Susitna River. Figure 3-2 shows the location of the ten Focus Areas within which detailed studies were conducted. These are described in ISR Study 8.5, Section 4.2.1.2.1. This study concentrates on development of a preliminary three dimensional groundwater MODFLOW model for FA-128 (Slough 8A), which was the same Focus Area used by other resource leads to demonstrate model capabilities during the April 15-17, 2014 Proof of Concept meetings (Figure 3-3).

4. METHODS

A preliminary three dimensional MODFLOW model (MODFLOW) was developed for the FA-128 study area following the methods specified in the Groundwater Study (7.5) Study Plan (RSP Section 7.5.4.4). Model code selection and calibration procedures followed American Society for Testing and Materials (ASTM) standard D6170 (ASTM 2010) and D5981 (ASTM 2008) respectively. Specified snowmelt and precipitation runoff stage-change events from the 2014 monitoring period were used to develop and perform preliminary model calibrations and to demonstrate evaluations of GW/SW interactions critical for riparian and aquatic habitat. Future recommendations to advance and improve the model for project purposes are summarized in section 7.0.

All elevations reported in this Appendix use the NAVD88/Geoid09 datum.

The following sections describe the conceptual geohydrologic setting which forms the basis for developing the MODFLOW model. Subsequent sections describe model design and model calibration methods in more detail.

4.1. Geohydrologic Setting and Conceptual Model

The following discussion of the geohydrologic setting is summarized from earlier project studies (HESJV 1984a; HESJV 1984b; R&M Consultants, Inc. 1985) and from the more recent Geology and Soils Characterization Study (4.5) Initial Study Report (AEA 2014)

Unconsolidated fluvial and glaciofluvial deposits occur within a very narrow interval along the Susitna River valley. The sloughs and mainstem of the river are part of the modern floodplain. Floodplain deposits are characterized as a mixture of cobbles, sand, and gravels with silty mantles. Above and adjacent to the valley floodplain lie a series of fluvial and glaciofluvial terraces deposited during the most recent Pleistocene glaciation. Older unconsolidated glacial deposits may underlie the terrace and floodplain deposits. The width of the floodplain near FA-128 (Slough 8A) is approximately 3,000 feet. Collectively the floodplain deposits and any underlying unconsolidated sediments are referred to as the alluvial aquifer in this report.

The uplands adjacent to the floodplain are composed of bedrock consisting of Mesozoic sedimentary rocks of the Kahiltna assemblage and Cenozoic granitic rocks. The bedrock also underlies the alluvial aquifer at an unknown depth. The thickness of the alluvial aquifer is therefore unknown, but is reportedly at least 100 to 120 feet deep. These reported depths are based on well driller logs for a 100-foot (ft) deep water supply well completed in the alluvial aquifer at Talkeetna Fire Hall, about 25 miles downstream of FA-128 (Slough 8A), and two well logs for water supply wells completed in the alluvial aquifer at depths of 112 and 120 feet respectively at Curry, about 4 miles downstream from FA-128.

Recent groundwater and surface water monitoring at FA-128 (Slough 8A) shows the alluvial aquifer is in hydraulic connection with the Susitna River and its associated side-channels and sloughs. Groundwater elevations and vertical gradients show a strong response to changes in river stages.

Groundwater recharge to the alluvial aquifer is derived from four potential sources:

- Direct infiltrating precipitation (rain and snow melt).
- Local groundwater underflow within the alluvial aquifer that is transported in the downstream direction of the Susitna River valley.
- Regional groundwater transported through the deeper bedrock towards the alluvial aquifer within the Susitna River valley.

- Seepage of surface water from the Susitna River, side channels, and sloughs (downwelling).

Groundwater discharge from the alluvial aquifer is predominantly towards the Susitna River and associated side channels and sloughs (upwelling). Areas of groundwater upwelling in side channels and sloughs create favorable conditions for aquatic habitat by providing warmer water during the critical winter months. Areas of groundwater upwelling and downwelling are driven by the magnitude, direction and duration of vertical hydraulic gradients between the river surface water stage and groundwater in the underlying aquifer. Areas of upwelling and downwelling are highly variable spatially and seasonally and are strongly dependent on river stage and aquifer response.

4.1.1. Susitna River Characteristics

The following descriptive information was summarized from Geo-Watersheds Scientific and R2 Resource Consultants, Inc. (2014) Technical Memorandum, Preliminary Groundwater and Surface-Water Relationships in Lateral Aquatic Habitats within Focus Areas FA-128 (Slough 8A) and FA-138 (Gold Creek) in the Middle Susitna River, submitted to the FERC September 30, 2014. The Susitna River is a large glacial river that exhibits large hydrologic changes at hourly, daily, and seasonal temporal scales. River discharge is typically highest during the snowmelt period in spring and large, short-term fluctuations in discharge often occur during the summer months in response to air temperature changes and precipitation events. During the summer open-water period, river discharge is fed primarily by surface and glacial runoff. The mean monthly streamflow at the Gold Creek gage (located approximately 10 miles upstream from FA-128) for June, July, and August during water years 1950 – 2010 ranged from 21,430 – 26,290 cubic feet per second (cfs) (USGS Susitna River at Gold Creek gage No. 15292000). Susitna River discharge levels typically decline during September through November and are lowest during December through April when the channel is largely ice covered. Mean monthly streamflow at this gage site for December through April during water years 1950 – 2010 ranged between 1,303 – 1,893 cfs (USGS Susitna River at Gold Creek gage No. 1529200). Winter streamflow is fed primarily by groundwater and is relatively stable, although large fluctuations in river stages can occur locally during the winter due to ice jams and breaching flows. Changes in side channel and slough surface water stages can occur from three hydrologic processes which can result in reversals of hydraulic gradients between the river stages and underlying groundwater: breaching flows (side-channel becomes connected to main stem of Susitna River), precipitation events, and spring snow melt and ice breakup (Figure 4-1).

4.2. Model Design

The preliminary MODFLOW model developed for FA-128 (Slough 8A) was designed to simulate the alluvial aquifer groundwater system and its interactions with the Susitna River and its associated side-channels and sloughs as open water systems. Ice jam processes and transient recharge from precipitation events that affect river stages were not explicitly simulated in the model.

The MODFLOW model was designed and calibrated to field data collected within FA-128 (Slough 8A) during 2014. The field program focused on the shallowest portions of the alluvial aquifer and surrounding surface water features. There is little to no data on the regional groundwater system or aquifer properties within the deeper bedrock system; therefore the regional system was not explicitly simulated in the model.

A steady state model was first developed to simulate average “baseflow” conditions (i.e., when little flooding is occurring in the Susitna River and side channels are predominantly fed by groundwater). The solution to the steady state model was then used as the initial groundwater condition at the start of the transient model.

A transient model was then developed to simulate a time-varying flooding event during the 2014 period and associated changes in groundwater gradients and fluxes. The transient simulation only involved changing the model river stages during discrete stress periods in the simulation. All other model parameter values were held constant. The simulated time periods for the steady state and transient simulations are discussed further in Section 4.3.

Calibration of the steady state model was performed by adjusting aquifer parameters to best match target groundwater elevations measured in FA-128 (Slough 8A). The transient model was developed, run, and compared to observed aquifer responses. Some limited transient calibration was achieved by varying the aquifer storage coefficient term but additional calibration efforts will be needed to further test model performance and make adjustments once additional data are incorporated into the model.

4.2.1. Model Code

The alluvial aquifer within FA-128 (Slough 8A) was simulated using the publically available U.S. Geological Survey (USGS) modular three-dimensional finite difference groundwater flow model, MODFLOW-2000 (Harbaugh et al. 2000). MODFLOW-2000 is a computer program that numerically solves the three-dimensional groundwater flow equation for a porous medium by using a finite difference method. MODFLOW-2000 uses packages to represent various processes in the groundwater system, such as recharge, discharge, and groundwater-surface water interactions. The MODFLOW model was constructed and run using Groundwater Vistas 6.0, a Graphic User Interface (GUI), for processing and viewing input and output MODFLOW files (ESI 2011).

Future refinements to the model may involve adding additional layers to enhance vertical discretization of groundwater gradients beneath surface water features. Increasing the vertical discretization may require switching to the use of MODFLOW-NWT (Niswonger et al. 2011). MODFLOW-NWT is capable of solving groundwater-flow problems that are nonlinear due to model cells going dry and is supported in Groundwater Vistas 6.0. Switching to MODFLOW-NWT in the future would be relatively straight forward.

4.2.2. Model Domain, Grid, and Layers

The total model domain covers approximately 18.2 square miles, with the active part of the domain representing the alluvial aquifer within the Susitna River floodplain from approximately PRM 126.4 to 131.7 (Figure 4-2). The Focus Area of the model is FA-128 (Slough 8A) from PRM 128.1 to 129.7; however the model was extended another 1.5 miles upgradient and 1.5

miles downgradient of the Focus Area in order to set far field general head boundary conditions that would not influence the result of the simulation in the Focus Area.

The model domain also extends about 1.5 miles to the northwest and 1.5 miles to the southeast beyond the Susitna River floodplain towards local topographic divides. This area of the model is currently inactive; however, the model domain was intentionally extended beyond the Susitna River floodplain to accommodate simulation of the regional groundwater flow system if data become available in the future. The active model domain (simulated alluvial aquifer within the Susitna River floodplain from PRM 126.4 to 131.7) covers approximately 3.3 square miles.

The model consists of two layers with 103 rows and 189 columns and a variable grid spacing ranging from 50 to 450 square feet. The smallest grid spacing (50 square feet) was positioned on FA-128 (Slough 8A) between the Upper Half Moon Bay Side Channel and the Upper Side Channel 8A where field data were available for model calibration (Figure 4-2). Grid spacing was progressively increased with distance from this area.

4.2.3. Modeled Aquifer

The model simulates groundwater processes in the alluvial aquifer, which was assumed to be uniformly 100-ft thick throughout the active model domain. A uniform thickness was achieved by setting the top elevation of the model to surface elevations using the project 2014 Light Detection and Ranging (LiDAR) data (Updated Fluvial Geomorphology Modeling Approach submitted to the FERC May 27, 2014 [Tetra Tech 2014]) and setting the bottom elevation of the model 100 feet below the top elevation. The 100-ft thickness was then equally divided between layer 1 and layer 2. Both layers are simulated in the model as unconfined so that aquifer transmissivity[1] varies as the saturated thickness of the aquifer varies.

4.2.3.1. Aquifer Properties

Aquifer properties assigned in the model include hydraulic conductivity and storage coefficient. Hydraulic conductivity is a measure of the ease with which water moves through the aquifer and has units of feet per day (ft/day). The storage coefficient is the volume of water released from storage per unit surface area of aquifer per unit decline in hydraulic head in the aquifer. The storage coefficient is unitless. The storage coefficient is required for transient simulations when time varying stresses are applied to the aquifer.

The hydraulic conductivity of the alluvial aquifer in the Susitna River floodplain is estimated to range from about 1 to 100 ft/day. These ranges are based on the following studies: a pumping test conducted on the water supply well at the Talkeetna Fire Hall (HESJV 1984a); specific capacity data from several Talkeetna Wells (HESJV 1984b); falling head borehole tests conducted at Slough 9 in the 1980s (R&M Consultants, Inc. 1985); and values reported for the lower Susitna River (USGS 2013). An initial value of 66 ft/day was assigned to the alluvial aquifer and later adjusted during the steady state calibration.

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[1] Transmissivity is the aquifer hydraulic conductivity multiplied by the saturated thickness of the aquifer.

No previous studies are available documenting the storage coefficient for the alluvial aquifer. Typical storage coefficient values for unconfined aquifers range from 0.01 to 0.3 while typical values for confined aquifers are much less and range from 0.005 to 0.00005 (Freeze and Cherry 1979).

Aquifer properties were adjusted during the calibration process within reasonable ranges assumed for the aquifer.

4.2.4. Model Boundary Conditions

Specified flux and head-dependent boundaries were used to represent hydrologic boundaries in the model. Specified flux boundaries are prescribed fluxes (rates of water applied to or from the aquifer) assigned at specific locations in the model by the user. Head dependent boundaries are fluxes calculated by the model for the boundary based on the user assigned boundary hydraulic head (i.e., groundwater elevation).

Specified flux boundaries were used to represent surface recharge to the alluvial aquifer from direct precipitation and subsurface flux to the alluvial aquifer along the valley walls from regional groundwater transport in the bedrock.

Head-dependent flux boundaries were used to represent groundwater flux to and from surface water features (the Susitna River and associated side channels and sloughs in FA-128 [Slough 8A]). Head-dependent flux boundaries were also used to represent groundwater underflow within the alluvial aquifer at both the upgradient and downgradient edges of the model.

No flow boundaries were assigned to model cells that extended beyond the immediate floodplain of the Susitna River valley. No flow cells represent inactive areas of the model grid.

Specified flux and head-dependent boundaries are simulated using MODFLOW packages as described below.

4.2.4.1. Recharge Package

A single steady state recharge rate of 10.5 in/year was assigned to the upper layer of the alluvial aquifer. Transient recharge rates were not simulated. Recharge was estimated as total annual precipitation (25 in/year) minus total annual evaporation (14.5 in/year). The average annual precipitation value of 25 in/year was based on total precipitation measured at the FA-128 meteorological station ESMFA128-8 between 7/26/2013 and 4/3/2014 (24.98 in/year). This value is similar to average annual precipitation measured between 1981 and 2010 at the three nearest SNOTEL[2] weather stations (Station 1091 – 64 miles SE of FA-128; Station 967 – 37 miles S-SW of FA-128; and Station 1094 – 84 miles NW-W of FA-128). Those stations have annual average precipitation values of 37.6, 26.5, and 21.5 in/year respectively.

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[2] SNOTEL is an automated system of snowpack and related climate sensors operated by the Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture in the Western United States.

The total annual evaporation of 14.5 in/year is based on average pan evaporation measured at 12 sites throughout Alaska[3].

4.2.4.2. River Package

The Susitna River and associated side channels and sloughs in FA-128 (Slough 8A) were simulated using the River Package in MODFLOW. The River Package simulates the flux of water between the aquifer and river. The volumetric flux (Q_{riv}) between the two is dependent on the difference between the simulated groundwater head[4] and assigned river stage and river bed conductance (resistance to flow):

$$Q_{riv} = C_{riv} * (\text{River Stage} - \text{Groundwater Head}) \qquad [1]$$

Where:

C_{riv} = Conductance = K_{riv}*L*W/M

And:

K_{riv} = hydraulic conductivity of the river bed sediments (ft/day)

L = length of river in model cell (ft)

W = width of river in model cell (ft)

M = thickness of river bed sediments

If the simulated groundwater head is greater than the river stage, the flux is towards the river and water is removed from the model domain (upwelling). If the simulated groundwater head is lower than the river stage, the flux is towards the aquifer and water is added to the model domain (downwelling). If the groundwater head drops below the bottom of the river, the flux added to the model is a constant rate set equal to:

$$Q_{riv} = C_{riv} * (\text{River Stage} - \text{River Bottom}) \qquad [2]$$

River cells in the model were divided into "nearfield" and "farfield" cells (Figure 4-2). Nearfield cells consist of the Susitna River main channel, side channels and sloughs in FA-128 (Slough 8A) from approximately PRM 128.1 to 129.7. Farfield cells consist of the Susitna River main channel beyond the FA-128 area. Side channels and sloughs in the farfield area were not simulated in the model.

River parameter values assigned to each river cell in the model include river bottom elevation, river stage, river bed sediment hydraulic conductivity, river length, river width, and river bed sediment thickness. Assignment of each river parameter value is discussed below.

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[3] http://www.wrcc.dri.edu/htmlfiles/westevap.final.html

[4] Groundwater head = groundwater hydraulic head

4.2.4.2.1. River Bottom Elevation

Methods for assigning river bottom elevations to nearfield river cells differed from farfield river cells based on data availability. Nearfield and farfield assignments are discussed separately below.

Nearfield River Bottom Elevation

Bottom elevations assigned to nearfield cells were based on a combination of bathymetry data in the SRH-2D fluvial geomorphology model for FA-128 (Slough 8A) and the project 2014 LiDAR data (Tetra Tech 2014). SRH-2D model output points vary in spacing such that in some cases more than one point from the SRH-2D model occurred within a MODFLOW river cell; however, in other cases no SRH-2D points occurred within a MODFLOW river cell. Similarly, more than one LiDAR data point typically occurred within a MODFLOW river cell. The method for assigning river bottom elevations to nearfield river cells was as follows:

- For those MODFLOW river cells that had SRH-2D model data points contained within the cell, the bottom elevation was assigned to either the minimum LiDAR or the minimum bathymetry from the SRH-2D model, which ever value was lower. The minimum from these two sources was used to ensure river bottom elevations were lower than any assigned river stage.
- If no SRH-2D model points occurred within the river cell, values were interpolated in Geographic Information System (GIS) from nearby SRH-2D model points and if the minimum interpolated value was less than the minimum LiDAR, that value was used, otherwise the minimum LiDAR value was used.

Farfield River Bottom Elevation

Bathymetry data were not available for farfield river cells. River bottom elevations assigned to farfield river cells were therefore estimated as the minimum LiDAR elevation in the river cell minus 5 feet. The subtraction of 5 feet from the LiDAR elevation is based on the average surface water depth in the nearfield river cells calculated as the steady-state stage (see Section 4.2.4.2.2 below) minus the river bottom elevation. These values can be updated if data on the bathymetry for the farfield river cells become available.

4.2.4.2.2. River Stage

Each river cell in the model requires the assignment of a river stage. Although field monitoring of river stages was conducted at a number of surface water stations in FA-128 (Slough 8A) between 2013 and 2014, these field measurements represent only isolated points in the surface water system. Rather than attempt to interpolate between relatively sparse distant points, river stages were assigned throughout the MODFLOW model based on the results of other project hydrologic modeling conducted for open water flow in the Susitna River and FA-128 side channels. River stages assigned to the farfield river cells were based on the Open-water Flow Routing Model (OWFRM) of the Susitna River and river stages assigned to the nearfield river cells were based on SRH-2D modeling of the FA-128 area (Tetra Tech 2014).

The OWFRM is based on routing measured discharge down the main channel of the Susitna River (Study 8.5 SIR, Appendix B, Open-water Hydrology Data Collection and Open-water Flow Routing Model (Version 2.8) submitted to the FERC November 2015 [R2 2015b]). Model output includes hourly stages and flows at discrete transects along the main channel of the Susitna River. For the 2013 and 2014 period, flows were only simulated in the OWFRM for the measured open water discharge period (June 1 to October 30, 2013 and May 8 to August 26, 2014). The transient groundwater model was developed to simulate changing surface water stages during the spring melting event between April 21 and May 17, 2014, when flows and stages were not simulated by the OWFRM. This period was selected for transient MODFLOW simulation because surface water stages and groundwater elevations changed significantly, which allows for a more robust calibration. Also, the simulated changes are not influenced by precipitation events, which were not explicitly modeled in the transient MODFLOW model. The synthesis of OWFRM output for the transient simulation period is described below under "Transient Model River Stages".

The SRH-2D model of FA-128 (Slough 8A) is based on discrete values of discharge in the main channel of the Susitna River. Thirteen discrete discharge values were simulated with the SRH-2D model ranging from 2,000 cfs to 100,000 cfs. Output from the SRH-2D model for each discharge increment provides stages throughout the FA-128 area (main channel, side channels, and sloughs).

Both hydrologic models (OWFRM and SRH-2D) were utilized for river stage assignment in the MODFLOW model. The methods used for assigning nearfield and farfield river stages in the steady-state and transient models are discussed below.

Steady State River Stages

The steady-state simulation is based on average conditions between May 20 and June 6, 2014 (see Section 4.3 below). During this period, observed groundwater elevations and surface water stages in the FA-128 (Slough 8A) area were relatively low and stable with little flooding or precipitation occurring and are therefore, likely to be representative of baseflow conditions. This time period was also modeled with the OWFRM model and therefore main channel discharges and stages could be used directly from the OWFRM model output.

Nearfield Steady State River Stages

Nearfield river cells were assigned stages from the SRH-2D model output based on the average discharge in the Susitna River between May 20 and June 6, 2014 as simulated by the OWFRM model at transect 129.7 (Figure 4-3). The average discharge simulated by the OWFRM model during this time period is 15,202 cfs. This value is slightly higher than the long term annual average for the 62 year record (1949 to 2014) at the Gold Creek gaging station No. 15292000 (9,800 cfs). Because the SRH-2D model only simulates stages for a limited number of discrete discharge values, stages associated with 15,202 cfs were estimated by linear interpolation between a lower bound (12,000 cfs) and upper bound (16,000 cfs) simulated stage. For SRH-2D model points that are predicted to be dry for a given discharge in the SRH-2D model (i.e., stage value = -999), stages were assigned the river bottom elevation. Assigning the river bottom elevation to the river stage in MODFLOW turns off the flux from the river when groundwater elevations are lower than river bottom elevation (see equation 2 above). However, it does not turn off the flux when groundwater elevations are above the river bottom elevation (see equation 1 above).

The following steps were used to assign river stages to nearfield river cells in the Steady State MODFLOW model:

- For river cells with SRH-2D model points contained within the cell, an average stage from the SRH-2D model points was assigned for both 16,000 cfs and 12,000 cfs.
- For river cells with no SRH-2D model points contained within the cell, average values were interpolated in GIS from the closest adjacent SRH-2D model points.
- The 15,202 cfs stage was then derived by linear interpolation at each river cell between the 16,000 cfs and 12,000 cfs assigned stages.
- For river cells with 16,000 cfs or 12,000 cfs stages predicted to be dry (i.e., stage value = -999), the river stage was set to the river bottom elevation.

Farfield River Stages

Farfield river cells were assigned average stages predicted from the OWFRM model for the period May 20 and June 6, 2014. Farfield river cells that intersect with the one-dimensional (1-D) transects were assigned values from that transect (Figure 4-2). Stage values for river cells located between transects were linearly interpolated between the closest upgradient and downgradient transects.

Transient River Stages

The transient simulation is based on a flooding event that occurred between April 21 to May 17, 2014 and that peaked on May 4th (see Section 4.3 below). This event represents the spring snowmelt/ice breakup period. During this period monitored groundwater elevations and surface water stages in FA-128 (Slough 8A) showed a significant increase in response to flooding. Little to no precipitation occurred during this period indicating the hydrologic response is exclusively related to increases in river stage that is most likely associated with ice jamming that constricts flows and results in localized but pronounced flooding and stage increases, and not localized recharge (Figures 4-3 and 4-4). The May 4th event was selected because simulation of a strong transient hydrologic stress on the groundwater system leads to a more robust calibration than smaller stresses. This time period also occurs when there are abundant field stations throughout FA-128 that are monitoring the response of groundwater elevations and surface water stages to which the model can be evaluated and calibrated. However, the OWFRM model does not simulate this flooding event explicitly since the OWFRM is applicable to open-water flow conditions only and the flood event occurred during the ice breakup period. A regression analysis and extrapolation of the OWFRM model output was therefore performed to estimate an equivalent discharge and stage of the main channel of the Susitna for the transient period. This approach is described further below. River stages during the modeled time period would have best been set based on results of the River1D and River2D Ice Processes modeling as described in ISR Study 7.6, but those models were still under development at the time of this effort. Future refinements to the MODFLOW model could include incorporation of the River1D and River2D model outputs (see Section 7.0).

There was a flooding event that occurred on August 21, 2013 related to a breaching event with no precipitation; however, this flooding event was of lower magnitude than the May 4, 2014 event and there were less field stations in FA-128 at that time to calibrate the MODFLOW model.

Regression Analysis and Extrapolation of OWFRM

An equivalent open water discharge and stage was developed for the April 21 to May 17, 2014 transient period at transect 129.7. The values were developed using a relatively robust (R^2 = 0.98, Figures 4-5 and 4-6) 2nd order polynomial regression fit between OWFRM modeled values at transect 129.7 and monitored stages at surface water station FA128-13 located within Slough 8A. Monitored stages at station FA128-13 cover the entire period from July 31, 2013 to November 3, 2014 and where corresponding data were simulated with the OWFRM model at transect 129.7, the stage responses are fairly similar (Figure 4-4).

The correlations showed some hysteretic effects in the 2013 data. Since the transient simulation is based on a flooding event in 2014, the regression was fitted to the 2014 data. Also, the regression fit was not as good for low stages from the OWFRM model at transect 129.7 (generally < 579 feet). Those data were therefore omitted from the regression fit. Because the correlation is being used to develop equivalent stages and discharges at transect 129.7 for a high stage flooding event, the omission of those data is unlikely to affect the model.

The regression equations were used to predict discharge and stage at transect 129.7 based on the stages observed at surface water station FA128-13 (Figures 4-3 and 4-4). The values developed with the regression equations match the OWFRM modeled values well for stages greater than 579 feet and discharge values greater than 17,000 cfs.

There is some uncertainty in the values derived with the regression analysis because values are extrapolated beyond those simulated with the OWFRM. For example the peak equivalent discharge during the flooding event on May 4, 2014 is predicted with the regression analysis to be about 115,000 cfs, which is much higher than the maximum discharge used for developing the regression (about 45,000 cfs). However, a stage/discharge rating curve developed for transect 129.7 for flows up to 100,000 cfs does show that the predicted stages using the regression analysis are fairly similar to stages that would be predicted with the rating curve, when using the regression predicted discharges in the rating curve (Figure 4-7).

The stage and discharge values derived with the regression analysis for transect 129.7 during the April 21 to May 17, 2014 transient period were used to develop transient river stages for the nearfield and farfield river cells in MODFLOW as described below.

Nearfield Transient River Stages

Nearfield river cells were assigned stages from the SRH-2D model output based on the predicted transient discharge values at transect 129.7 with the regression analysis above. The same approach that was used for assigning nearfield steady state river stages was used for each stress period in the transient simulation (see above).

Farfield Transient River Stages

Transient river stages predicted at transect 129.7 with the regression analysis above were extrapolated to the other transects based on the average stage gradient between each transect observed in the OWFRM model output. Farfield river cells that intersect transects were assigned stage values from those transects, and stage values for river cells located between transects were linearly interpolated between the upgradient and downgradient transects.

Comparison of Assigned and Monitored Transient River Stages

To assess the methodology of transient river stage assignment, the assigned river stages in the MODFLOW model were compared to monitored surface water stages at field stations having data during the same time period (4/21/14 to 5/17/14). Figures 4-8 through 4-12 show river stage plots for surface water stations 128-1, 128-6, 128-7, 128-11, and 128-13. The plots show that monitored and simulated stages are generally similar, with the stages at stations 128-6 and 128-13 especially so. However, the simulated peak stages at stations 128-7 and 128-11 were over predicted by about 2 feet indicating some imprecision in the methodology. Future modeling with incorporation of results from River1D and River2D ice modeling should improve the precision of river stage assignment in the MODFLOW model.

4.2.4.2.3. River Conductance

The river conductance term (C_{riv}) accounts for the length (L) and width (W) of the river channel within a model cell, the thickness of the riverbed sediments (M), and their vertical hydraulic conductivity (K_{riv}) (Anderson and Woessner 1992):

$$C_{riv} = K_{riv} * L * W / M$$

The lengths and widths for each river cell were assumed to be constant and the same lengths and widths of the MODFLOW model cells that the river occupies. This may be somewhat inaccurate because the width of the river is not in fact constant, for example during low stages when the width of the river may decrease substantially. A variable conductance term could be incorporated with future modeling to improve the representation of transient stream widths within the model cells (see Section 7.0).

The thickness of the riverbed sediments was assigned a uniform value of 15 feet throughout the model. This value is based on a middle value from a range of estimates (10 to 20 feet) for the lower Susitna River valley (USGS 2013).

The vertical hydraulic conductivity of the riverbed sediments was set to an arbitrary uniform value of 1 ft/day for all river cells, but was later adjusted during the steady state calibration (see Section 5.1).

4.2.4.3. Well Package

Specified flux boundaries were assigned to the northwest and southeast edges of the MODFLOW model using the Well Package to represent regional groundwater inflow along the valley side walls (subflow). The Well Package is a MODFLOW add-on which allows for simulation of surface water bodies. An initial value of 2.1 ft^2/day per linear foot was assigned to the model based on estimated regional groundwater fluxes to the Susitna River valley as reported in the 1980s (HESJV 1984b). This value was based on estimated values using professional judgement of regional aquifer properties, gradients, and thicknesses, but not empirical data. The specific flux was later reduced by an order of magnitude (0.21 ft^2/day per linear foot) during the calibration of the steady state model because it resulted in a better match to target water levels.

4.2.4.4. General Head Package

The General Head Boundary Package (GHB) was used to assign flux into and out of the upgradient and downgradient edges of the MODFLOW model, respectively (Figure 4-2). The GHB package is used to allow the horizontal groundwater flow to vary in proportion to the groundwater elevation at the boundary. These fluxes represent groundwater underflow within the alluvial aquifer that is transported in the downstream direction of the Susitna River valley. The boundaries were placed about 1.5 miles upgradient and 1.5 miles downgradient of FA-128 (Slough 8A) as “farfield” fluxes that would have little influence on model results.

The GHB package is similar to the River Package in that flux into and out of the model (Q_b) is calculated as the product of conductance of the boundary (C_b) and the difference between the assigned groundwater head at the boundary or beyond the boundary (h_b) and the groundwater head simulated in the aquifer at the boundary (h):

$$Q_b = C_b*(h_b-h).$$

$$C_b = K_b*W*L/D$$

Where:

K_b = hydraulic conductivity of the boundary (set to 66 ft/day[5])

W = width of boundary perpendicular to flow direction (set to model cell thickness)

L = length of boundary perpendicular to flow direction (set to model cell width)

D = Distance of the GHB from the model boundary (set to 1 foot)

The assigned boundary groundwater head (h_b) was estimated from “baseflow” river stages predicted from average values during the steady state period (5/20/14 to 6/6/14) modeled with the OWFRM at upgradient transect (131.4) and downgradient transect (126.4).

4.3. Model Time Period and Targets

Field data collected and QC3 validated from the FA-128 (Slough 8A) area were used as target values to calibrate and assess the accuracy of the MODFLOW model. The simulated time periods and target data for the steady state and transient models are discussed below.

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[5] A value of 66 ft/day for hydraulic conductivity was used in the prior 1980s studies to estimate groundwater transport in the downstream direction of the alluvial aquifer (HESJV 1984b)

4.3.1. Steady State Time Period and Targets

A steady state model was first developed to simulate average "baseflow" conditions (i.e., when little flooding is occurring in the Susitna River and side channels are predominantly fed by groundwater). The solution to the steady state model was then used as the initial groundwater conditions for the transient flooding event model.

Because groundwater elevations in the alluvial aquifer can respond to several stresses, including changes in river stages, local recharge from precipitation, and groundwater pumping from wells, the most suitable period to simulate for steady state conditions would be late fall/early winter when river stages are low, there is little to no precipitation, and before onset of ice processes begin to affect surface water stages. Unfortunately, data for low main channel river stages during the late fall/early winter period were not available during the initial model development. Instead, a period of relatively low river stages with little to no precipitation in late May/early June (following the initial spring melt in early May) was used to represent the steady state period (Figure 4-4). This period (May 20 to June 6, 2014) was modeled with the OWFRM model, which provided the required low river stages and low discharges necessary to assign river stages in the MODFLOW model (see Section 4.2.4.2.2 above). Model calibration required a period of time when groundwater elevations were only affected by surface water stages and not precipitation and related recharge. Simulations ultimately conducted with the model were only related to changes in river stages. Precipitation and recharge were not modified during model simulations.

The steady state model was calibrated to 14 groundwater elevation monitoring stations in FA-128 (Slough 8A) (Table 4-1). Each monitoring station was assigned a single groundwater elevation target value based on the average observed value monitored between May 20 and June 6, 2014.

4.3.2. Transient Time Period and Targets

The transient simulation is based on a flooding event that occurred between April 21 and May 17, 2014 and peaked on May 4th (Figure 4-4). This event represented the spring snowmelt/ice breakup period. During this period, the monitored groundwater elevations and surface water stages in FA-128 (Slough 8A) showed a substantial increase in response to flooding. Little to no precipitation occurred during this period indicating the hydrologic response is exclusively related to increases in river stage and not localized recharge. This flooding event was selected for transient simulation because it represents a strong river stage stress and associated response on the groundwater system to which the model may be calibrated. As mentioned in Section 4.2.4.2.2, the OWFRM model does not explicitly simulate this flooding event since it occurs during the ice cover and ice breakup period; therefore, river stages assigned for the transient simulation were based on a regression analysis approach described in Section 4.2.4.2.2.

The transient simulation was divided into 54 stress periods (SP) to represent the time period between April 21 and May 17, 2014. Each stress period was set equal to 12 hours and simulates a different stress on the groundwater system (i.e., river stage). Transient river stages assigned to the model were developed from data with much shorter time steps (i.e., hours). Similarly, monitored groundwater elevations and surface water stages at field stations in FA-128 (Slough

8A) are collected on much shorter time intervals (i.e., hourly or 15 minute increments). Data used from these sources were therefore averaged over the 12 hour intervals for each stress period in the MODFLOW model.

The simulated groundwater elevation response over time was compared to 15 groundwater monitoring stations (targets) in FA-128 (Slough 8A) for evaluation of model accuracy. Simulated vertical gradients and groundwater/surface water fluxes were also compared to 4 stations in FA-128 that include both surface water and groundwater stations. These stations have monitored groundwater elevations and surface water stages during the duration of the transient simulation. However, the groundwater well at each of these stations is not located immediately adjacent to the surface water station (wells ranged from 20 to 100 feet distance from the surface water station); therefore, the presumed vertical gradients at these stations likely incorporate a small component of horizontal gradient.

For this Proof of Concept demonstration, the transient model was developed, run, and compared to the 15 observed groundwater elevation responses (targets). For these model runs, the calibration process was limited to modifications to the aquifer storage coefficient. Further calibration to the transient model will be required and should result in improved model performance.

5. MODEL RESULTS

A preliminary three dimensional MODFLOW model was successfully developed for FA-128 (Slough 8A). The model consisted of both a steady state model and a transient model. The steady state model was developed to simulate average “baseflow” conditions in FA-128 (i.e., when little flooding is occurring in the Susitna River and side channels are predominantly fed by groundwater). The results of the steady state model were then used as starting groundwater conditions for the transient model which was developed to simulate the spring melt flooding event in May 2014 and responses to groundwater elevations, gradients between groundwater and surface water, and fluxes between groundwater and surface water.

The steady state model was calibrated to observed groundwater elevations and required little calibration because steady state groundwater elevations are largely controlled by the assigned river stages in the model (i.e., a relatively good calibration could be achieved with a range of aquifer parameters assigned to the model). The transient model was partially calibrated against observed changes in groundwater elevations and gradients between the groundwater and surface water. The transient model calibration was limited to adjustment of the aquifer storage coefficient parameter.

5.1. Steady State Model Calibration and Results

The steady state model was calibrated to 14 observed groundwater elevations (targets) in FA-128 (Slough 8A) through trial and error. Calibration focused primarily on adjustment of hydraulic conductivity of the alluvial aquifer and the river bed sediments (Table 5-1). These values were assumed to be spatially consistent throughout the model; however, future model refinements may include incorporation of heterogeneity to improve model calibration. Other values that may be varied in calibration include storage coefficient, anisotropy, river conductance, recharge, and boundary conditions. These variables may also be varied spatially over the model. Future calibration of these parameters would likely result in an improved simulations.

Specific fluxes along the sides of the model (regional groundwater subflow) were initially assigned a value of 2.1 ft^2/day per unit length of valley wall based on a previous rough estimate of regional groundwater fluxes to the Susitna River valley (HESJV 1984b), but was later reduced by an order of magnitude to improve the overall calibration.

The best model fit to the groundwater elevation targets was achieved using a horizontal hydraulic conductivity of 6 ft/day, a vertical hydraulic conductivity of 0.66 ft/day, and a river bed hydraulic conductivity of 6 ft/day (Table 5-1). Figure 5-1 shows a plot of observed and simulated groundwater elevations; a perfect fit would fall along the straight line. Figure 5-2 shows a map of the head target locations and corresponding residuals (difference between simulated and observed groundwater elevations). A negative residual value indicates the simulated groundwater elevation is too high and a positive residual indicates it is too low. The target residuals were evenly divided between negative and positive values indicating the model does not trend towards over prediction or under prediction of groundwater elevations. The absolute value of all target residuals was less than 1 foot, except at station 128-26 (3.25 feet) and station 128-4 (-1.37). The poorer fit of the model at these stations may indicate the presence of aquifer heterogeneities not represented with the current model configuration (Figure 5-2).

There are a number of target residual statistical measures to evaluate the overall model accuracy: the residual mean, standard deviation, absolute residual mean, sum of squares and residual mean square error (Table 5-1). The objective of the calibration is to minimize these statistical measures. One measure often used to evaluate the acceptable error for a model is the ratio of the residual mean square error to the total range in targets (scaled Root-Mean-Square Error [RMSE] in Table 5-1). A value less than 10% is generally considered good. For the best fit model, the scaled RMSE was 9% (Table 5-1).

The simulated steady state groundwater elevations are strongly influenced by the assigned river stages in the model and adjustments of the hydraulic conductivity of the aquifer and river bed sediments resulted in only slight improvements or worsening of the overall calibration. A number of flooded model cells occurred in layer 1 in the farfield area of the steady state model (Figure 5-3). Flooded cells are areas where the simulated groundwater elevations are above the land surface and overestimate the saturated thickness of the aquifer in layer 1. These are analogous to seeps or springs. The amount of flooding ranged from less than 1 foot to about 10 feet in these areas. Future model refinements can reduce flooded cells with the incorporation of the MODFLOW Drain Package, which simulates groundwater seepage diversion from the aquifer (see Section 7.0).

A few dry cells also occurred in layer 1 near valley walls in the far field area of the model, but are not expected to have much effect on the model results. Dry cells are areas where the simulated groundwater elevations are below the bottom elevation of model layer 1. Future refinements of the model may include additional model layers to refine simulation of vertical gradients in the aquifer. Increased vertical discretization would likely increase the tendency of model cells to go dry. Simulation of drying and rewetting model cells can be easily resolved during future refinements of the model with the use of MODFLOW-NWT instead of the current MODFLOW-2000 code (Section 7).

5.2. Transient Model Results

A limited amount of time was spent adjusting the storage coefficient (S) in the transient model within acceptable ranges to achieve a reasonable fit to the transient targets. Except for the prescribed transient changes in river stages, all other model input parameters were held constant from the calibrated best fit steady state model. The storage coefficient was initially set to 0.2, but was eventually reduced to a value of 0.001 to achieve a better match to the observed groundwater elevation response. This value is somewhat low for an unconfined aquifer and may suggest the aquifer is semi-confined.

The simulated transient changes in groundwater elevations were compared to observed changes at 15 target locations (Table 4-1). The comparison shows the model generally obtained a good fit for target stations located adjacent to simulated surface water features (Figure 5-4), but targets further from the river were less well matched (Figure 5-5);either the magnitude of the elevation change was off, and/or the timing of the response was delayed. A plot of all transient target results is provided in Attachment 1. Despite the poor match to groundwater elevation changes at some stations, the calibration statistics for the transient model were relatively good (Table 5-1).

Like the steady state model, the transient model simulation also resulted in an increase in the number of flooded model cells during the peak of the flooding event. As mentioned above, future simulations can resolve flooded model cells with the use of the MODFLOW Drain Package (Section 7).

5.2.1. Simulated Transient Gradients and Fluxes

Output from the MODFLOW model can be used to quantify changes in vertical gradients and fluxes between groundwater and surface water during the flooding event. Some preliminary model runs were conducted to demonstrate use of the MODFLOW model output for evaluating groundwater/surface water interactions. Additional model refinement and calibration is recommended before using the model to evaluate potential project impacts to aquatic and floodplain habitats.

Figures 5-6, 5-7, 5-8, and 5-9 are plots of the monitored and simulated differences between groundwater elevations and adjacent surface water stages at four target stations (128-6, 128-7, 128-11, and 128-13) during a transient simulation. These plots can be used to evaluate periods of upwelling and downwelling groundwater responses before, during, and after the flooding event.

At all stations, the simulated groundwater response showed downwelling conditions prevailing during the flooding event as river stages increased above the groundwater elevations in the underlying aquifer. At all stations except 128-13, the conditions prior to the flooding event were slightly upwelling; conditions at station 128-13 were slightly downwelling. Following the peak flood event, the simulated downwelling conditions were followed by a relatively quick change to upwelling conditions as the river stage dropped and groundwater drained back into the river.

The observed groundwater response differed somewhat from the simulated response. The observed response at some stations showed upwelling conditions prevailing during the initial flooding. The observed upwelling response at a particular location during the flooding event could be due to aquifer recharge from higher flooding stages upgradient of that location. Alternatively, the observed groundwater response could be partly related to changes in horizontal gradients. The monitoring wells at stations 128-6, 128-7, 128-11, and 128-13 are not immediately adjacent to the surface water gaging station. Distances between wells and surface water gages range from about 20 to 100 feet distance. The calculated differences between groundwater elevations and surface water stages could therefore represent a combination of horizontal and vertical gradients.

Figures 5-10, 5-11, 5-12, and 5-13 are plots of the simulated transient fluxes between surface water and groundwater at the four target stations (128-6, 128-7, 128-11, and 128-13). The plots show that as the flooding event occurred, fluxes out of the river (downwelling) increase as surface water stages rise above groundwater elevations. Downwelling fluxes are quickly followed by conversion to upwelling fluxes as groundwater flows back towards the surface water.

Note that simulated differences between groundwater and surface water elevation can be as little as 0.1 feet, which is much less than the calibrated target residuals of the model. Consequently, the current MODFLOW model requires further calibration before simulation of small vertical gradients (both in magnitude and direction). Also, the transient river stages are currently based on estimates of an equivalent open water stage during the spring melt flooding event (see Section 4.2.4.2.2). Calibration to observed responses may therefore be difficult to achieve. More representative flooding stages may be obtained in the future with output from the River1D and River2D ice processes modeling (see Section 7.0).

6. DISCUSSION

A preliminary three-dimensional MODFLOW groundwater model was developed for and applied to FA-128 (Slough 8A) as a means to quantitatively evaluate GW/SW interactions spatially and temporally. The preliminary model was successfully developed using existing data and information and has been initially calibrated. However, use of the model to evaluate effects of different Project operational scenarios will require further model refinement and model calibration.

Preliminary simulation results show transient flooding events on the Susitna River lead to short term reversals in groundwater gradients and fluxes into and from surface water. The results demonstrate that output from the MODFLOW model can be used to quantify the magnitude and duration of changing groundwater gradients and fluxes into and from surface water features, including the lateral habitats (e.g., side channels, side sloughs) that contain important fish habitats.

Output from the groundwater model can also be incorporated into other resource models (including the Physical Habitat Simulation (PHABSIM) based models [ISR Study 8.5, Section 4.6.1.1] for fish habitat) for evaluating potential impacts to aquatic habitat from future project operations. Specifically, groundwater response functions can be developed from the MODFLOW output as analytical expressions which can be used to quantify the predicted changes in groundwater fluxes due to different scenarios of project operations. Impacts to water temperatures can also be evaluated with model output but this will require additional model refinement (see Section 7.3 below).

7. RECOMMENDATIONS

The following sections provide recommendations for improving groundwater model development and application for project evaluations.

7.1. Model Refinements and Calibration

A preliminary MODFLOW model was developed for FA-128 (Slough 8A) to demonstrate its utility for evaluating GW/SW interactions and upwelling processes, and for quantifying potential impacts imposed by project operations. Further refinements to the model will be needed to improve its accuracy and predictive capability. Specific recommendations for this include:

- Improve steady state and transient calibration (both to groundwater elevations and vertical gradients). Model parameters that may be further adjusted to improve calibration include:
    - Aquifer hydraulic conductivity (horizontal and vertical)
    - River bed conductance
    - Specific flux boundaries along valley walls (i.e., regional groundwater influx to the alluvial aquifer).
    - Aquifer storage coefficient
- Evaluate improvements made through dividing the model domain into subareas of differing hydraulic conductivity, storage coefficients, and possibly other model parameters. Currently one value is used for the entire model domain for each variable.
- Incorporate ice process impacts on river stage response. The model currently incorporates only stages modeled for open water flow.
- Estimate and include transient recharge. The model currently uses a single value rather than variable recharge based on the season. The USGS Deep Percolation Model (DPM) would be an appropriate model to evaluate recharge.
- Increase vertical discretization by adding model layers if additional vertical gradient data become available. This would likely require use of MODFLOW-NWT for simulation of cells drying and rewetting instead of the current MODFLOW-2000 model code.
- Increase time discretization (if warranted) to simulate shorter transient stresses (i.e., hourly stress periods). Current transient model uses ½ day stress periods.

- Turn off river flux in MODFLOW model when side channels are predicted to be dry by setting conductance to zero for those cells and time periods.
- A variable conductance term could also be incorporated to improve representation of transient stream widths within the model cells.
- Simulate drainage of flooded model cells with the MODFLOW Drain Package to divert water.
- Validate the model through simulation of another flooding event after final transient calibration.
- Perform a sensitivity analysis to test model sensitivity to critical parameters including hydraulic conductivity, storage coefficient, recharge, and boundary conditions.

7.2. Additional Data Collection and Analysis

The preliminary MODFLOW model was developed using existing QC-checked data and information current through 2014. Additional data collected since then will be analyzed and integrated into the model and will likely serve to improve model calibration and performance. In addition, seasonal groundwater elevations have been well documented for the study areas and will provide a means to compare changes in vertical gradients in response to precipitation events versus ice damming events. This type of analysis should be made on a station by station basis, and then generalized to evaluate spatial distribution. The relationship between vertical gradient and temperature both in the aquifer and side channels will also be evaluated and will be an important first step for use of the model to evaluate the influence of groundwater gradients on slough temperature.

7.3. Model Implementation

Once the model has been fully calibrated and validated, predictive simulations can be made to evaluate the effects of different project operational scenarios on groundwater vertical hydraulic gradients within FA-128 (Slough 8A). Changes in surface/groundwater temperatures can also be evaluated, but will first require an assessment of the effects of current hydrograph changes on vertical gradients and temperatures.

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9. TABLES

Table 4-1. Groundwater and Surface Water Field Stations and MODFLOW Calibration Targets.

Field Station Full Name	Field Station Short Name	Station Type	Steady State Target	Transient Target
ESGFA128-10-W1	128-10-W1	Groundwater well	No	No
ESGFA128-11-W1	128-11-W1	Groundwater well	Yes	Yes
ESGFA128-12	128-12-W1	Groundwater well	No	No
ESGFA128-13-W1	128-13-W1	Groundwater well	Yes	Yes
ESGFA128-13-W2	128-13-W2	Groundwater well	No	No
ESGFA128-18-W1	128-18-W1	Groundwater well	Yes	Yes
ESGFA128-19-W1	128-19-W1	Groundwater well	Yes	Yes
ESGFA128-20-W1	128-20-W1	Groundwater well	No	No
ESGFA128-21-W1	128-21-W1	Groundwater well	Yes	Yes
ESGFA128-23-W1	128-23-W1	Groundwater well	Yes	Yes
ESGFA128-24-W1	128-24-W1	Groundwater well	Yes	Yes
ESGFA128-25-W1	128-25-W1	Groundwater well	Yes	Yes
ESGFA128-26-W1	128-26-W1	Groundwater well	Yes	Yes
ESGFA128-27-W1	128-27-W1	Groundwater well	Yes	Yes
ESGFA128-2-W1	128-2-W1	Groundwater well	No	Yes
ESGFA128-3-W1	128-3-W1	Groundwater well	No	No
ESGFA128-4-W1	128-4-W1	Groundwater well	Yes	Yes
ESGFA128-5-W1	128-5-W1	Groundwater well	Yes	Yes
ESGFA128-6-W1	128-6-W1	Groundwater well	Yes	Yes
ESGFA128-7-W1	128-7-W1	Groundwater well	Yes	Yes
ESGFA128-7-W2	128-7-W2	Groundwater well	No	No
ESMFA128-8-W1	128-8-W1	Groundwater well	No	No
ESGFA128-9-W1	128-9-W1	Groundwater well	No	No
ESGFA128-9-W2	128-9-W2	Groundwater well	No	No
ESSFA128-1	128-1	Surface-water gage	No	No
ESGFA128-11	128-11	Surface-water gage	No	No
ESGFA128-12	128-12	Surface-water gage	No	No
ESGFA128-13	128-13	Surface-water gage	No	No
ESSFA128-14	128-14	Surface-water gage	No	No
ESSFA128-15	128-15	Surface-water gage	No	No
ESSFA128-16	128-16	Surface-water gage	No	No
ESSFA128-17	128-17	Surface-water gage	No	No
ESGFA128-2	128-2	Surface-water gage	No	No
ESSFA128-22	128-22	Surface-water gage	No	No
ESGFA128-5	128-5	Surface-water gage	No	No
ESGFA128-6	128-6	Surface-water gage	No	No
ESGFA128-7	128-7	Surface-water gage	No	No

Table 5-1. Model Calibration Results - shaded simulations = best fit model run.

		Parameters Adjusted during Model Calibration[1]					**Model Calibration Statistics[2]**						
Model Name	**Model (Steady State or Transient)**	**Specified Flux (ft^2/dy per unit length)**	**Kh (ft/dy)**	**Kz (ft/dy)**	**Kv (ft/dy)**	**Storage Coefficient (S)**	**Residual Mean (ft)**	**Residual Standard Deviation (ft)**	**Absolute Residual Mean (ft)**	**Residual Sum of Squares (ft)**	**Residual Mean Square Error (ft)**	**Target Range (ft)**	**Scaled RMSE (%)**
Susitna_SS_V12	SS	2.1	66	66	6.6		0.61	1.33	0.91	30.10	1.47	12.09	12.2
Susitna_SS_V18	SS	0.21	6	0.66	1		-0.20	1.10	0.79	17.40	1.12	12.09	9.3
Susitna_SS_V19	**SS**	**0.21**	**6**	**0.66**	**6**		**0.18**	**1.07**	**0.80**	**16.50**	**1.09**	**12.09**	**9.0**
Susitna_SS_V20	SS	0.21	66	6	6		0.63	1.34	0.93	30.60	1.48	12.09	12.2
Susitna_SS_V21	SS	0.21	100	10	10		0.69	1.35	0.96	32.00	1.51	12.09	12.5
Susitna_SS_V22	SS	0.21	20	1	1		0.12	1.28	0.84	23.10	1.28	12.09	10.6
Susitna_SS_V23	SS	0.21	10	1	1		0.02	1.18	0.82	19.50	1.18	12.09	9.8
Susitna_SS_V24	SS	0.21	10	1	6		0.44	1.14	0.81	20.70	1.22	12.09	10.1
Susitna_SS_V25	SS	0.21	66	0.1	6		0.61	1.29	0.89	28.70	1.43	12.09	11.8
Susitna_SS_V26	SS	0.21	20	2	2		0.38	1.26	0.82	24.40	1.32	12.09	10.9
Susitna_SS_V27	SS	0.21	50	5	5		0.61	1.33	0.92	29.80	1.46	12.09	12.1
Susitna_T_V19_Run1	**T**	**0.21**	**6**	**0.66**	**6**	**0.001**	**-0.01**	**1.27**	**0.91**	**1200**	**1.27**	**13.25**	**9.6**

Notes:

1 Kh = aquifer horizontal hydraulic conductivity; Kz = aquifer vertical hydraulic conductivity; Kv = river bed vertical hydraulic conductivity, and S = aquifer storage coefficient (not required for steady state model).

2 Scaled RMSE = (Residual Sum of Squares)/(Target Range)

10. FIGURES

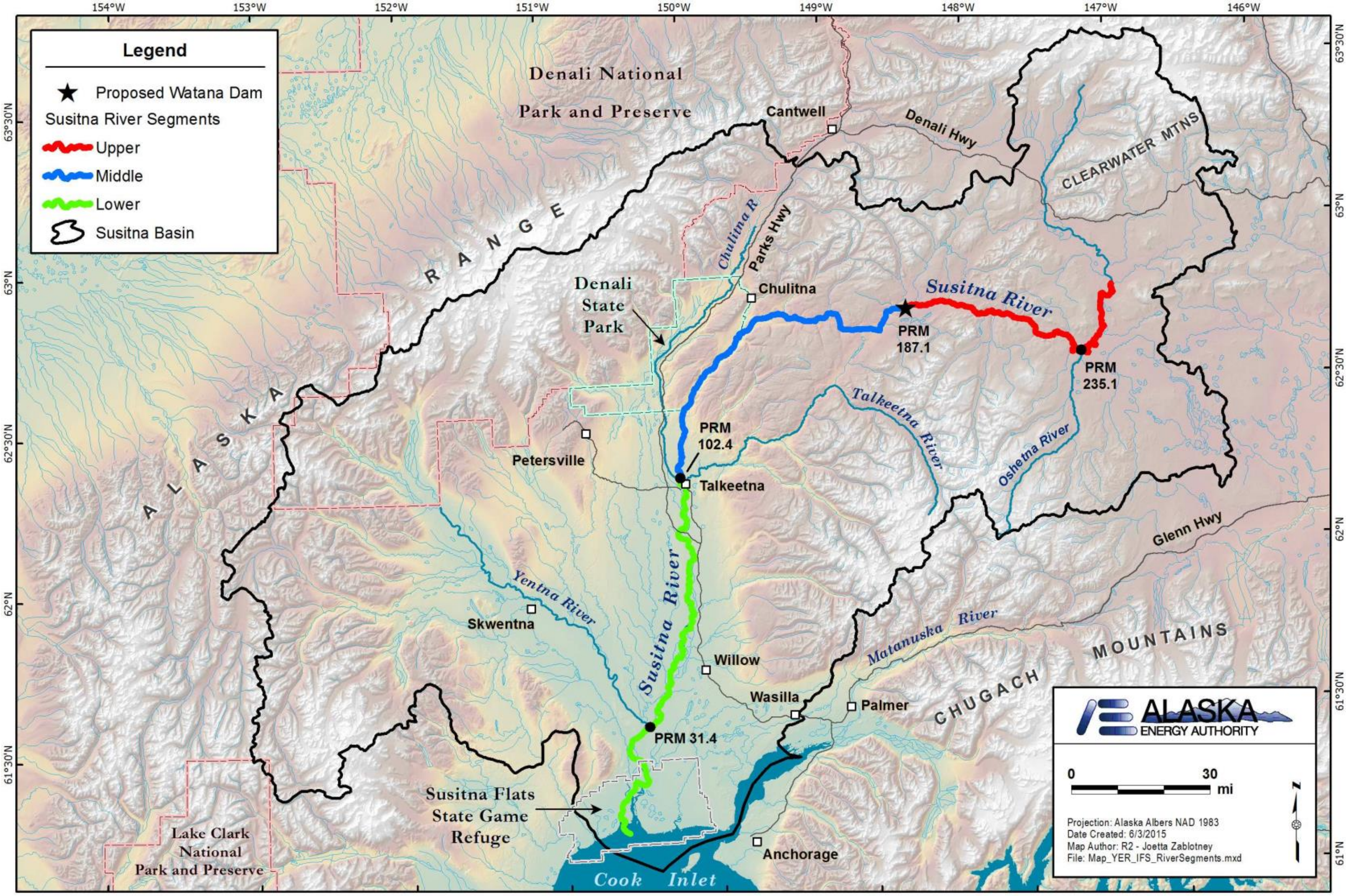


Figure 3-1. Susitna Watershed basin boundaries, showing the Project designation of upper, middle, and lower river segments.

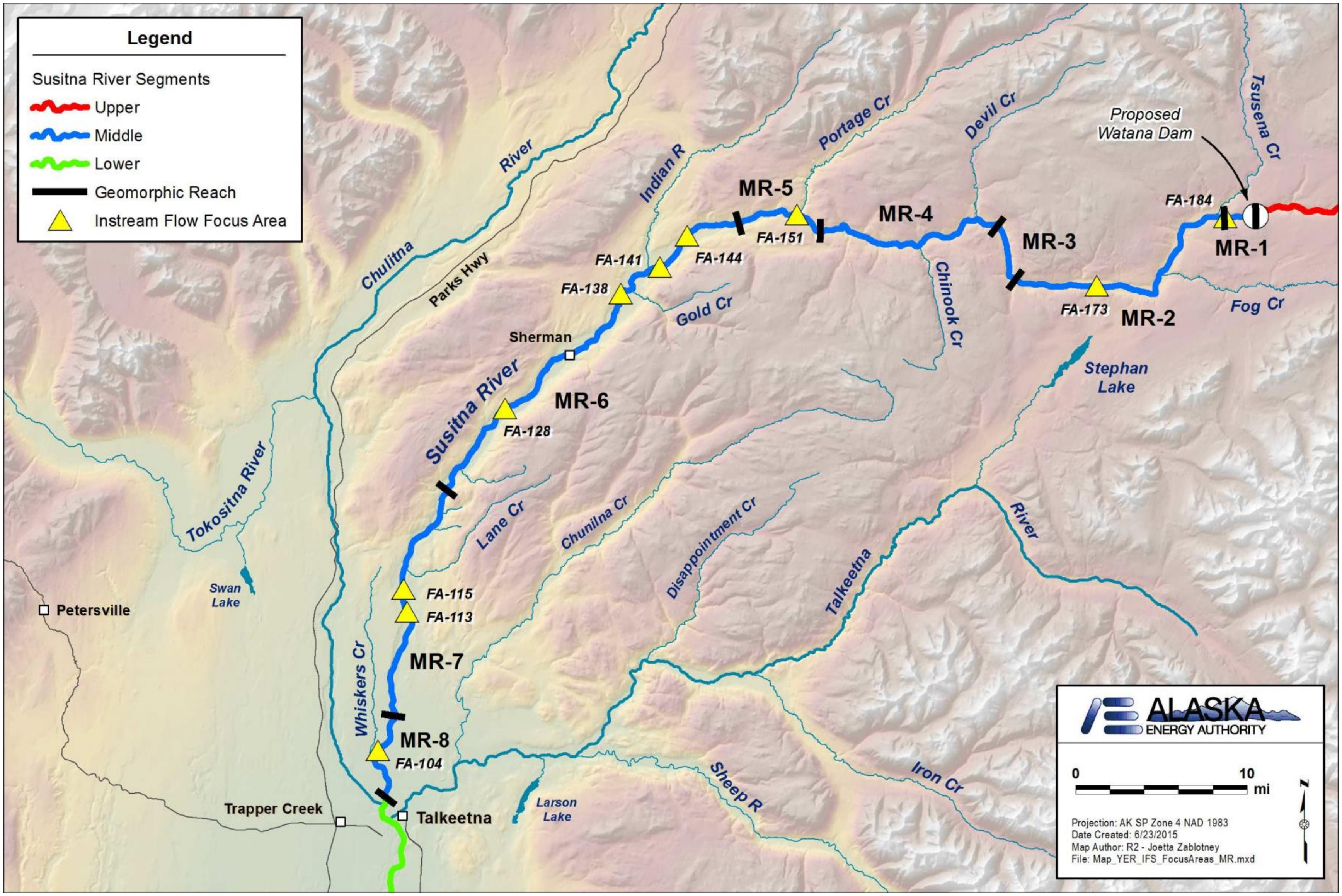


Figure 3-2. Susitna Watershed Middle River Segment, with geomorphic reaches and Focus Areas indicated.

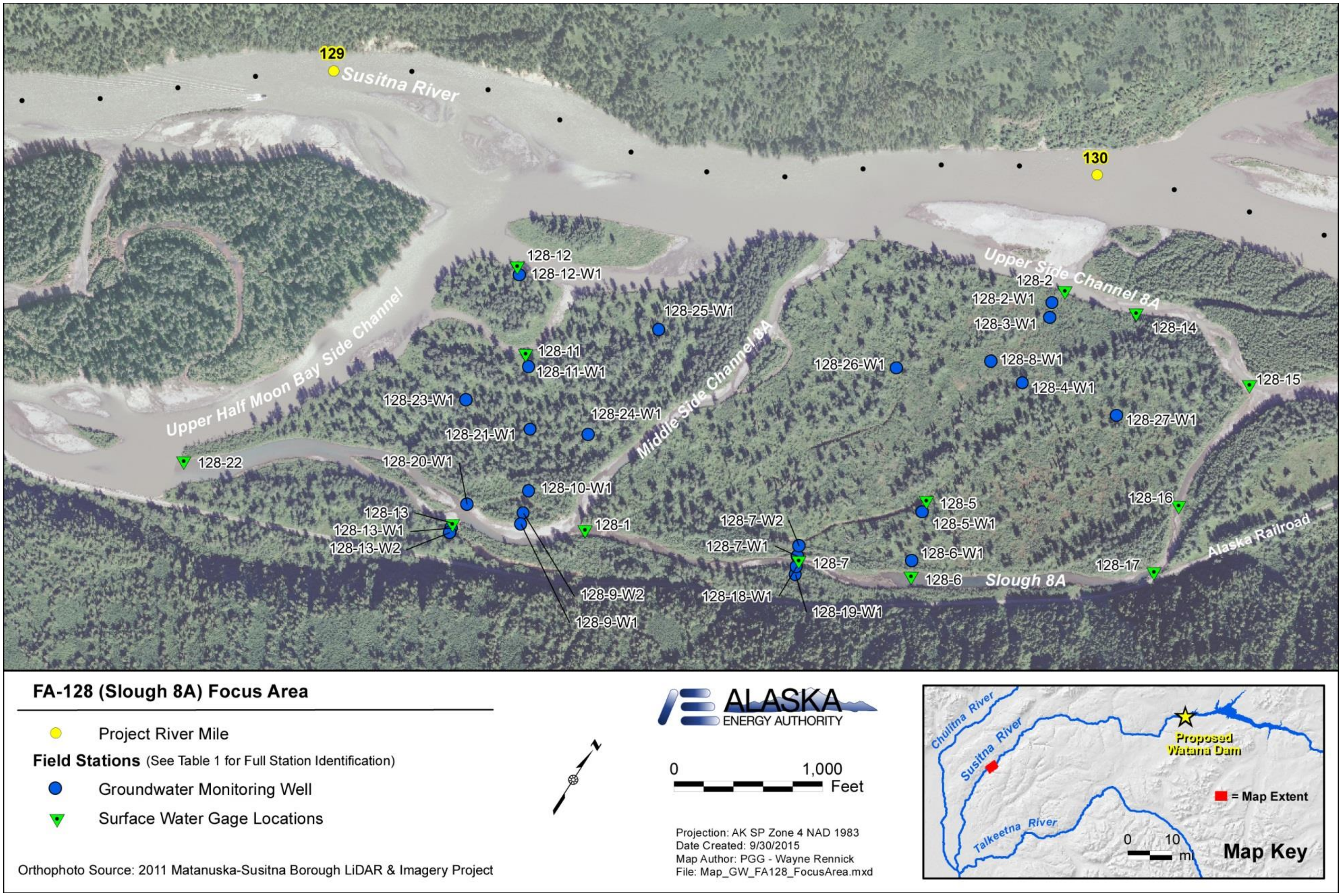


Figure 3-3. FA-128 (Slough 8A) Focus Area with groundwater and surface water monitoring locations.

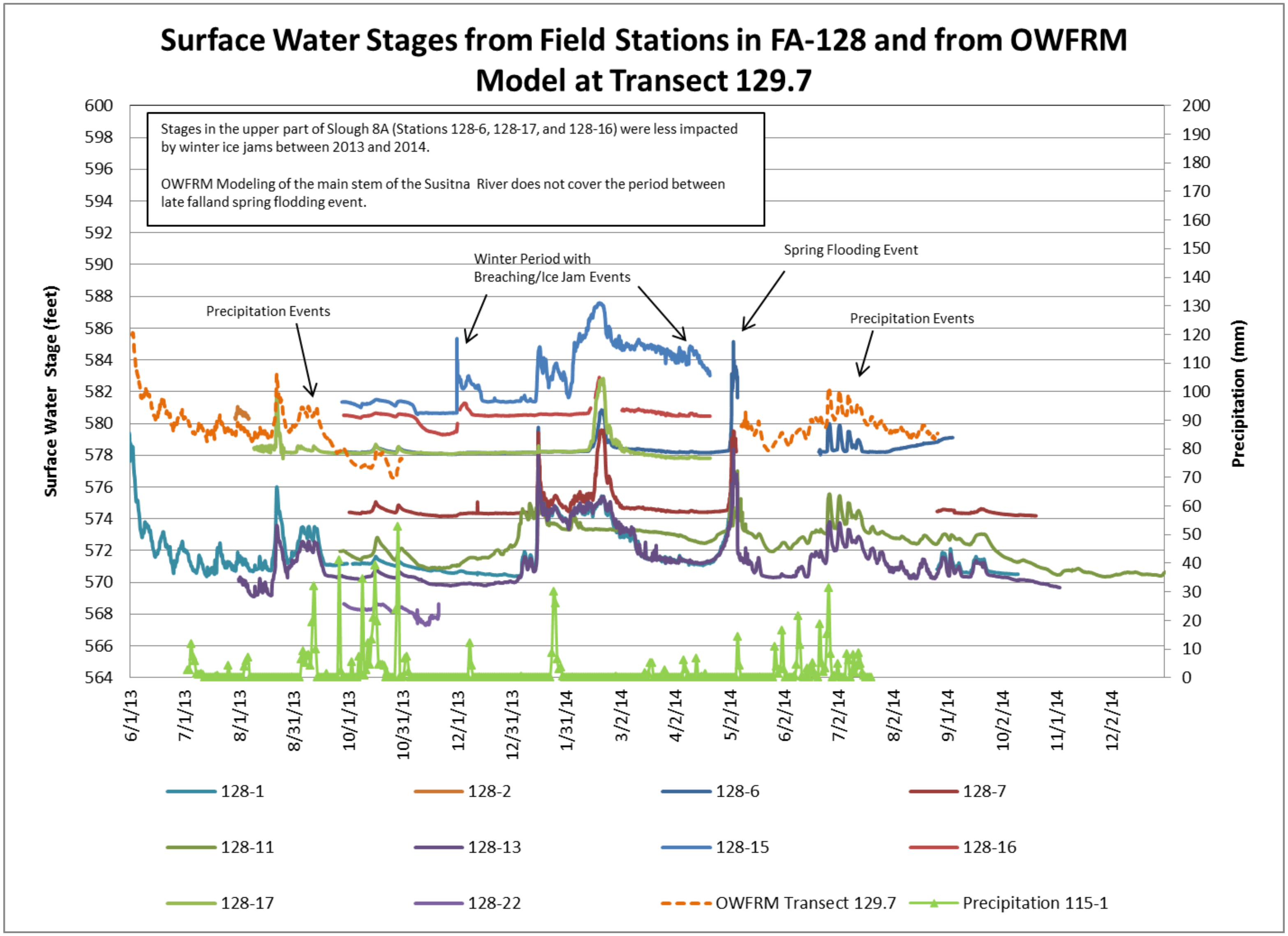


Figure 4-1. Hydrograph of surface water stages measured at FA-128 field stations and simulated at OWFRM model transect 129.7.

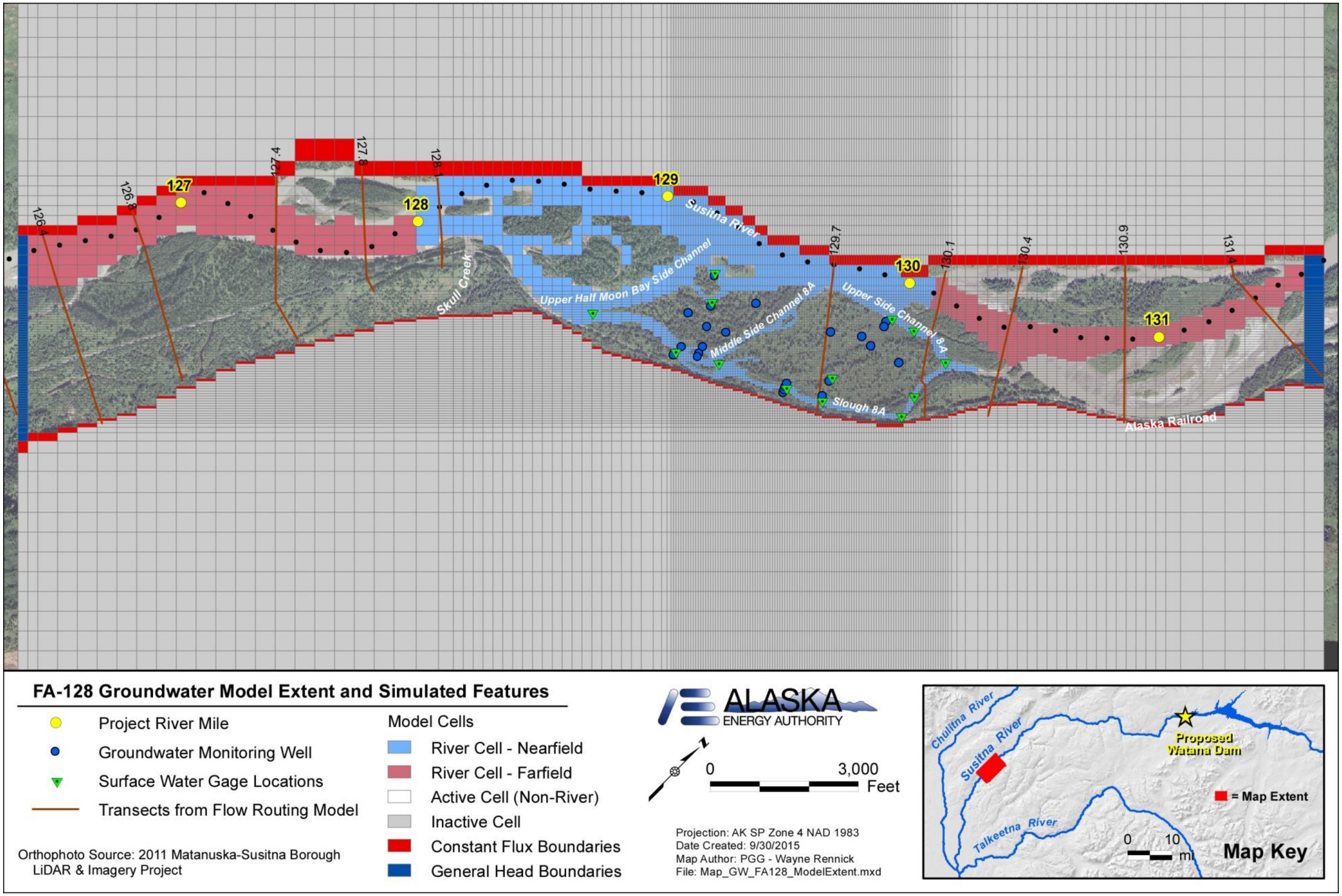


Figure 4-2. Groundwater Model Extent and Simulated Features in FA-128 Area.

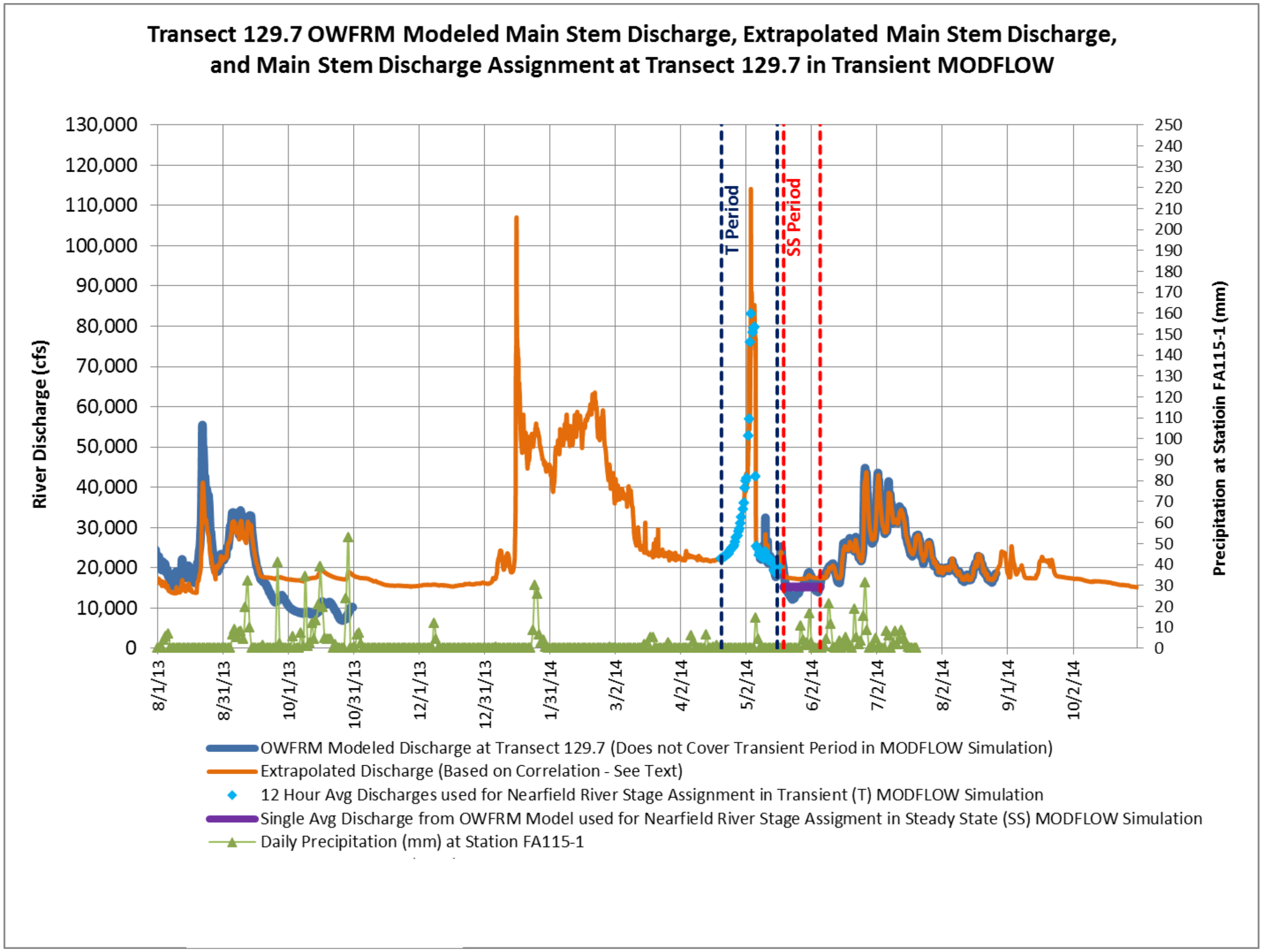


Figure 4-3. Hydrographs of Susitna Main-Stem Discharge as modeled at Transect 129.7 with the OWFRM model, Extrapolated Main-Stem Discharge, and Main-Stem Discharge at Transect 129.7 used for Nearfield River Stage Assignments in MODFLOW. Steady-State and Transient MODFLOW Simulation Time Periods also shown.

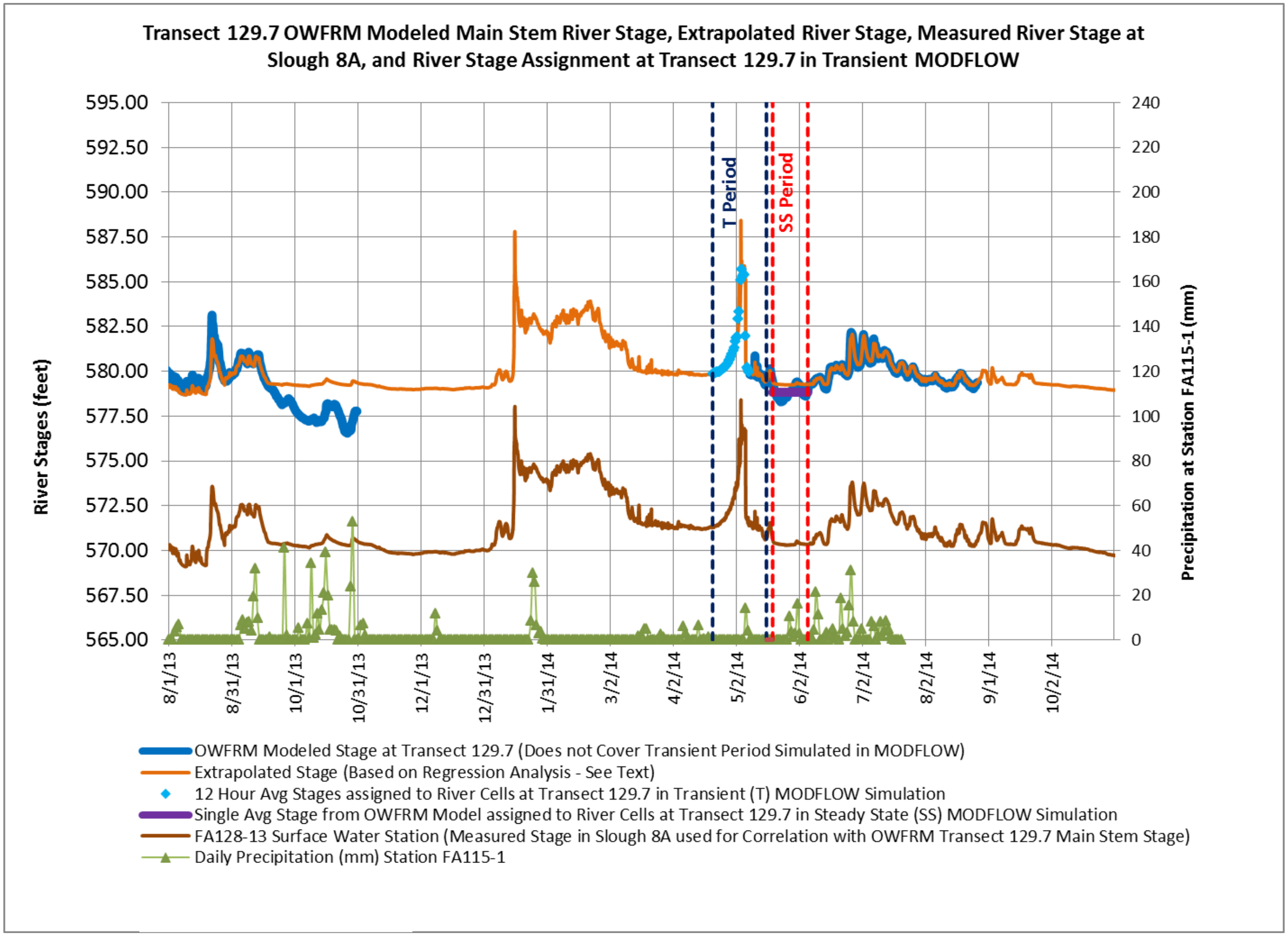


Figure 4-4. Hydrographs of Susitna Main-Stem Stage as modeled at Transect 129.7 with the OWFRM model, Extrapolated Main-Stem Stage, and Main-Stem Stage Assigned in Steady-State and Transient MODFLOW simulations at Transect 129.7. Steady-State and Transient MODFLOW Simulation Time Periods also shown.

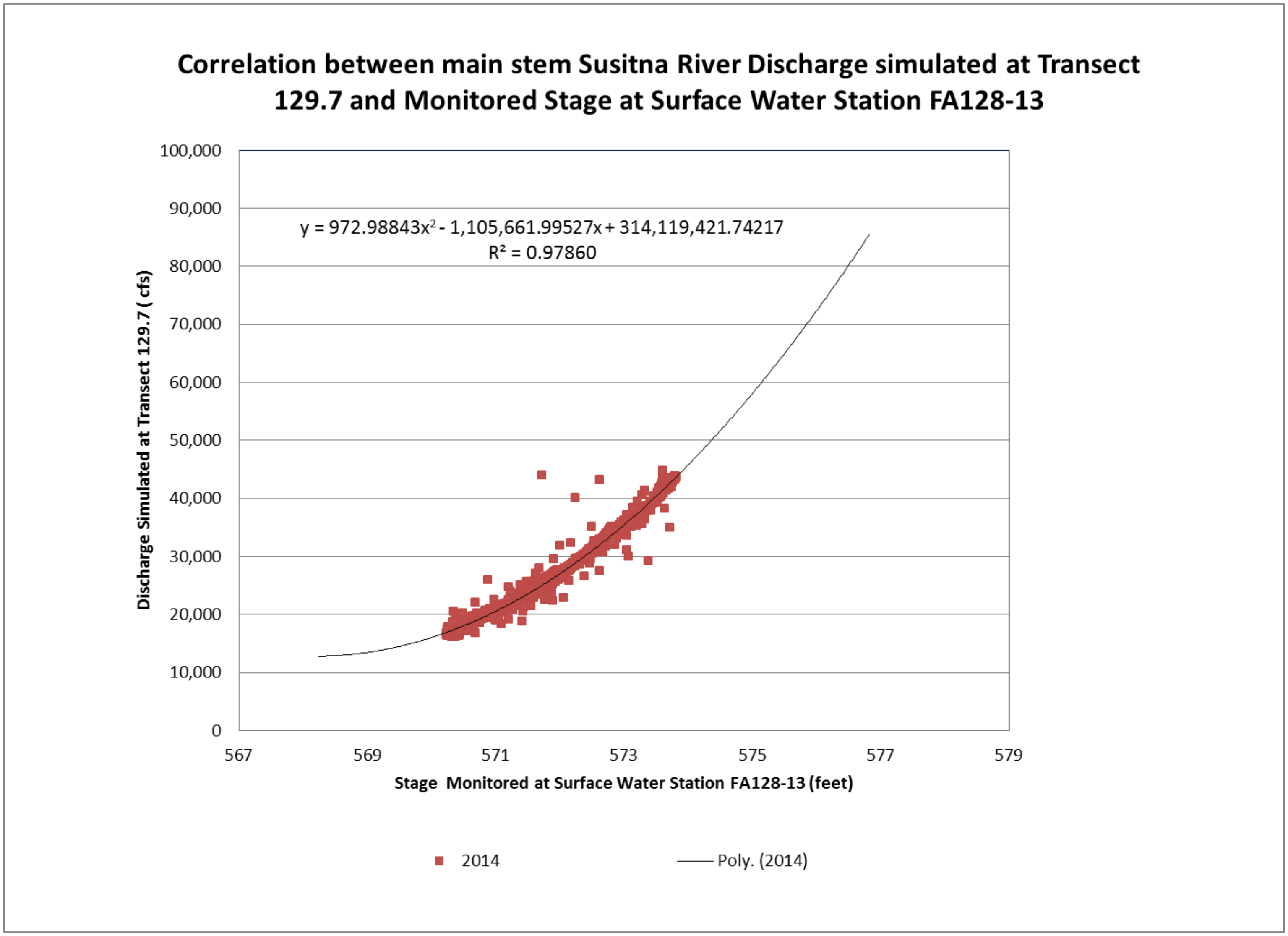


Figure 4-5. Correlation and Regression between Susitna Main-Stem Discharge simulated with OWFRM model and Surface Water Stage Elevation Measured at Monitoring Station FA128-13.

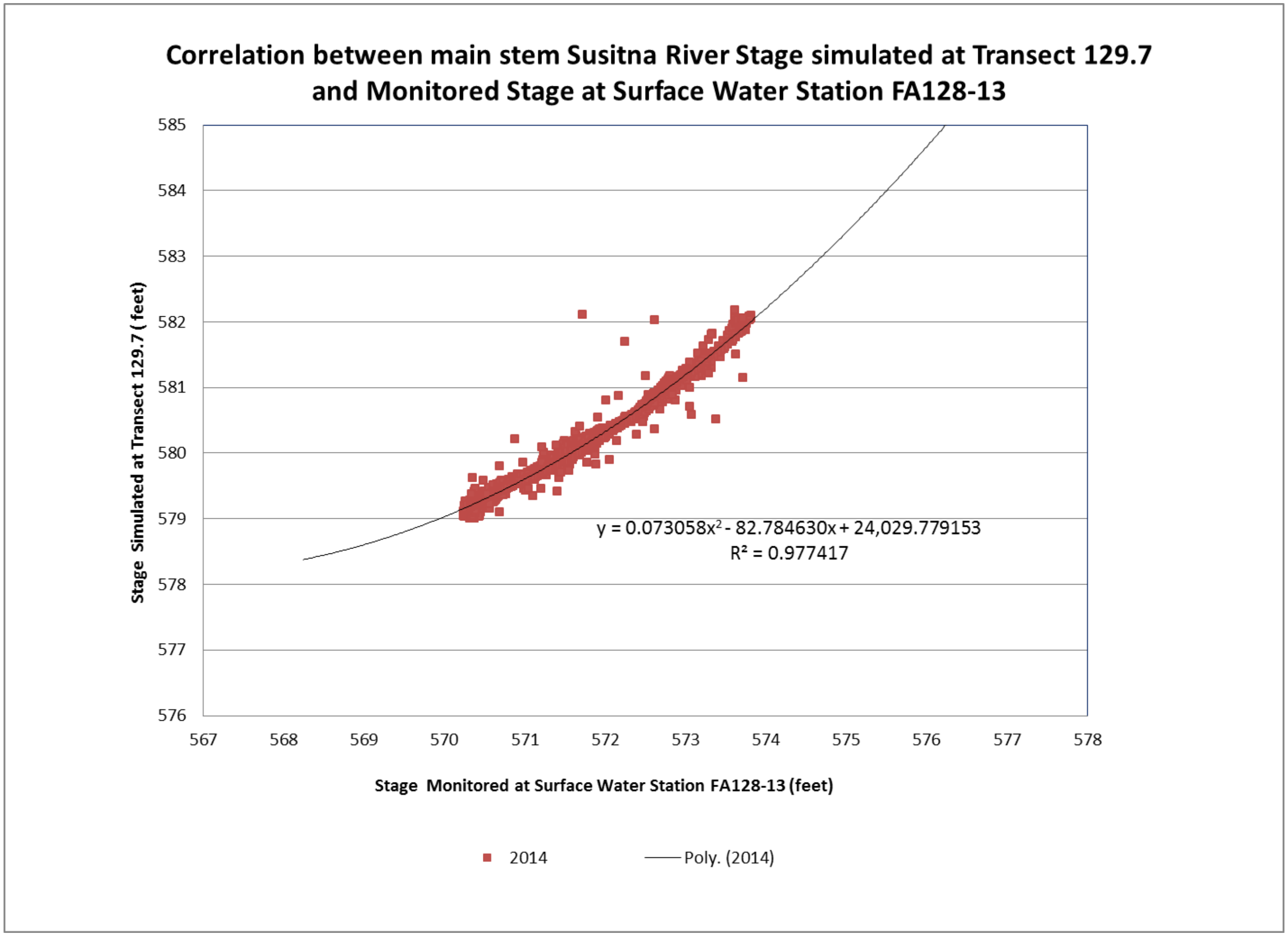


Figure 4-6. Correlation and Regression between Susitna Main-Stem Stage simulated with OWFRM model and Surface Water Stage Elevation Measured at Monitoring Station FA128-13.

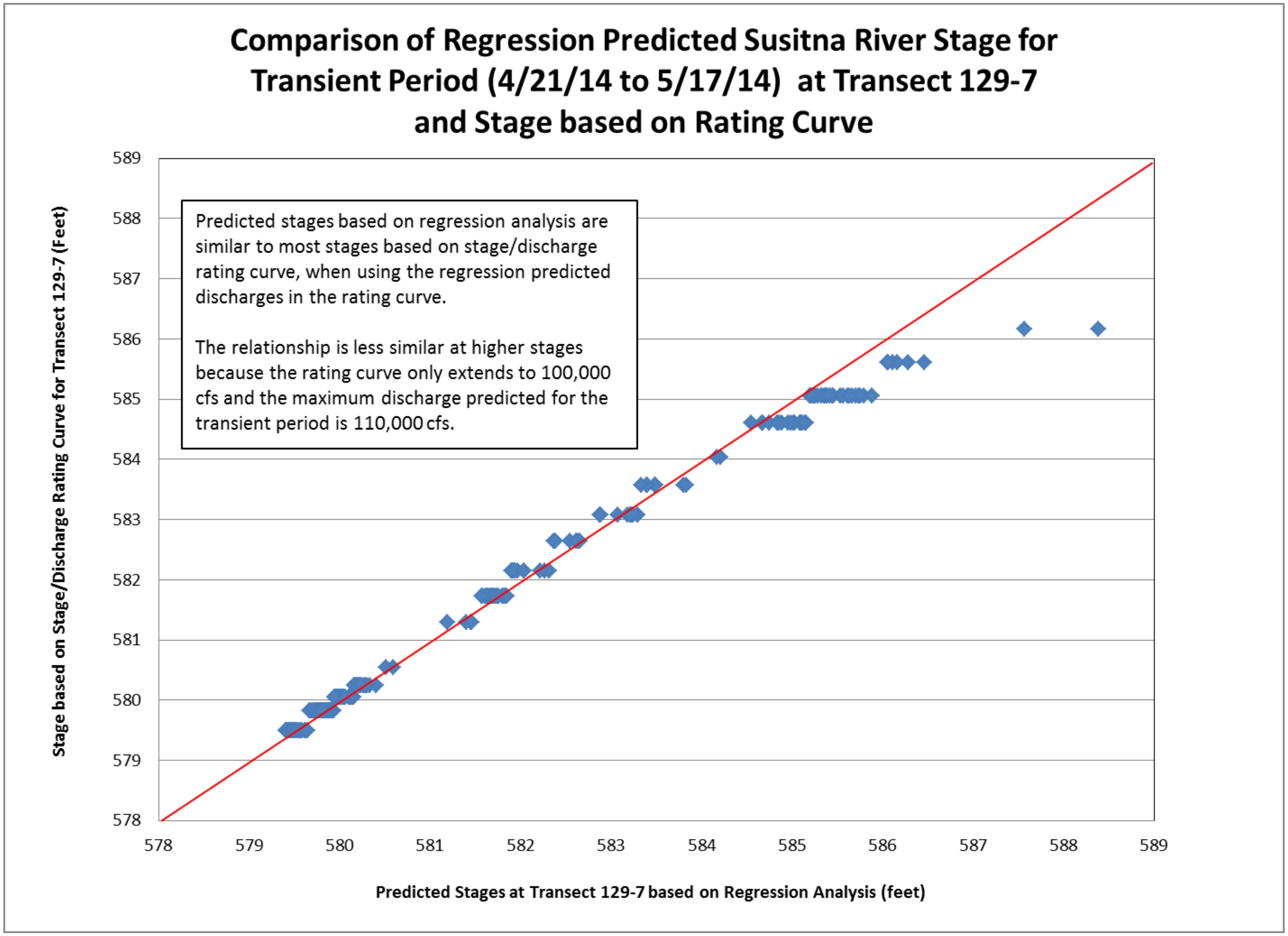


Figure 4-7. Comparison of Regression Predicted Susitna River Stage at Transect 129-7 and Stage based on Rating Curve, for Transient Period (4/21/14 to 5/17/14).

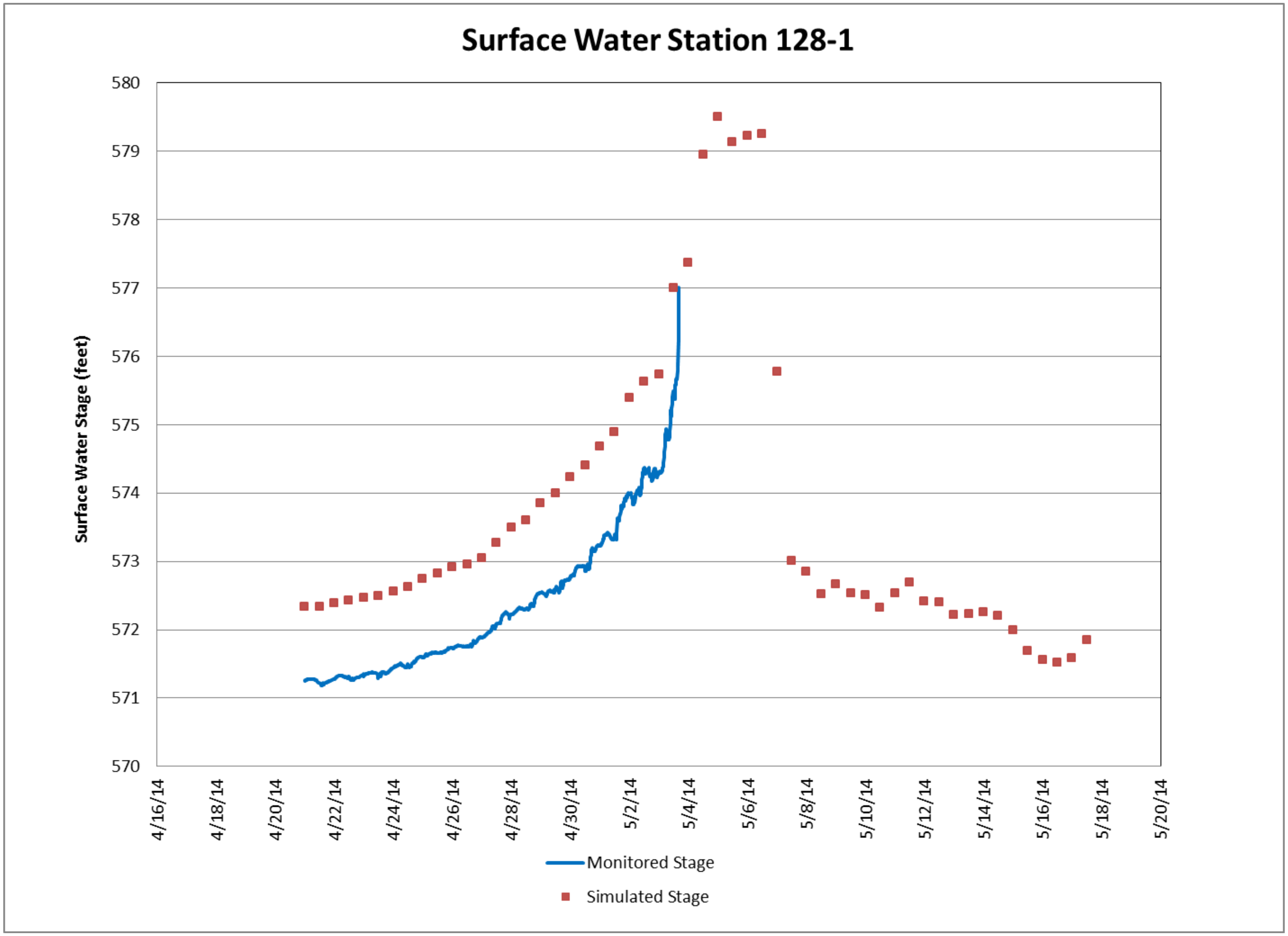


Figure 4-8. Comparison of Simulated River Stage and Monitored River Stage at Field Station FA128-1.

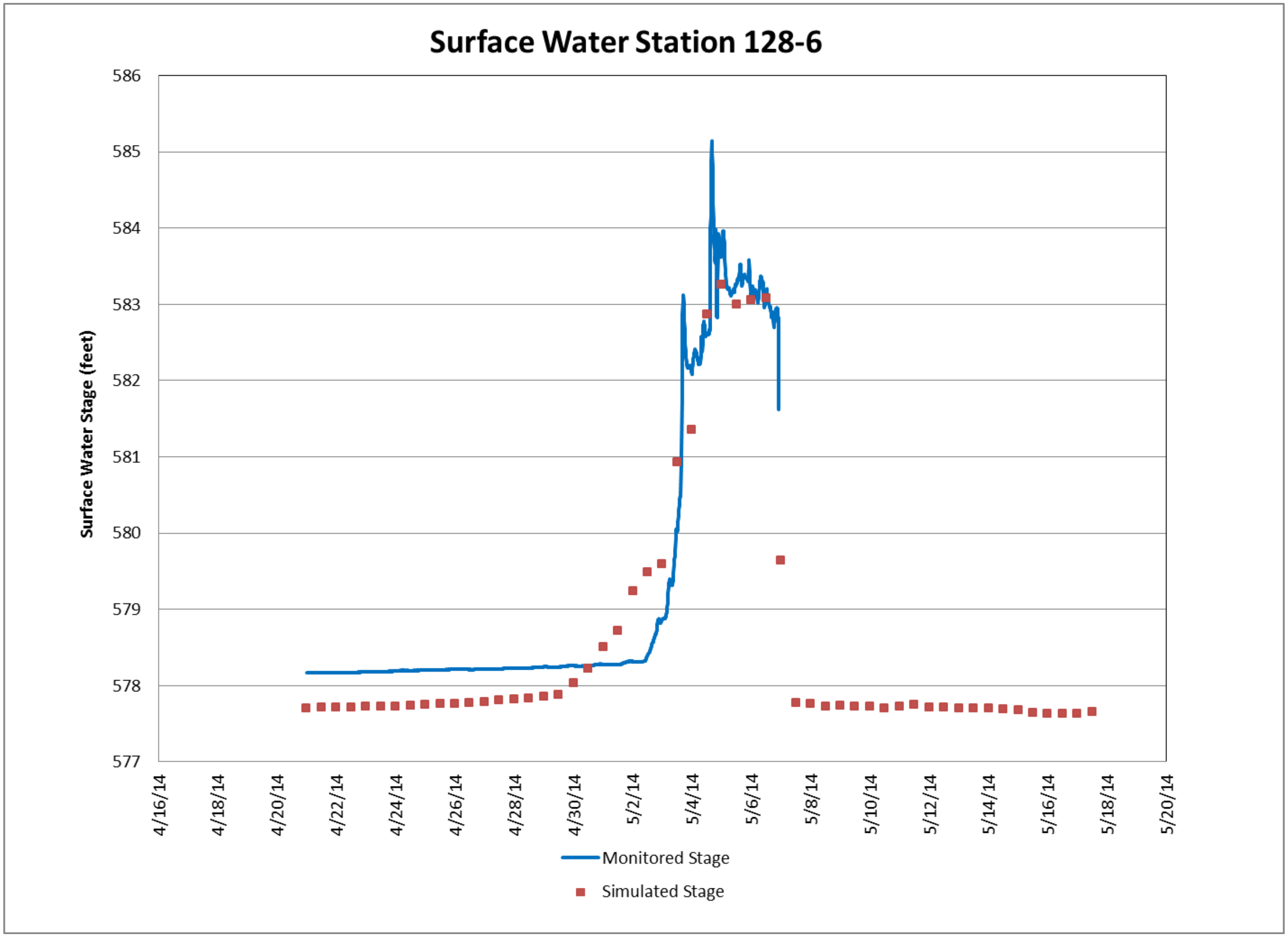


Figure 4-9. Comparison of Simulated River Stage and Monitored River Stage at Field Station FA128-6.

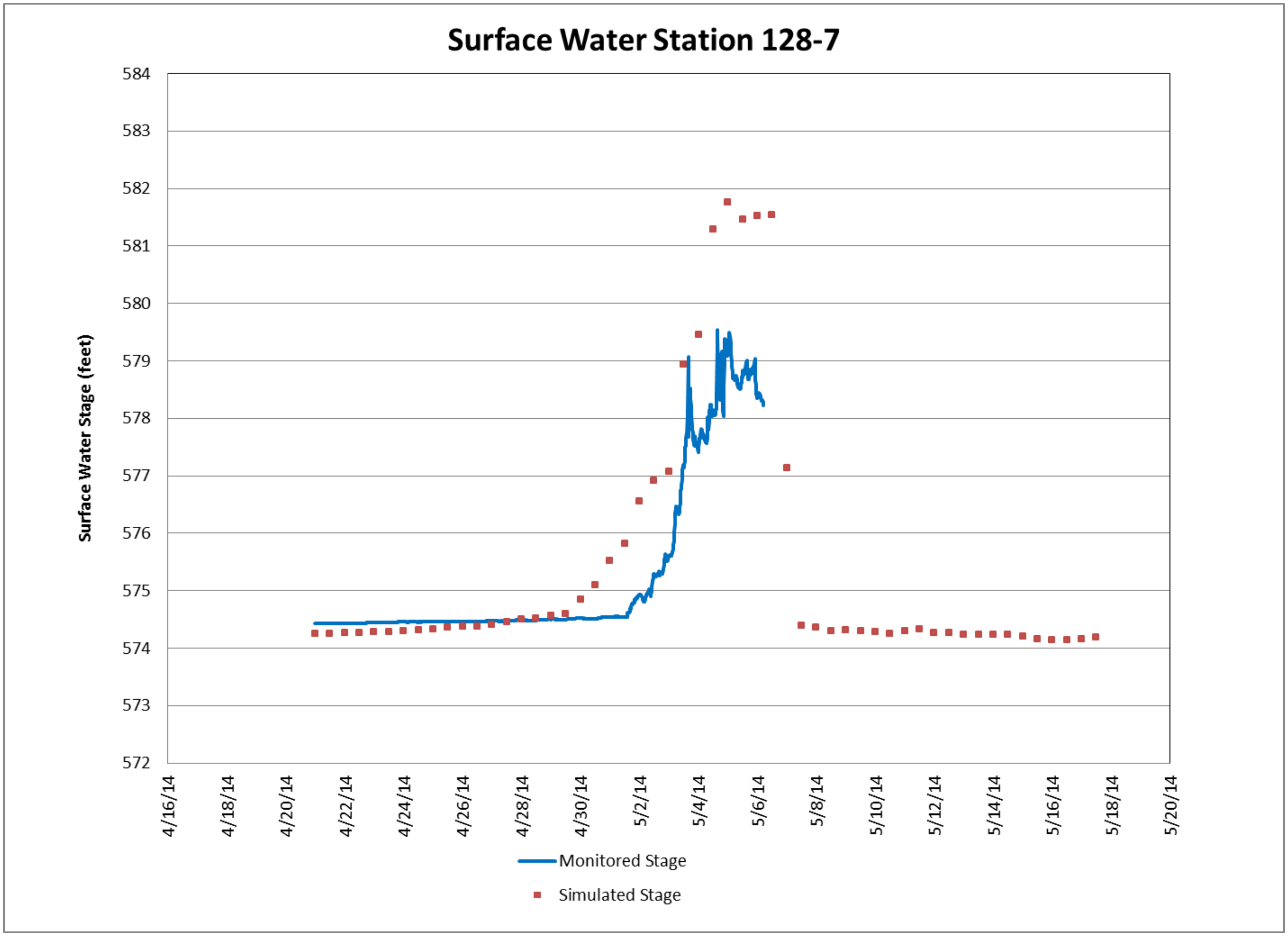


Figure 4-10. Comparison of Simulated River Stage and Monitored River Stage at Field Station FA128-7.

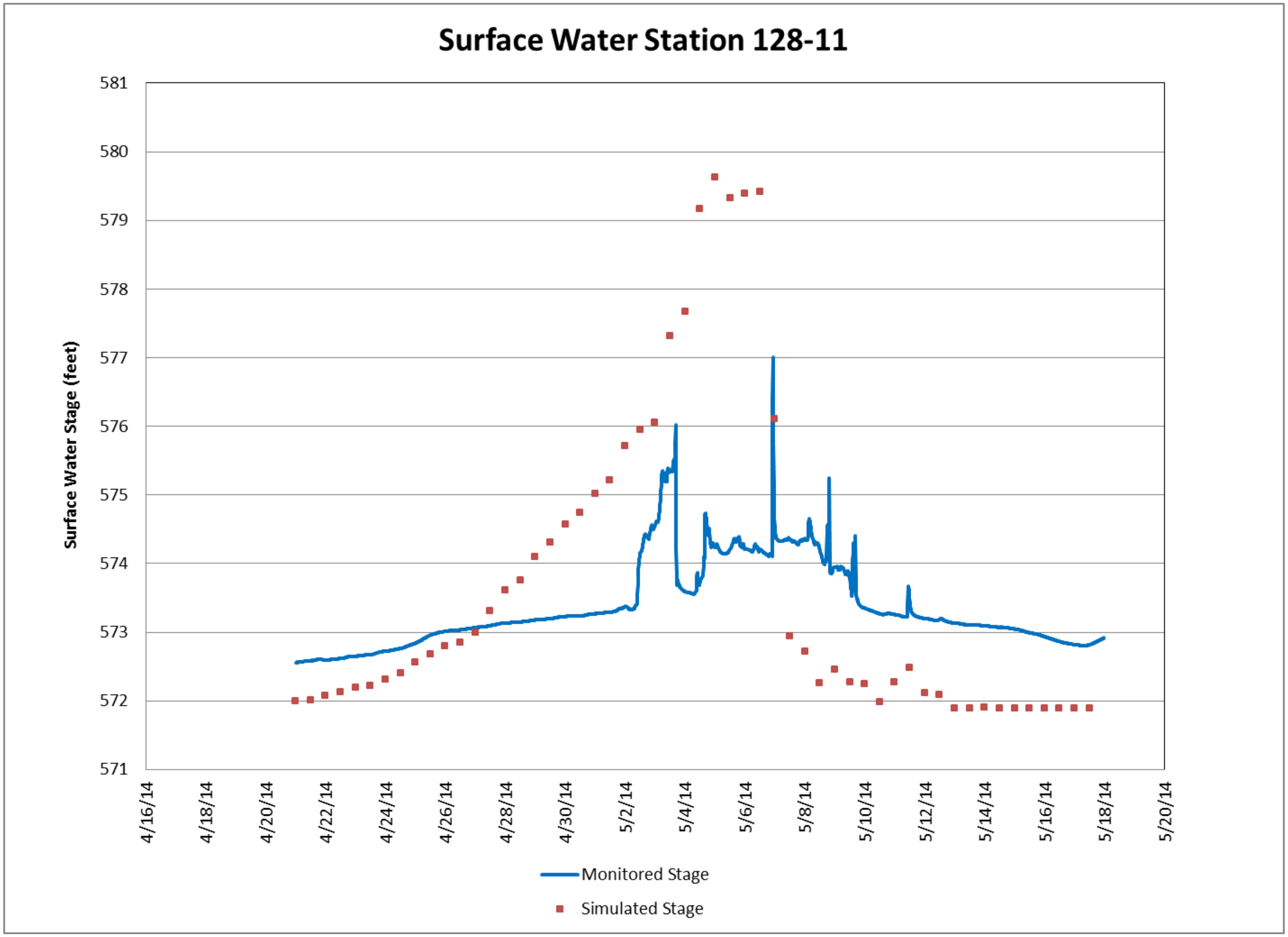


Figure 4-11. Comparison of Simulated River Stage and Monitored River Stage at Field Station FA128-11.

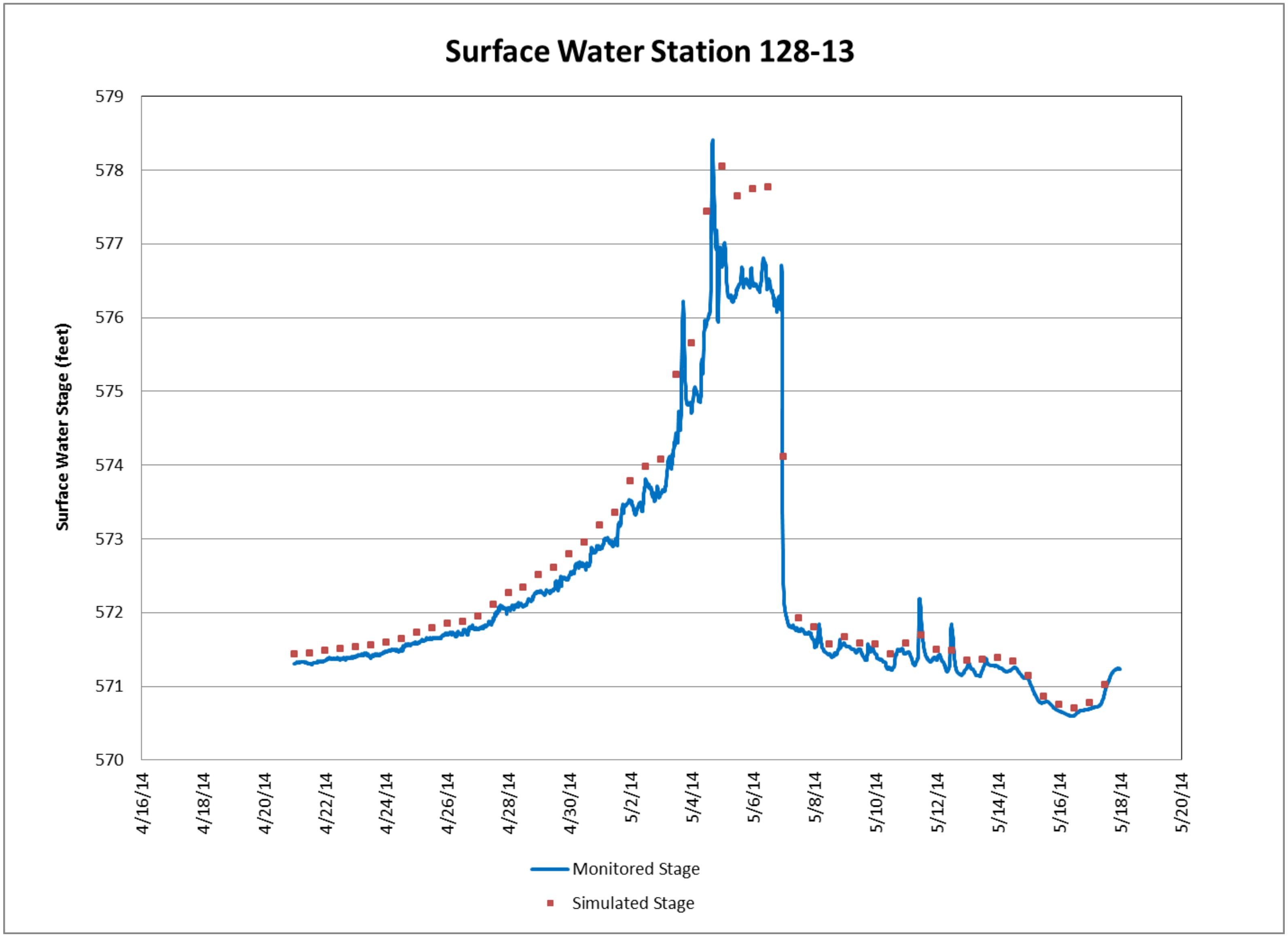


Figure 4-12. Comparison of Simulated River Stage and Monitored River Stage at Field Station FA128-13.

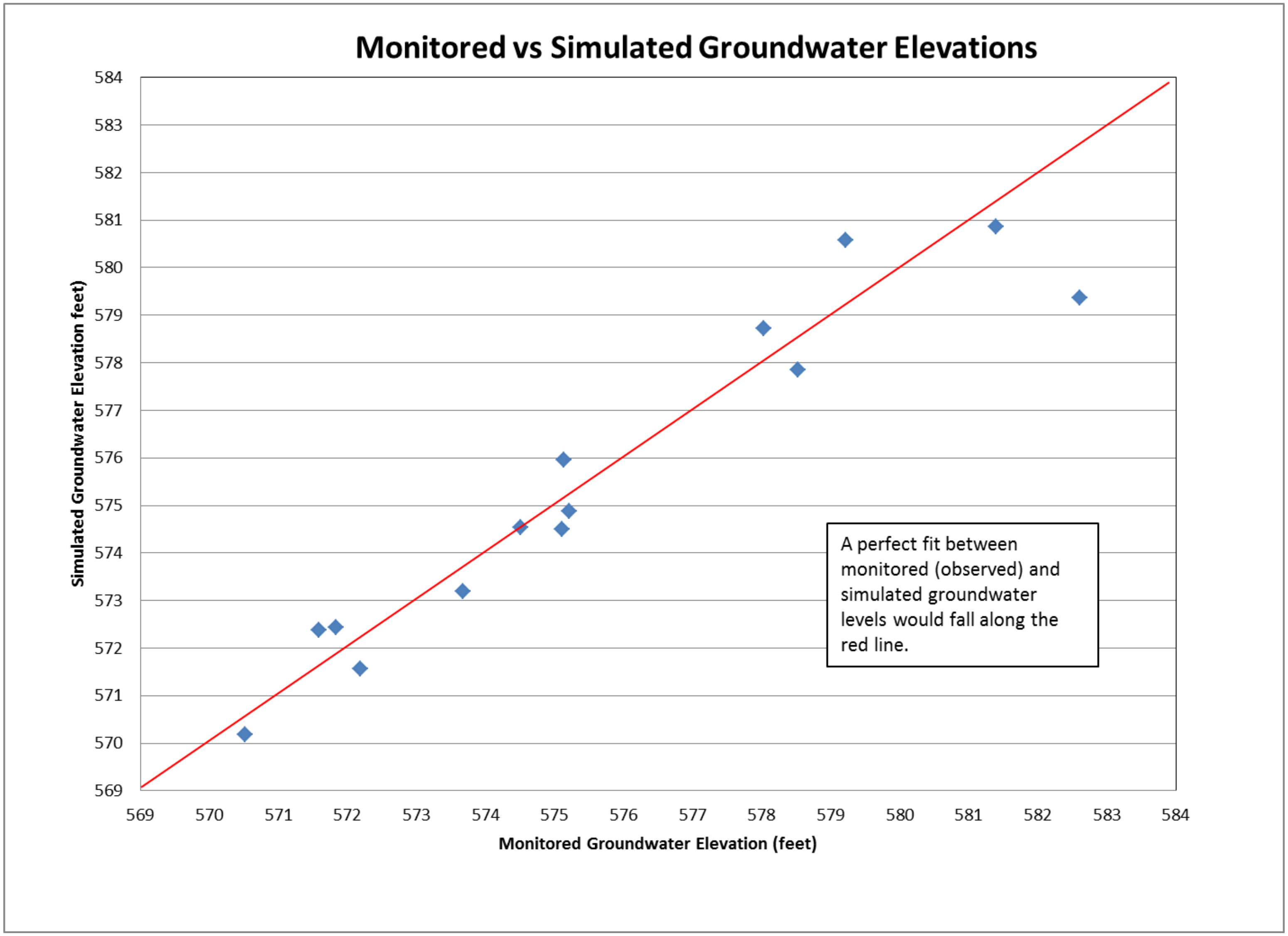


Figure 5-1. Monitored versus Simulated Steady State Groundwater Elevations.

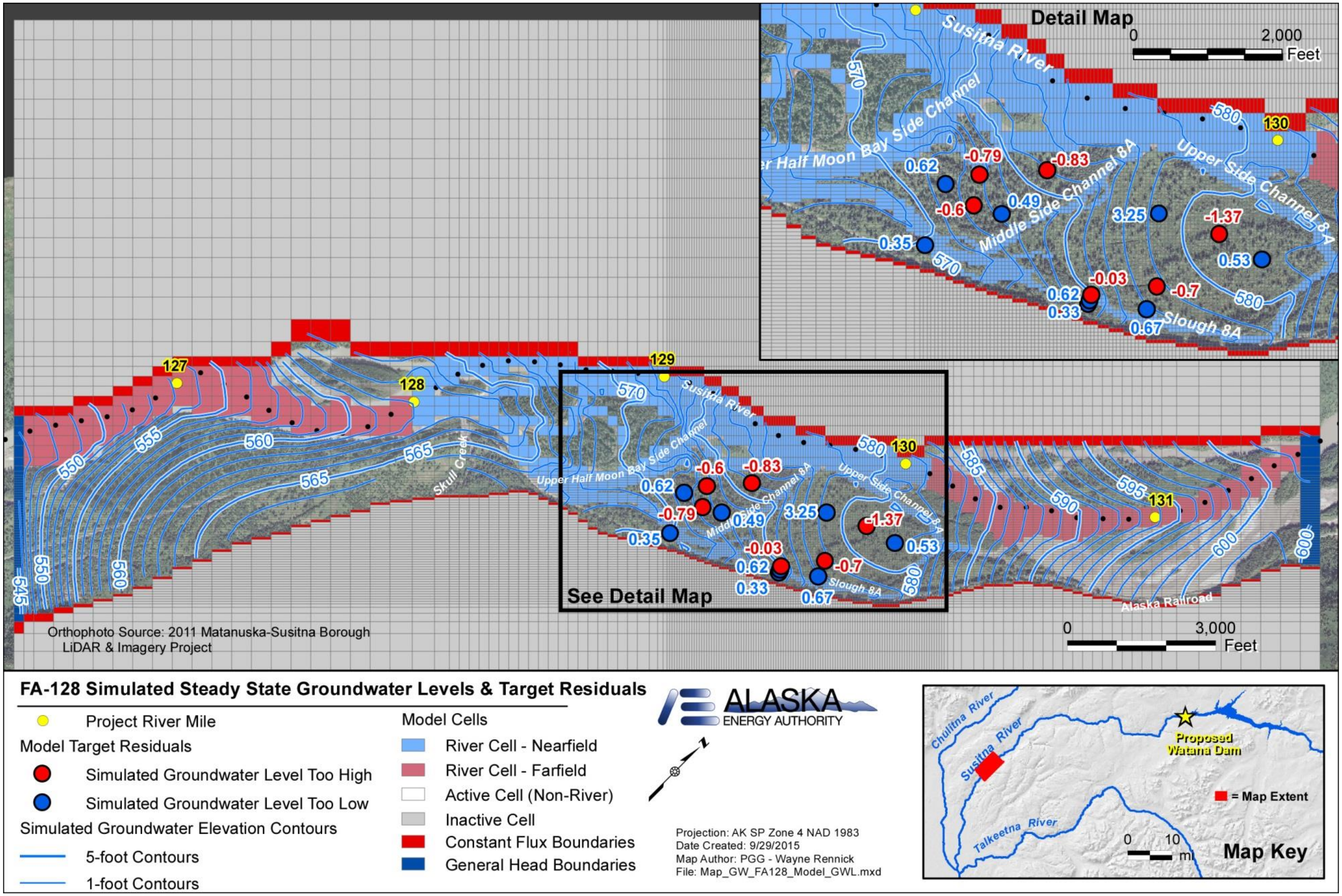


Figure 5-2. Simulated Steady State Groundwater Elevations and Model Target Residuals in FA-128 Area.

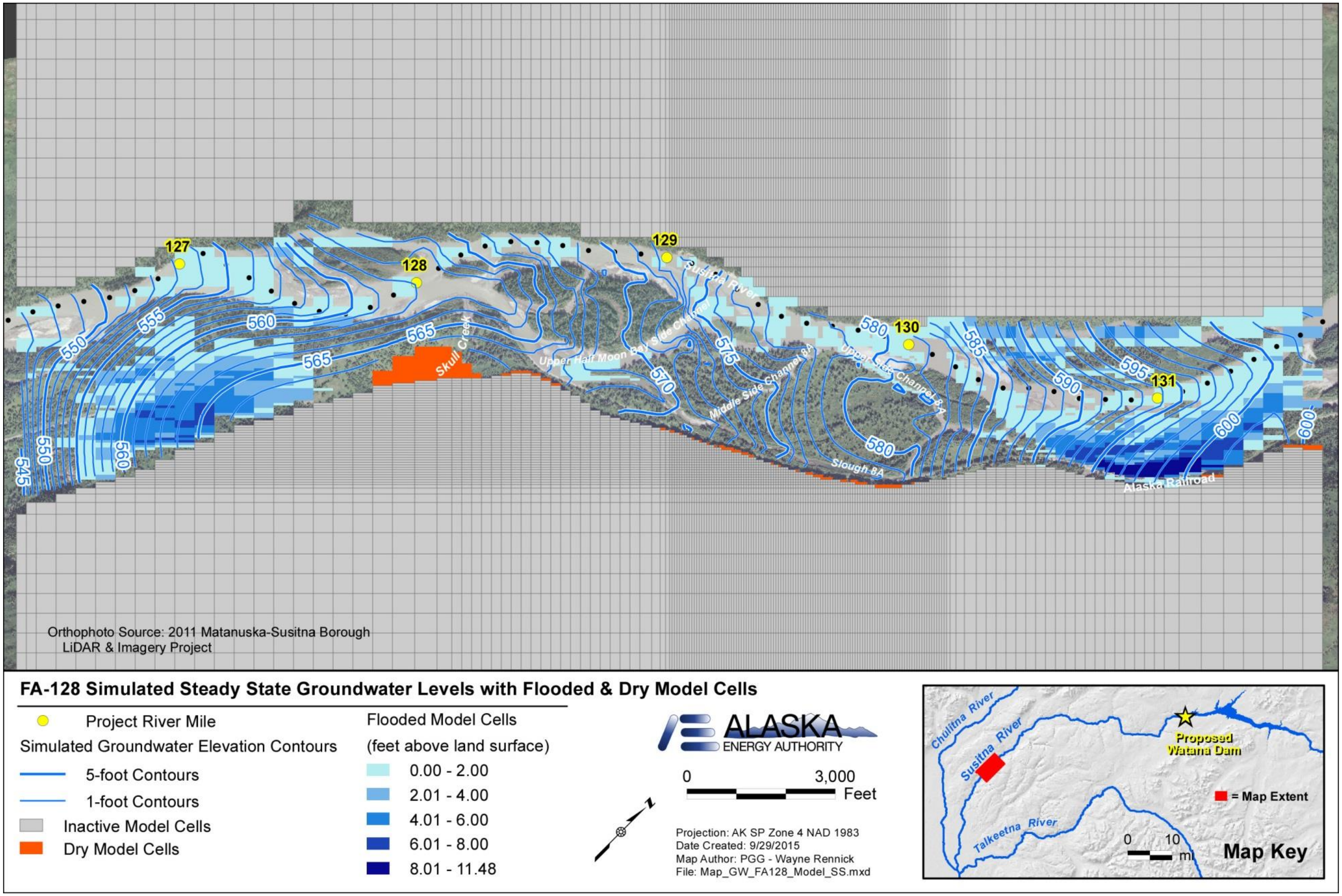


Figure 5-3. Simulated Steady State Groundwater Elevations with Flooded and Dry Model Cells Shown.

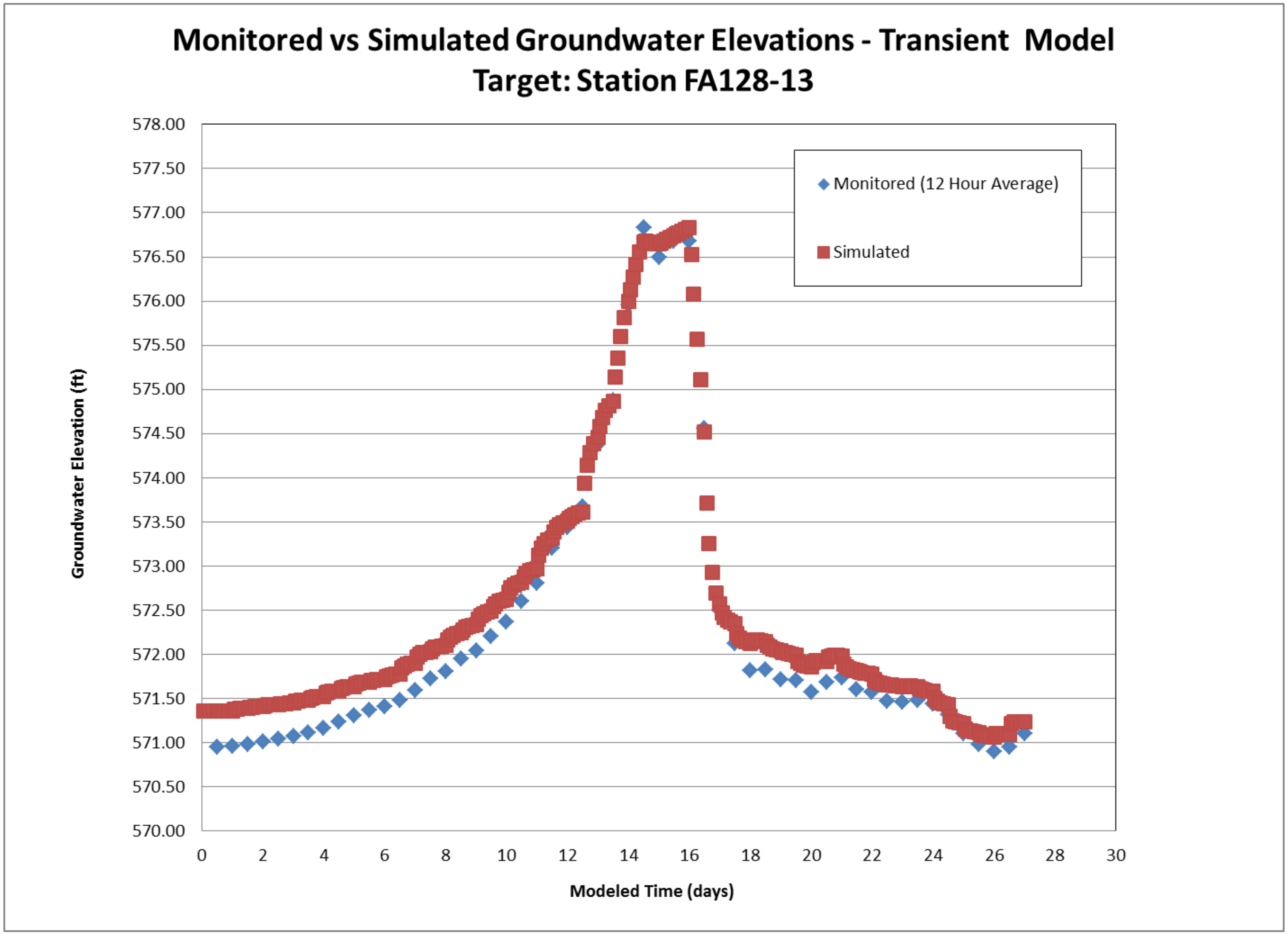


Figure 5-4. Monitored versus Simulated Steady State Groundwater Elevations (Station 128-13).

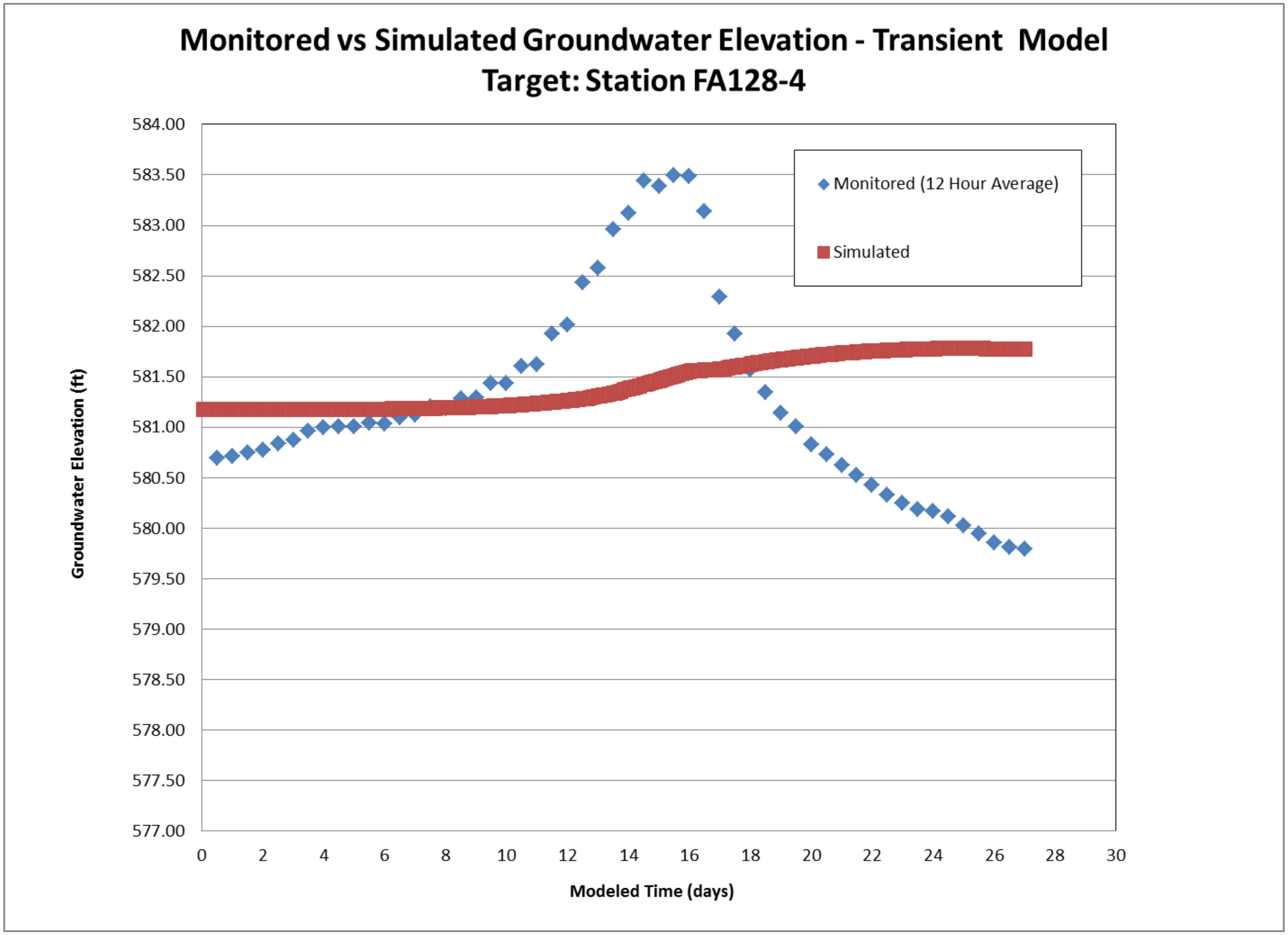


Figure 5-5. Monitored versus Simulated Steady State Groundwater Elevations (Station 128-4).

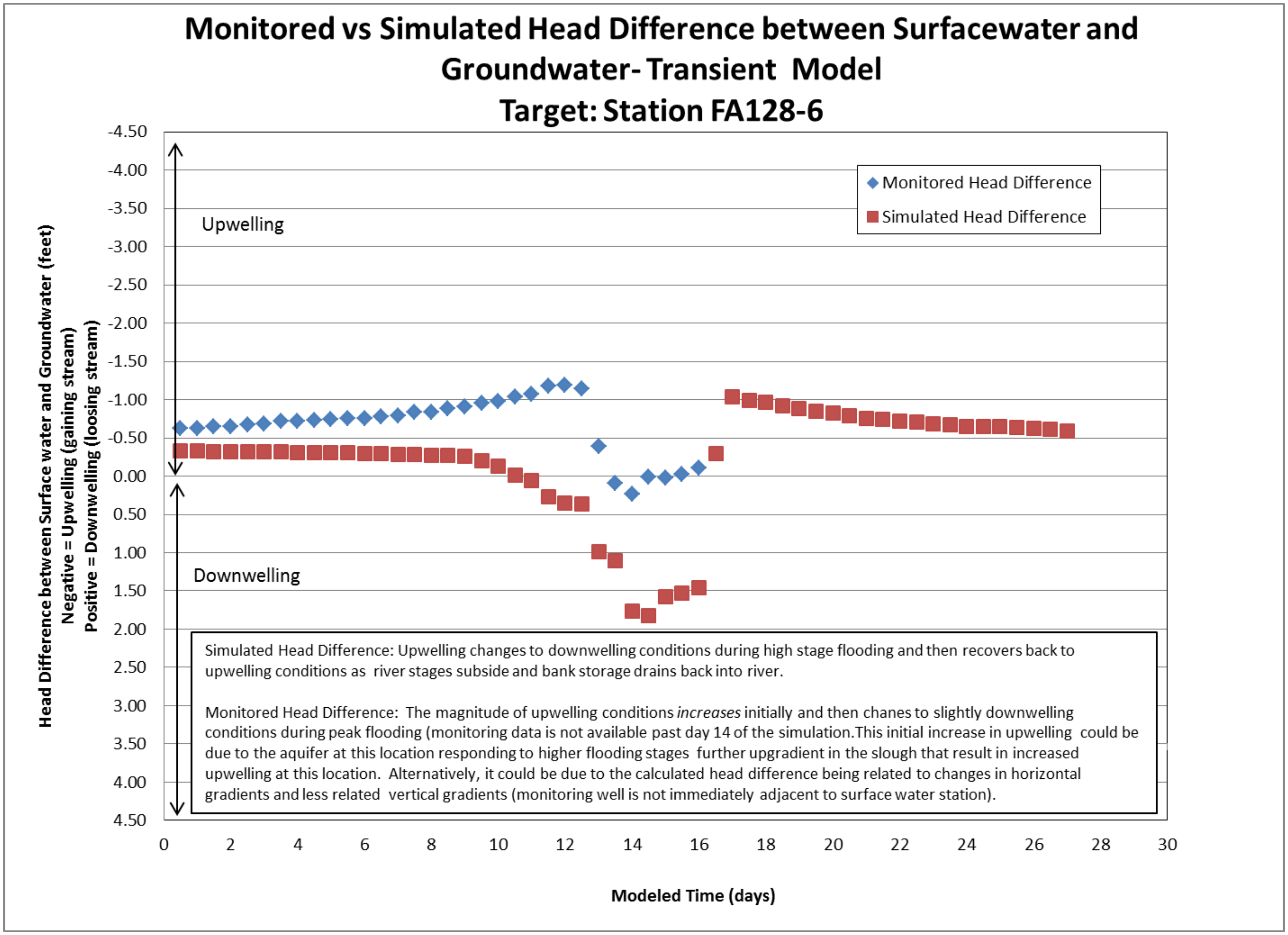
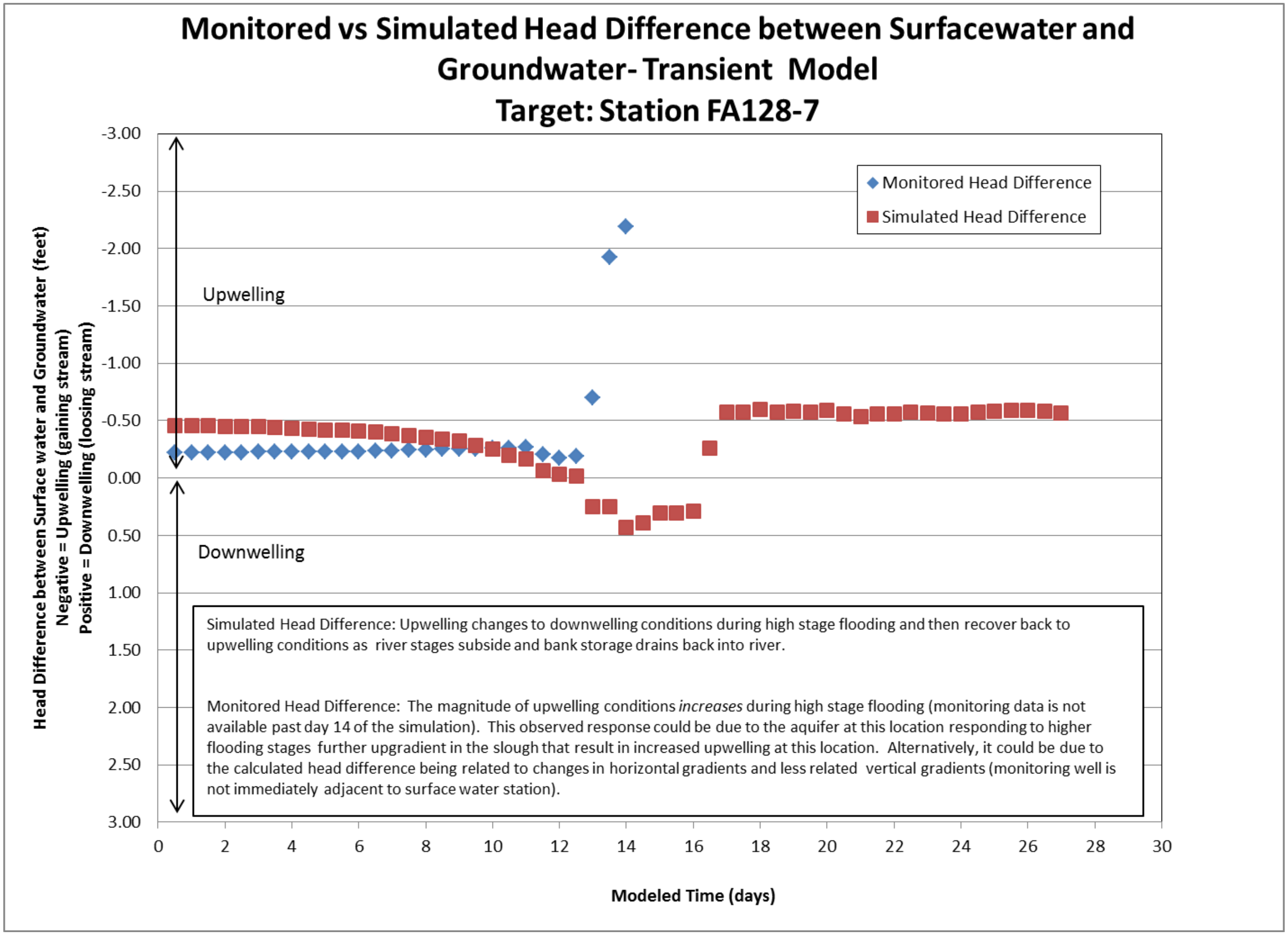


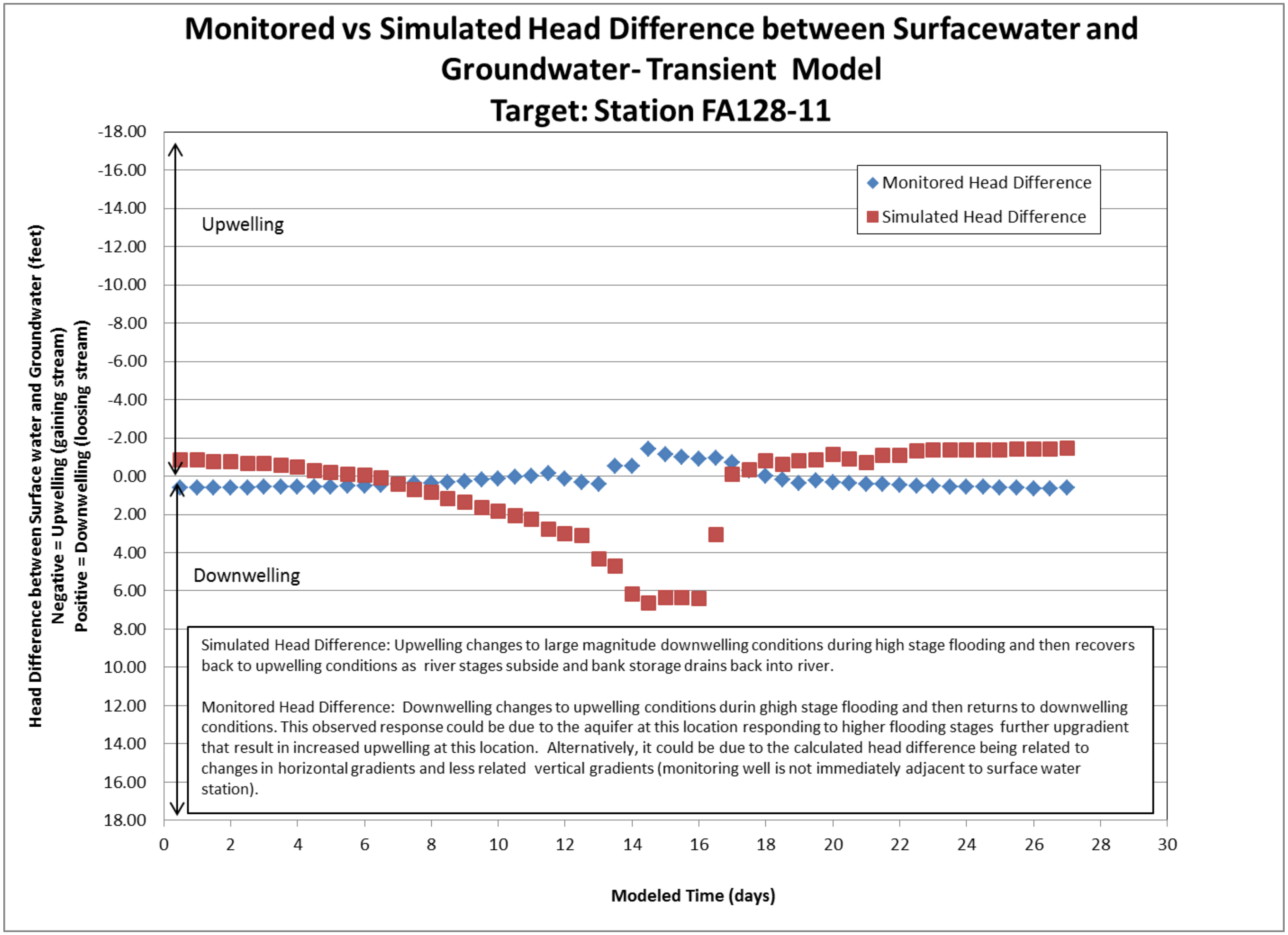
Figure 5-6. Monitored versus Simulated Transient Head Difference between Surface water and Groundwater at Target Station 128-6.


Monitored vs Simulated Head Difference between Surfacewater and Groundwater- Transient Model
Target: Station FA128-7

Simulated Head Difference: Upwelling changes to downwelling conditions during high stage flooding and then recover back to upwelling conditions as river stages subside and bank storage drains back into river.

Monitored Head Difference: The magnitude of upwelling conditions *increases* during high stage flooding (monitoring data is not available past day 14 of the simulation). This observed response could be due to the aquifer at this location responding to higher flooding stages further upgradient in the slough that result in increased upwelling at this location. Alternatively, it could be due to the calculated head difference being related to changes in horizontal gradients and less related vertical gradients (monitoring well is not immediately adjacent to surface water station).

Figure 5-7. Monitored versus Simulated Transient Head Difference between Surface water and Groundwater at Target Station 128-7.



Simulated Head Difference: Upwelling changes to large magnitude downwelling conditions during high stage flooding and then recovers back to upwelling conditions as river stages subside and bank storage drains back into river.

Monitored Head Difference: Downwelling changes to upwelling conditions durin ghigh stage flooding and then returns to downwelling conditions. This observed response could be due to the aquifer at this location responding to higher flooding stages further upgradient that result in increased upwelling at this location. Alternatively, it could be due to the calculated head difference being related to changes in horizontal gradients and less related vertical gradients (monitoring well is not immediately adjacent to surface water station).

Figure 5-8. Monitored versus Simulated Transient Head Difference between Surface water and Groundwater at Target Station 128-11.

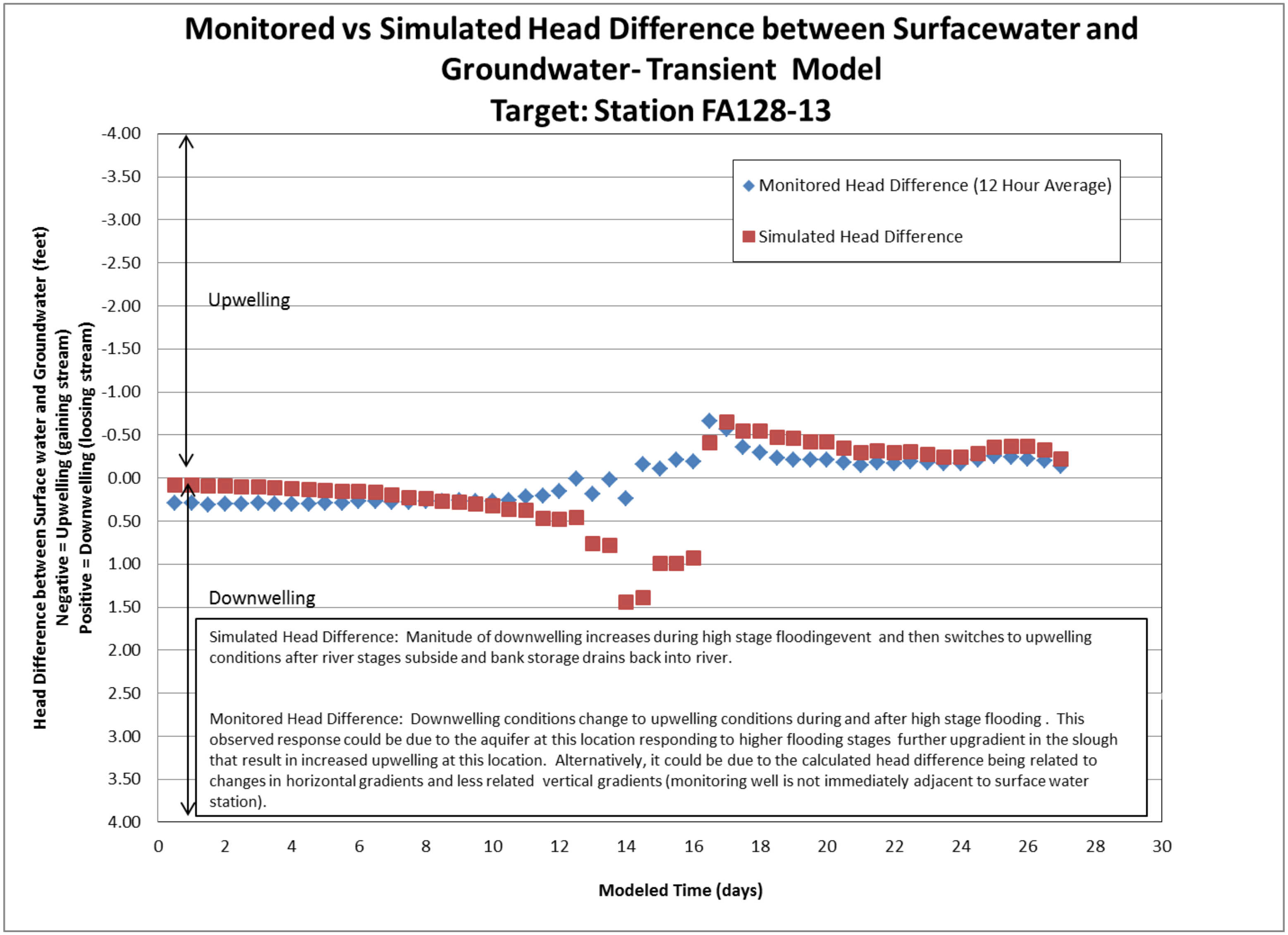


Figure 5-9. Monitored versus Simulated Transient Head Difference between Surface water and Groundwater at Target Station 128-13.

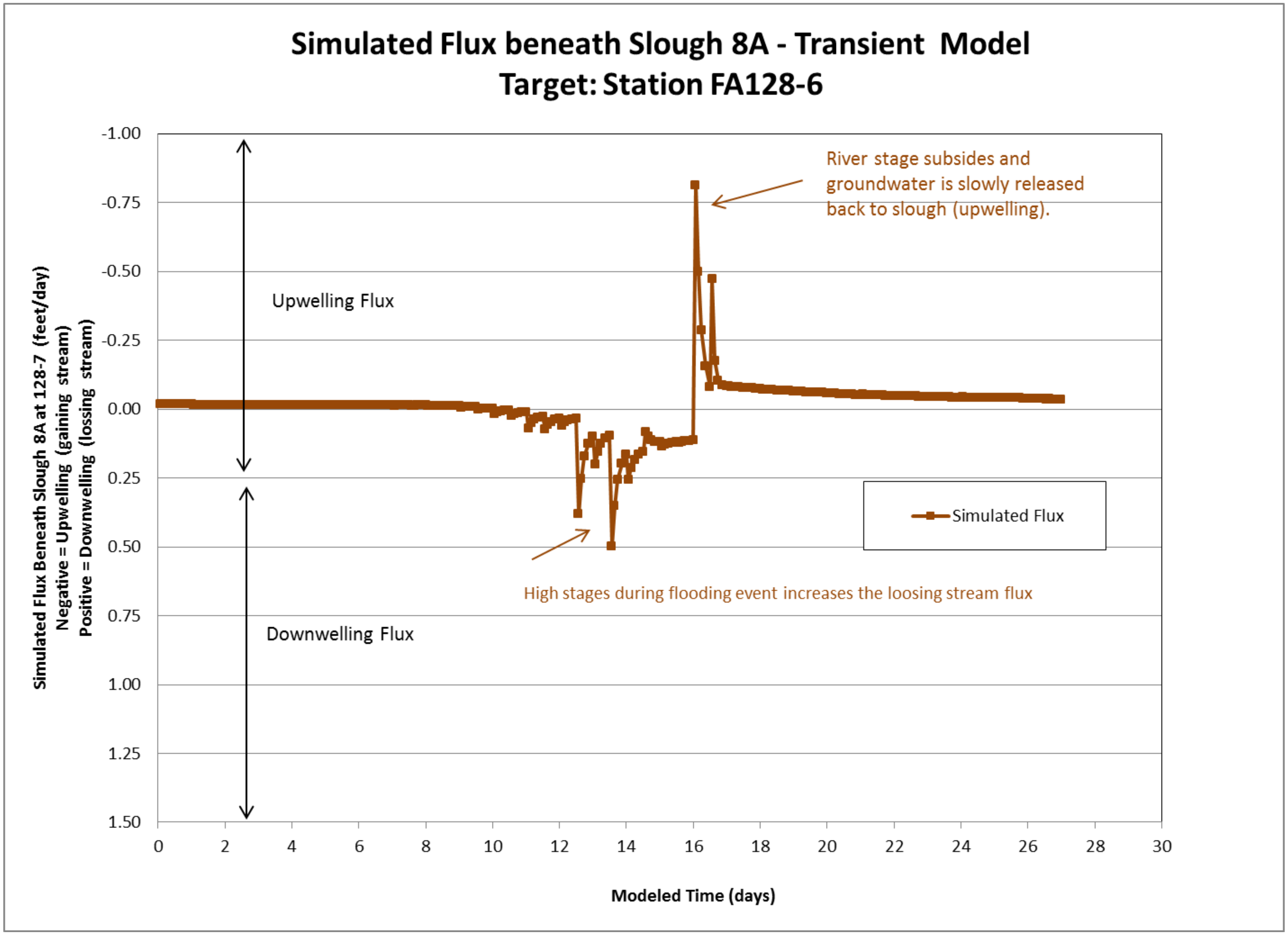


Figure 5-10. Simulated Transient Flux beneath Slough 8A at Target Station 128-6.

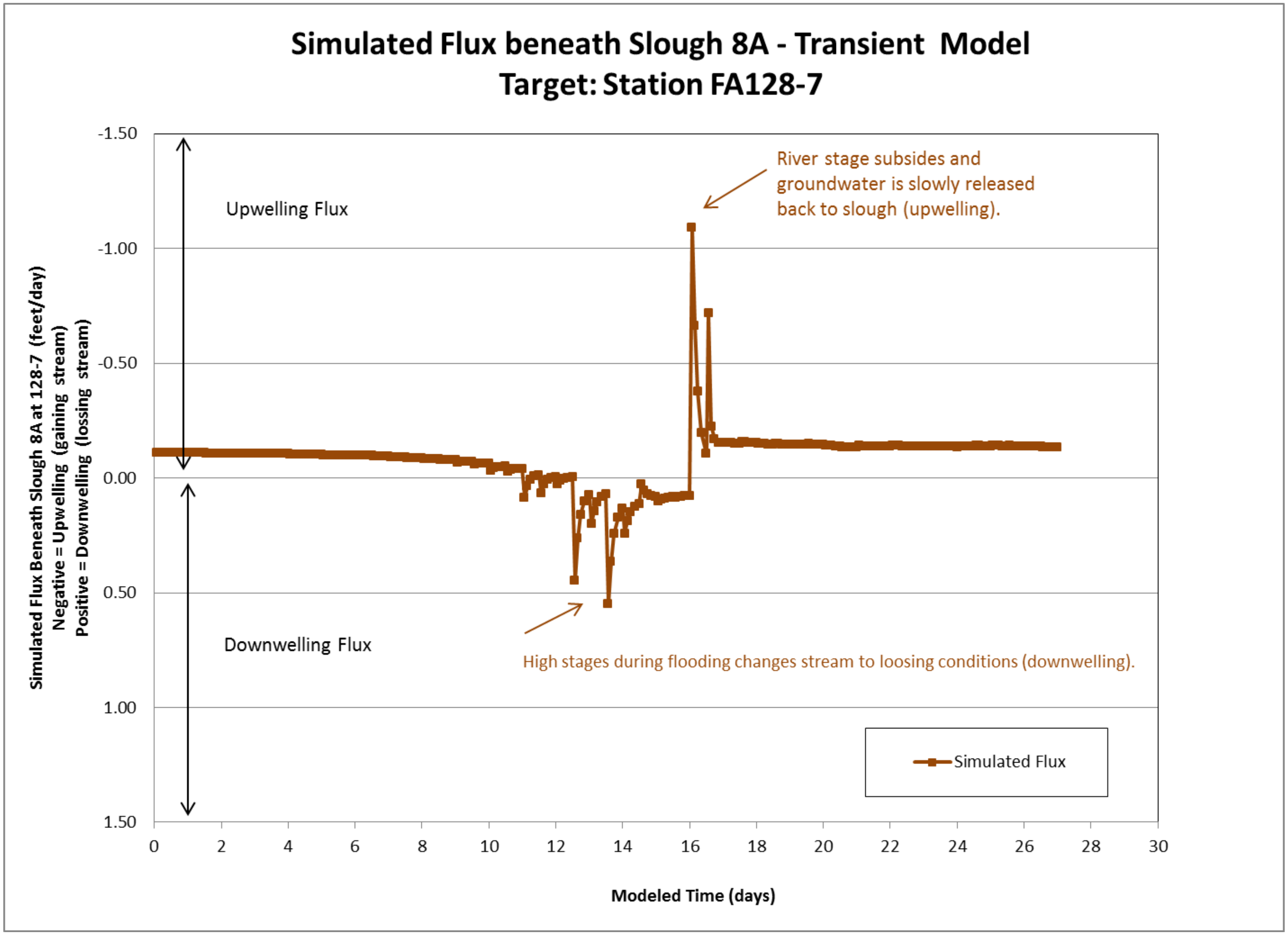


Figure 5-11. Simulated Transient Flux beneath Slough 8A at Target Station 128-7.

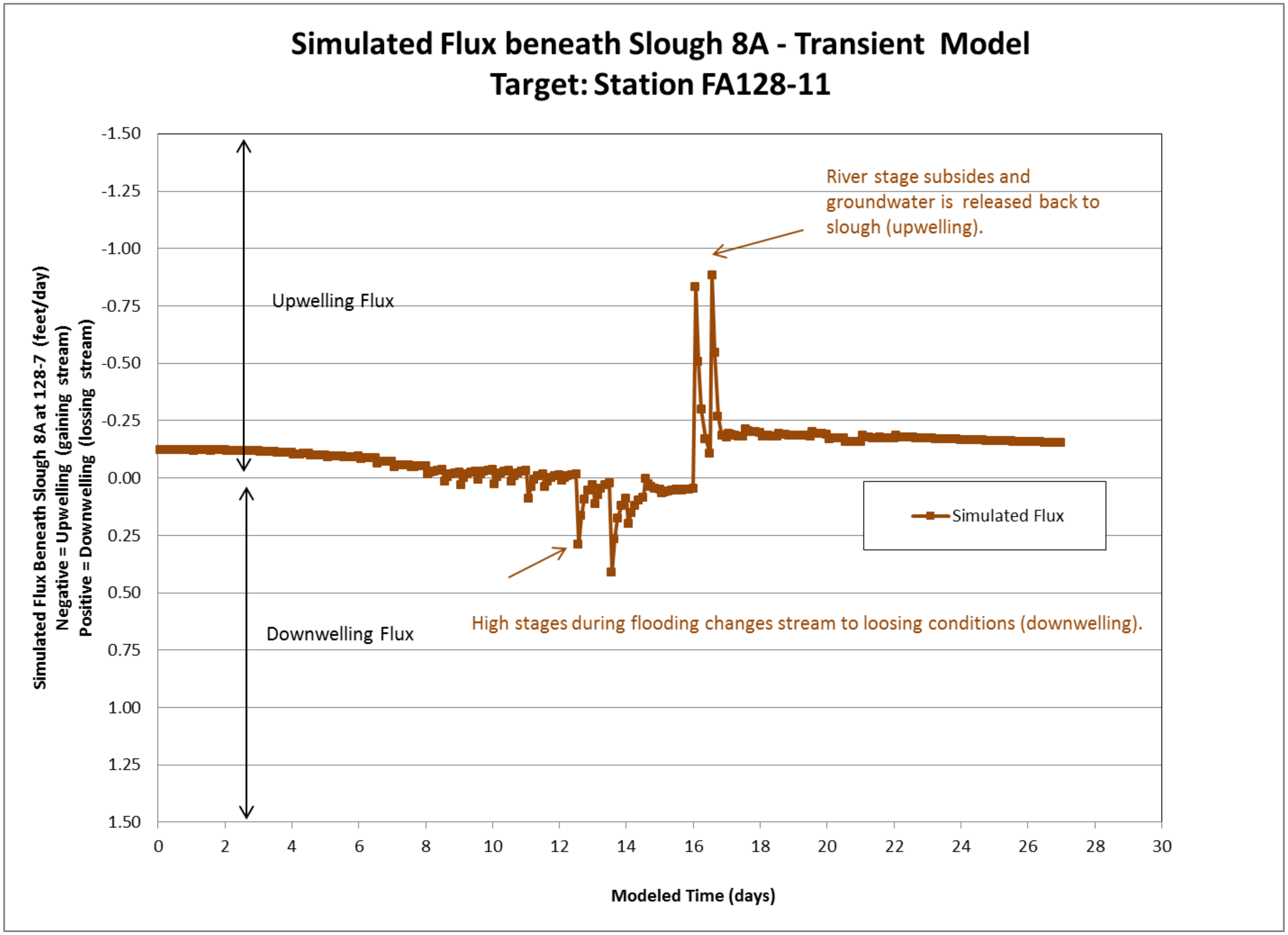


Figure 5-12. Simulated Transient Flux beneath Slough 8A at Target Station 128-11.

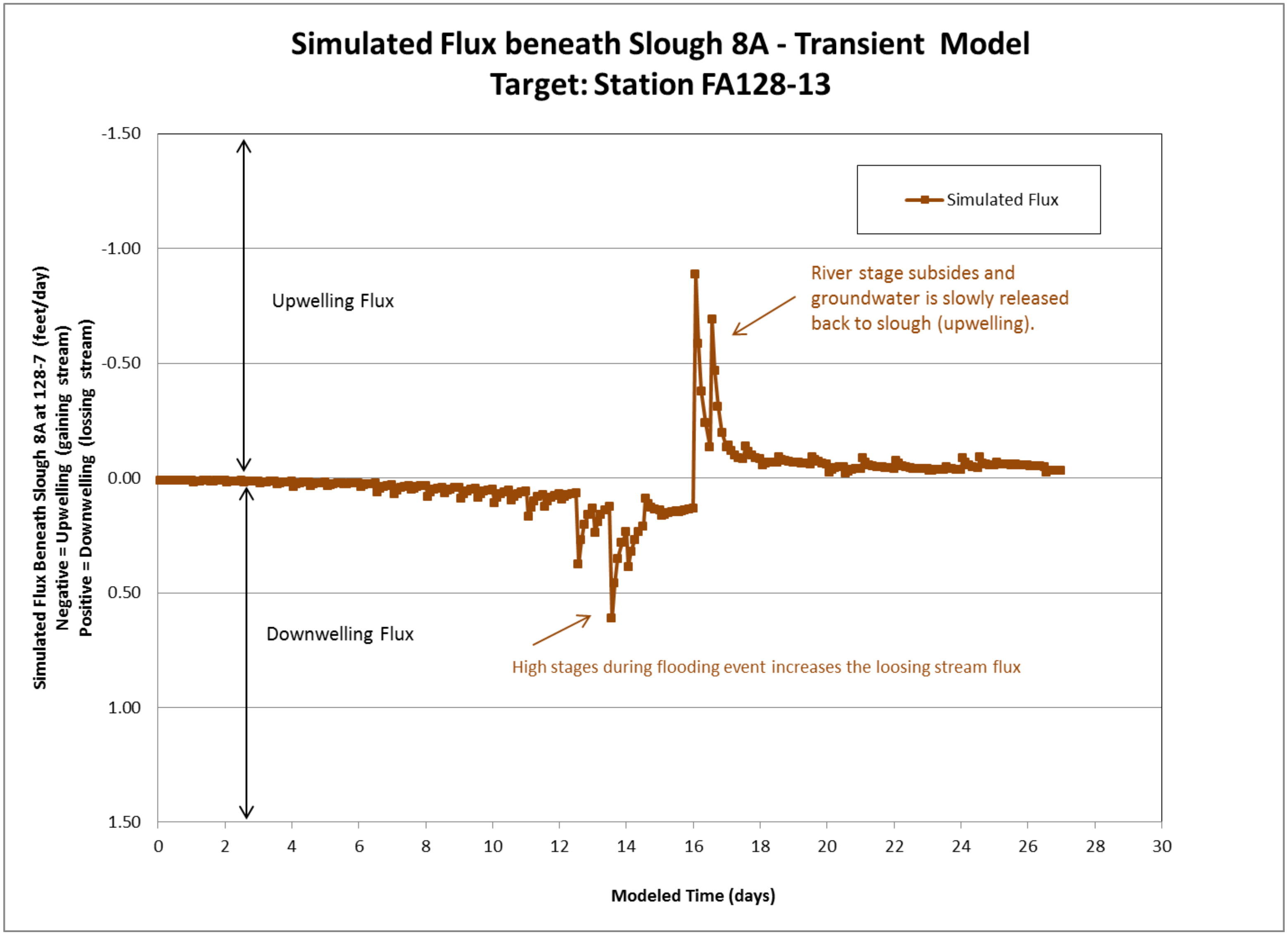


Figure 5-13. Simulated Transient Flux beneath Slough 8A at Target Station 128-13.

ATTACHMENT 1: TRANSIENT TARGET RESULTS

LIST OF FIGURES

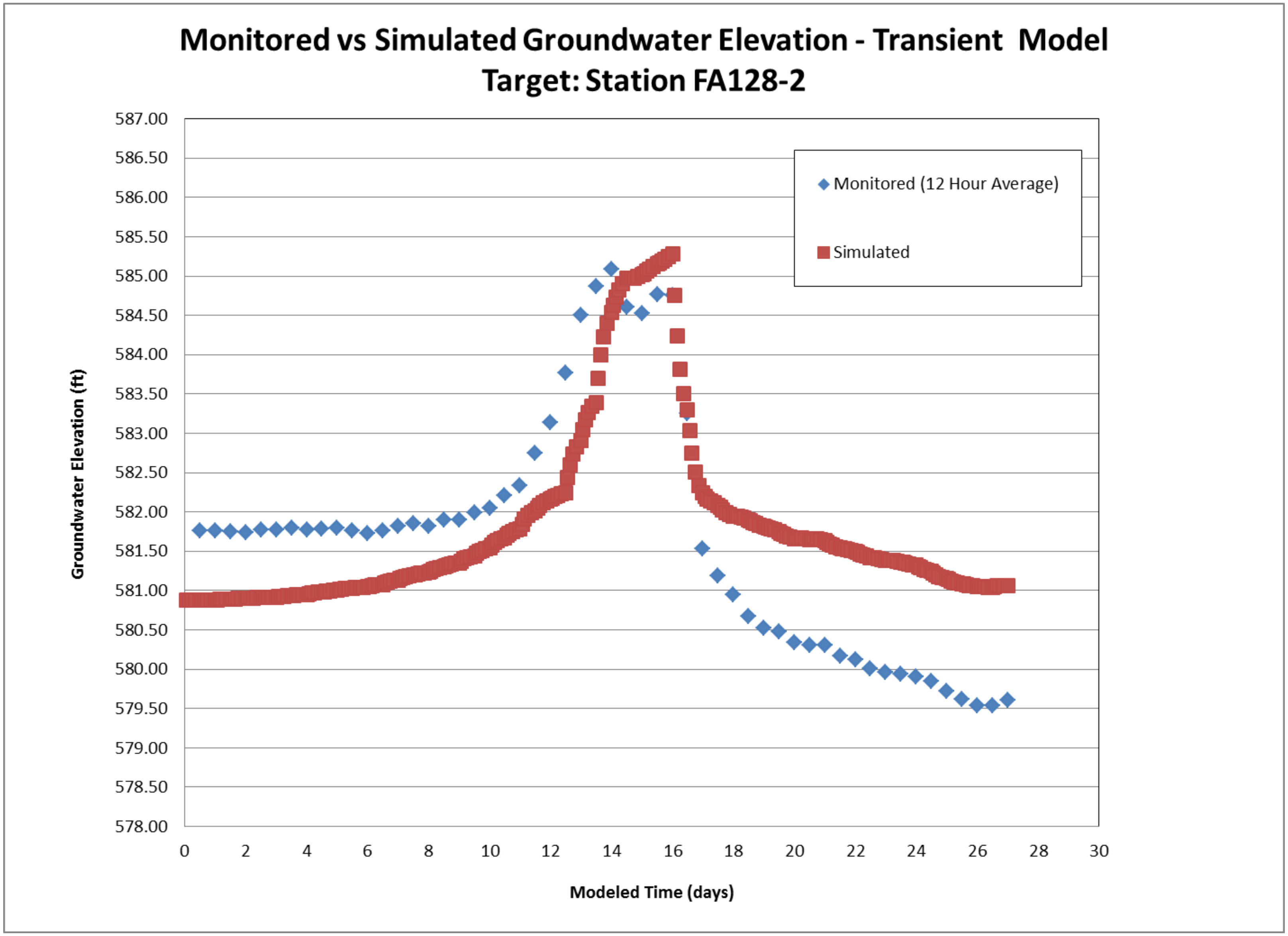


Figure B1-1. Monitored vs. Simulated Groundwater Elevation – Transient Model at Target Station FA128-2.

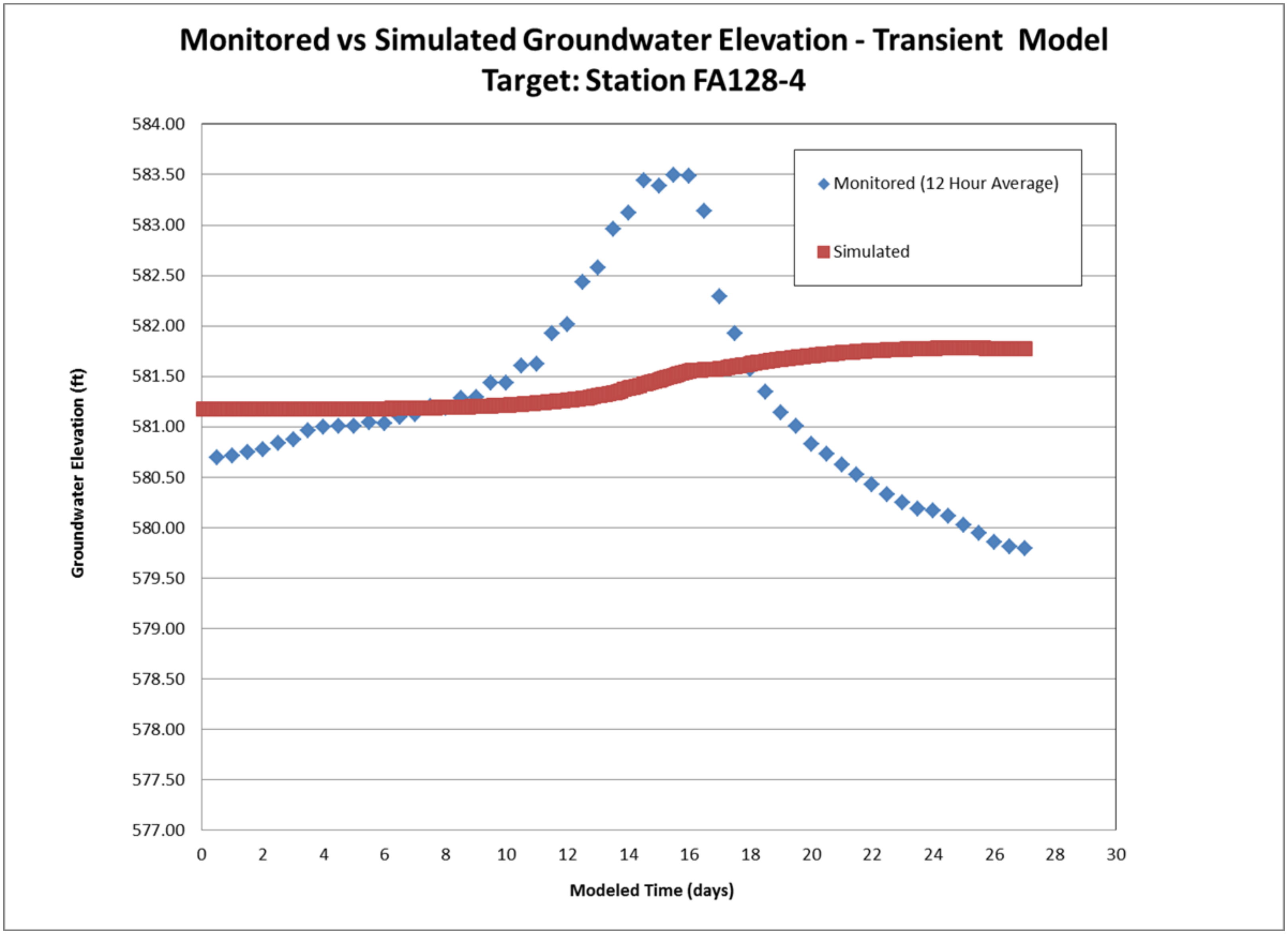


Figure B1-2. Monitored vs. Simulated Groundwater Elevation – Transient Model at Target Station FA128-4.

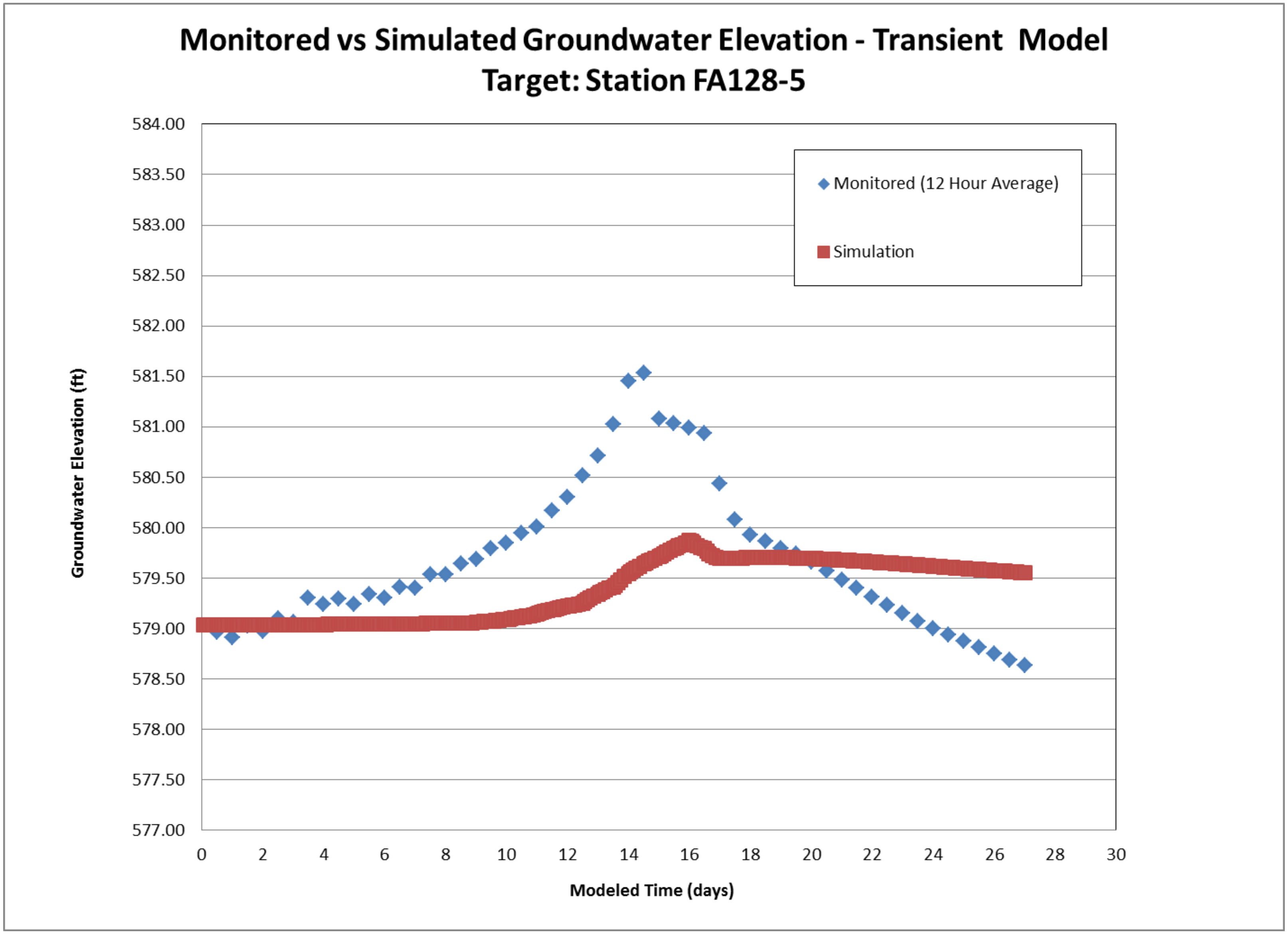


Figure B1-3. Monitored vs. Simulated Groundwater Elevation – Transient Model at Target Station FA128-5.

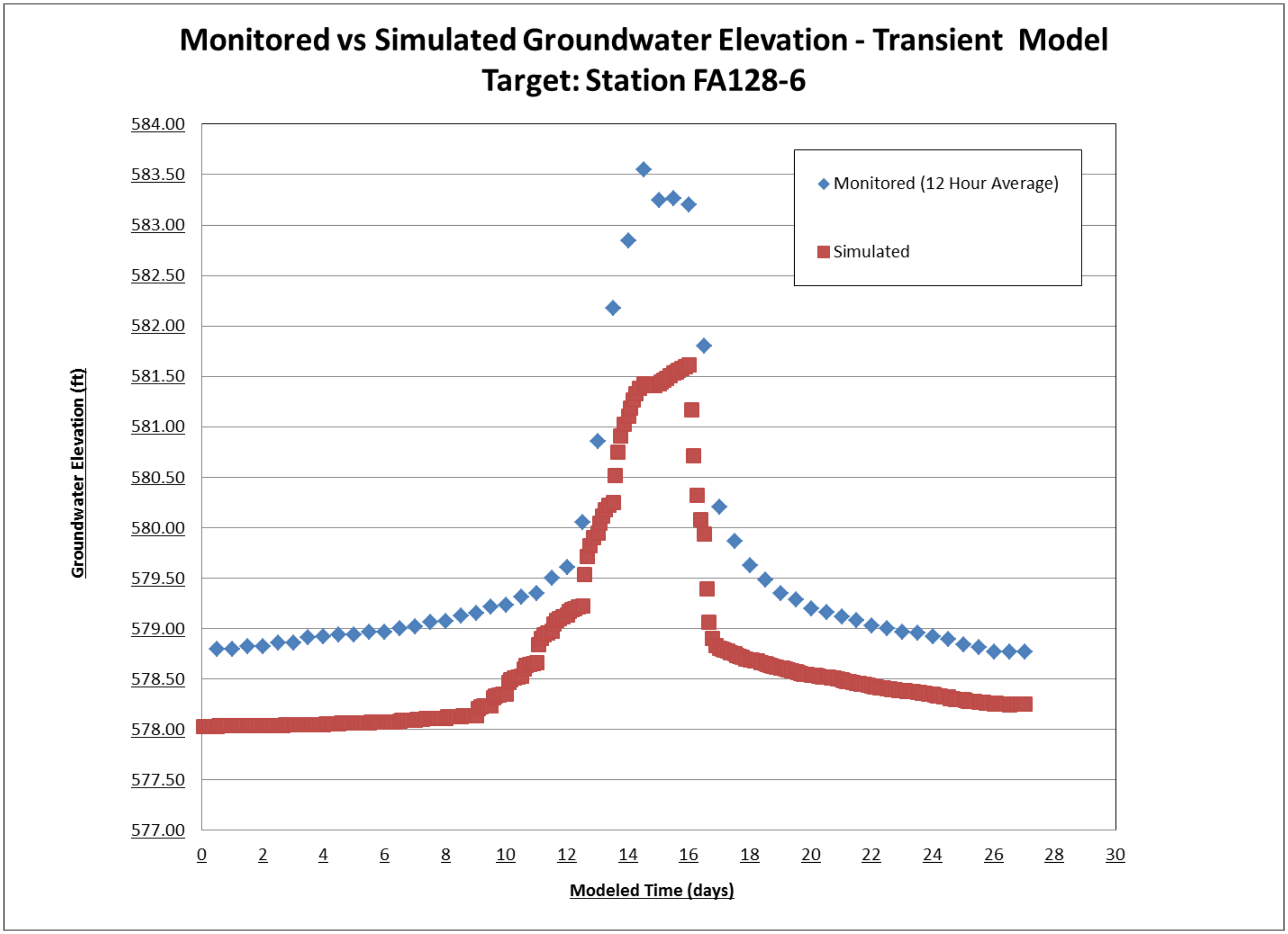


Figure B1-4. Monitored vs. Simulated Groundwater Elevation – Transient Model at Target Station FA128-6.

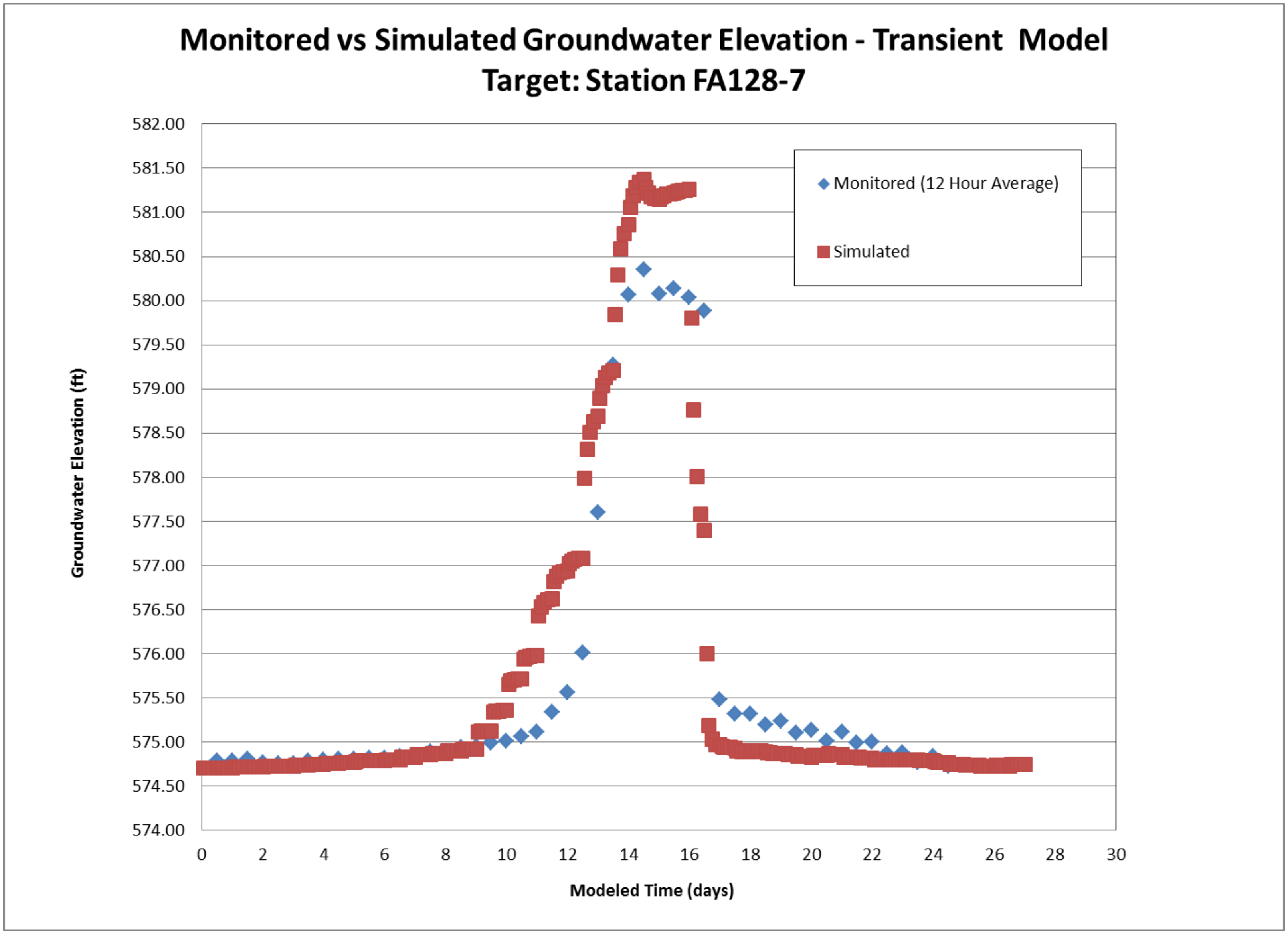


Figure B1-5. Monitored vs. Simulated Groundwater Elevation – Transient Model at Target Station FA128-7.

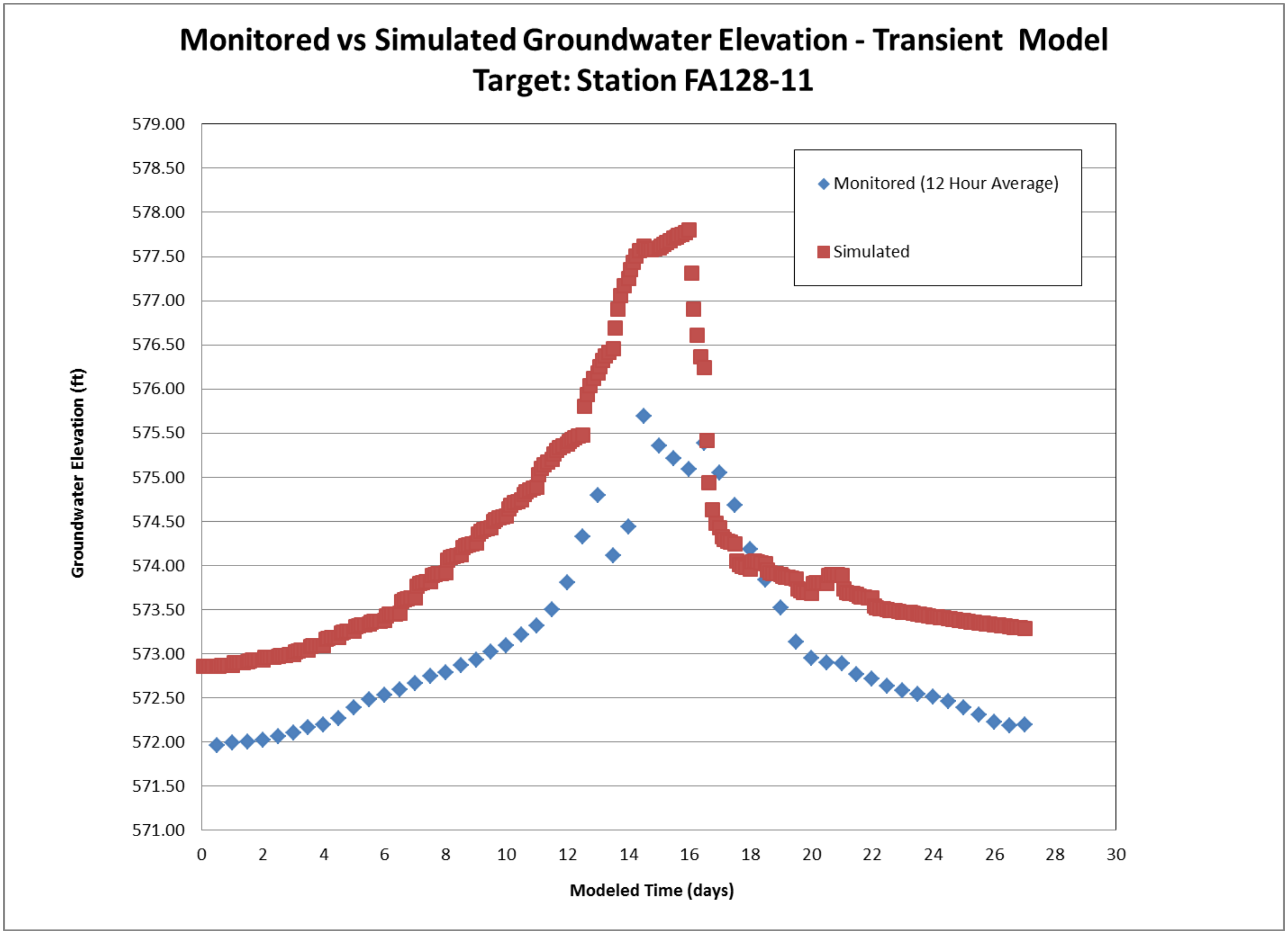


Figure B1-6. Monitored vs. Simulated Groundwater Elevation – Transient Model at Target Station FA128-11.

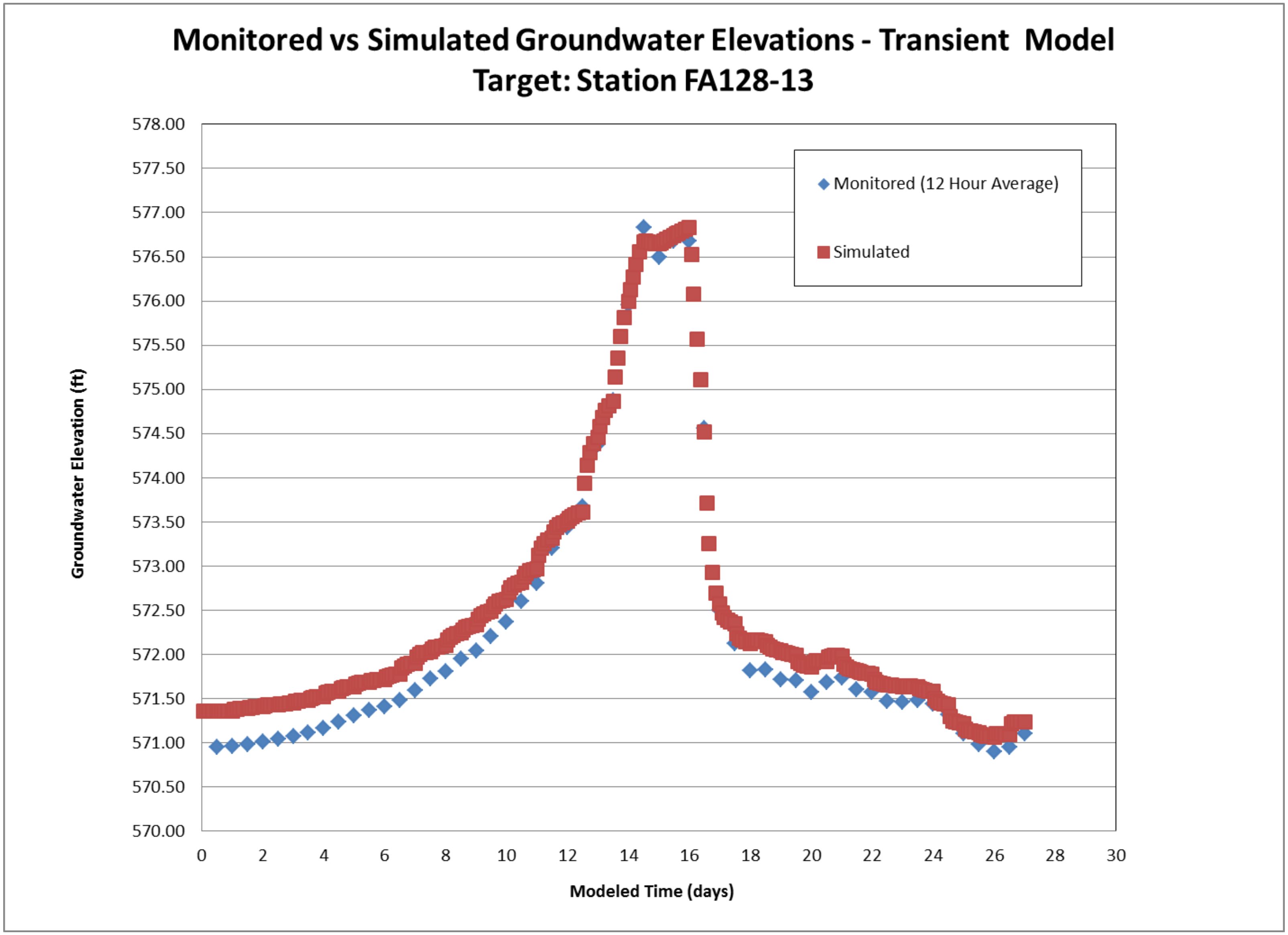


Figure B1-7. Monitored vs. Simulated Groundwater Elevation – Transient Model at Target Station FA128-13.

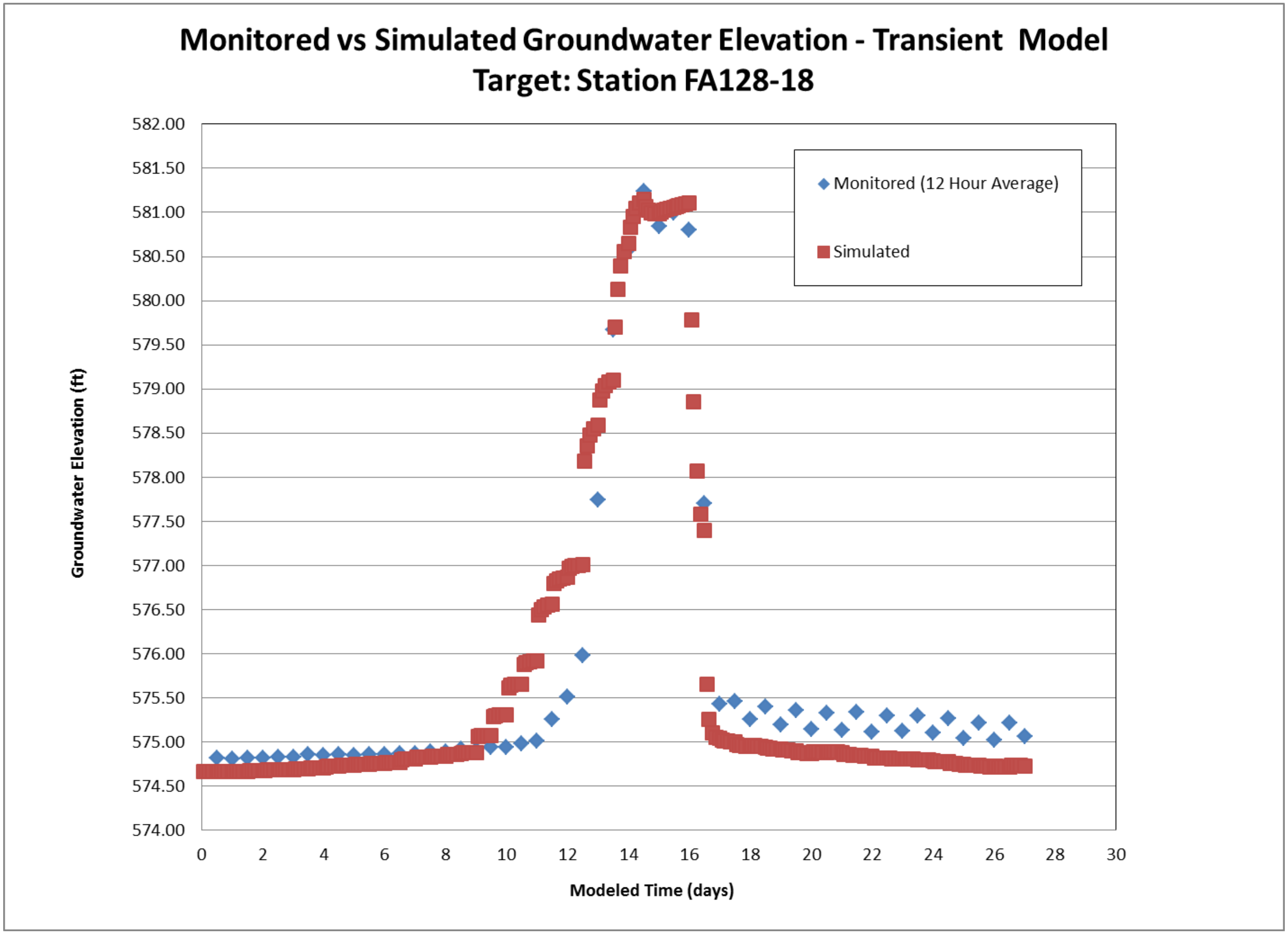


Figure B1-8. Monitored vs. Simulated Groundwater Elevation – Transient Model at Target Station FA128-18.

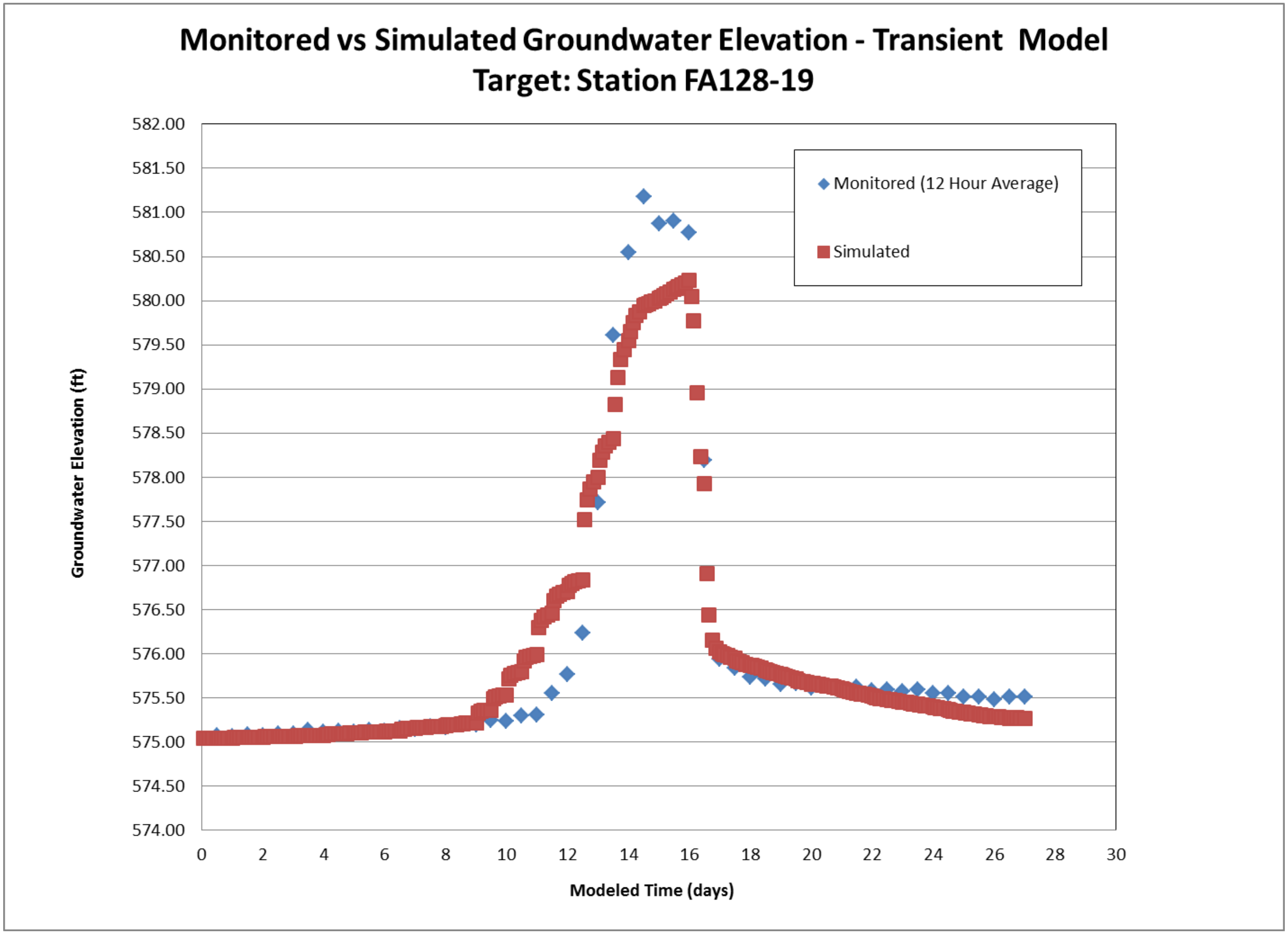


Figure B1-9. Monitored vs. Simulated Groundwater Elevation – Transient Model at Target Station FA128-19.

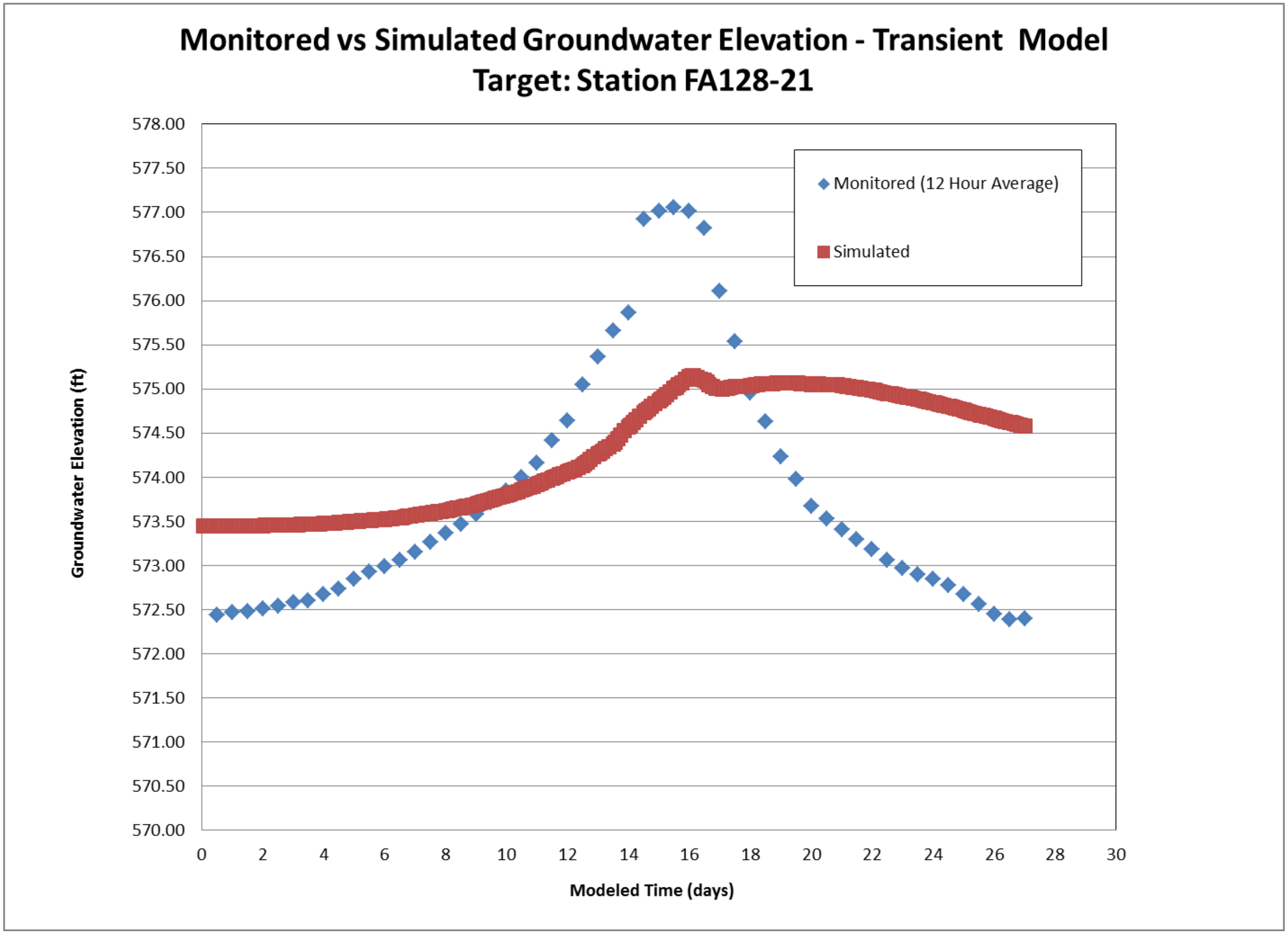


Figure B1-10. Monitored vs. Simulated Groundwater Elevation – Transient Model at Target Station at FA128-21.

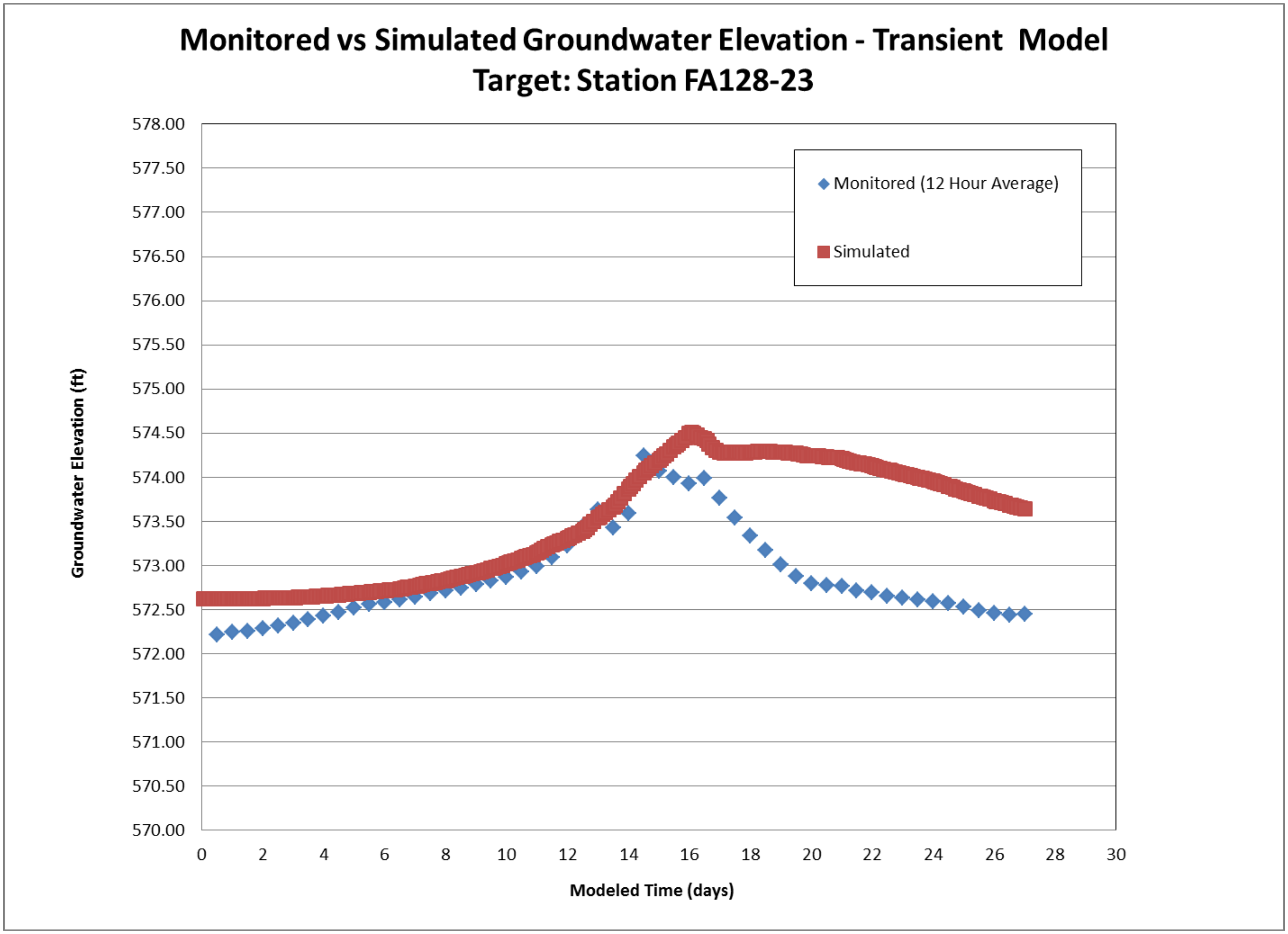


Figure B1-11. Monitored vs. Simulated Groundwater Elevation – Transient Model at Target Station FA128-23.

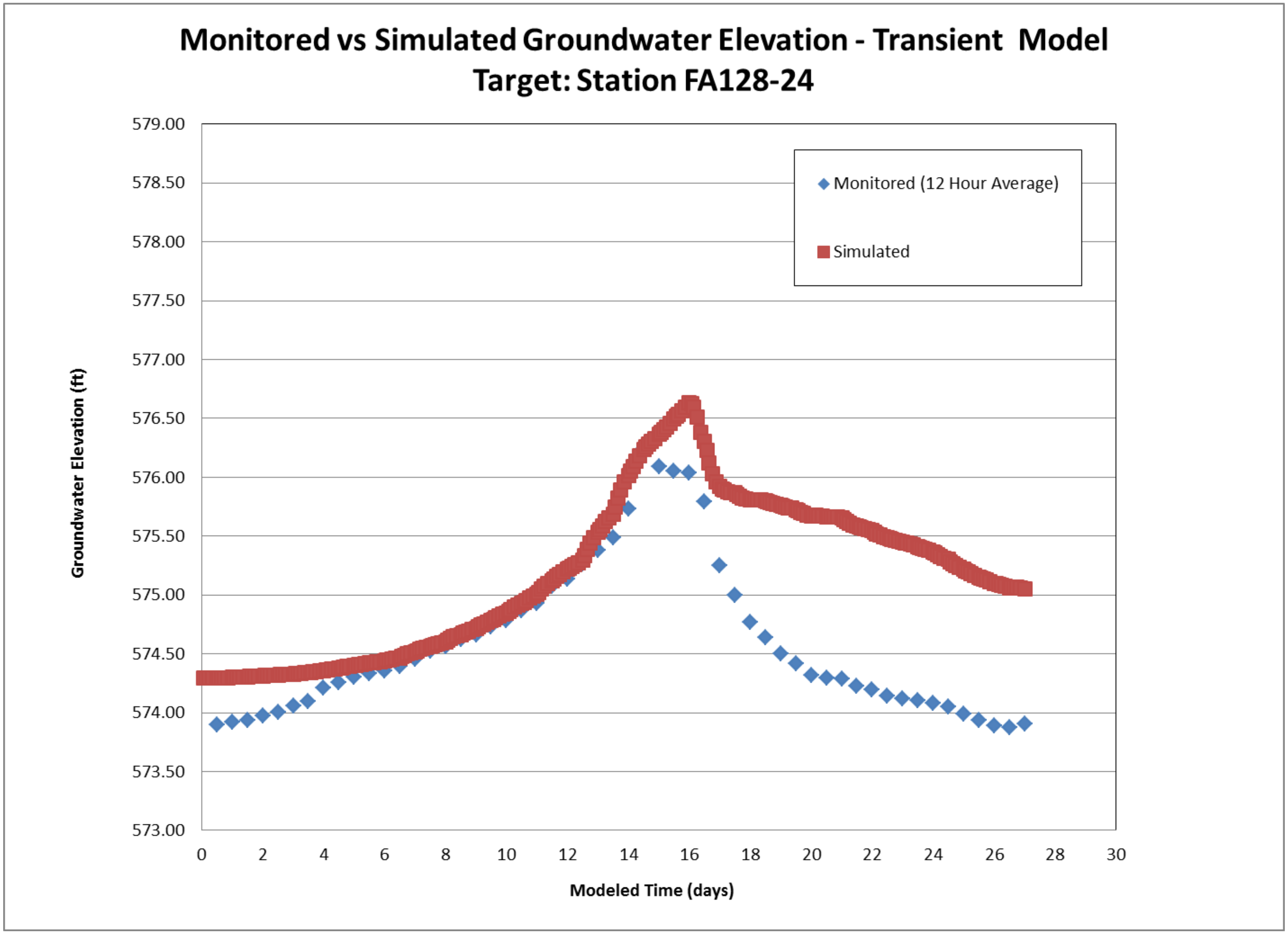


Figure B1-12. Monitored vs. Simulated Groundwater Elevation – Transient Model at Target Station FA128-24.

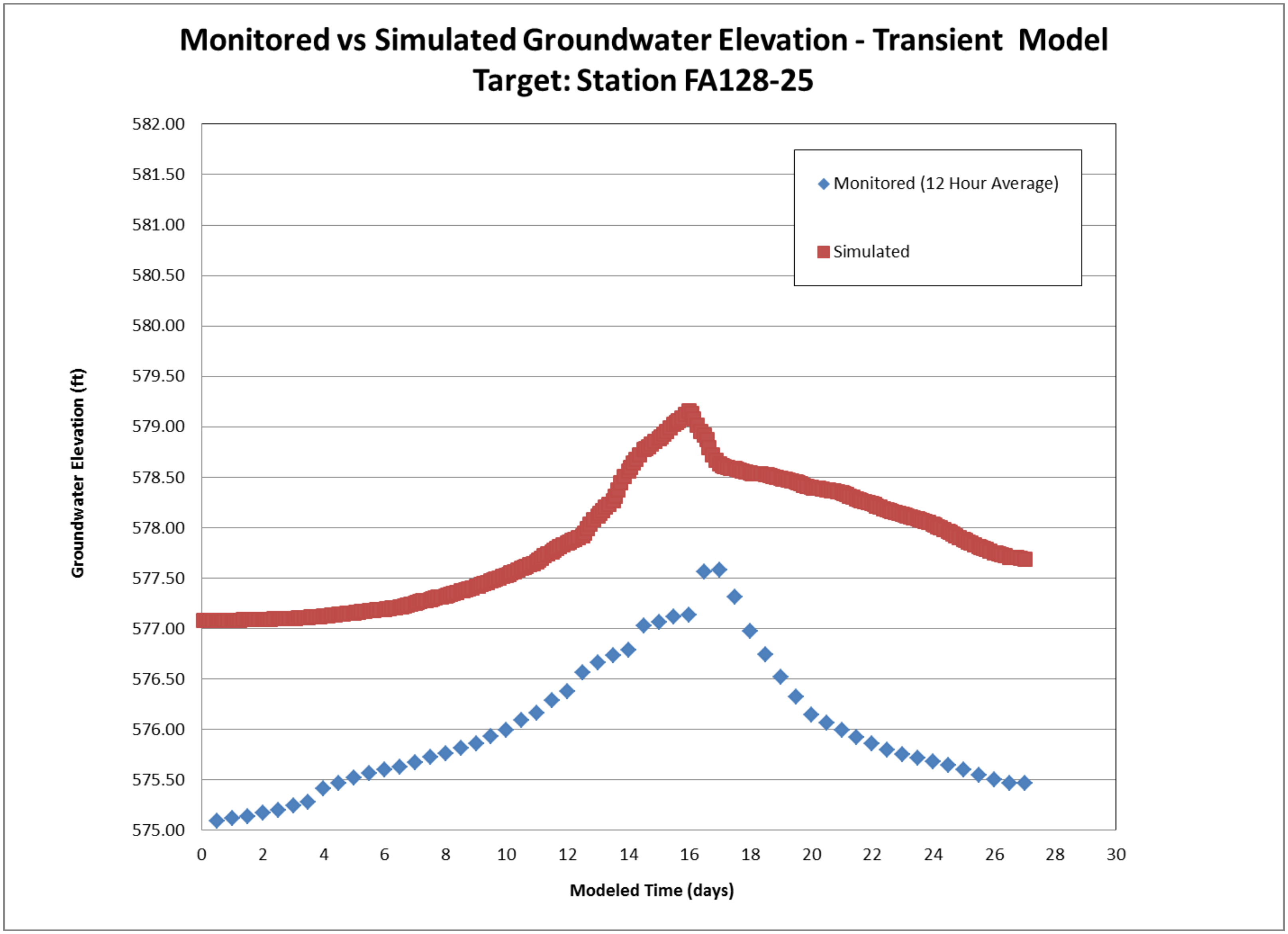


Figure B1-13. Monitored vs. Simulated Groundwater Elevation – Transient Model at Target Station FA-128-25.

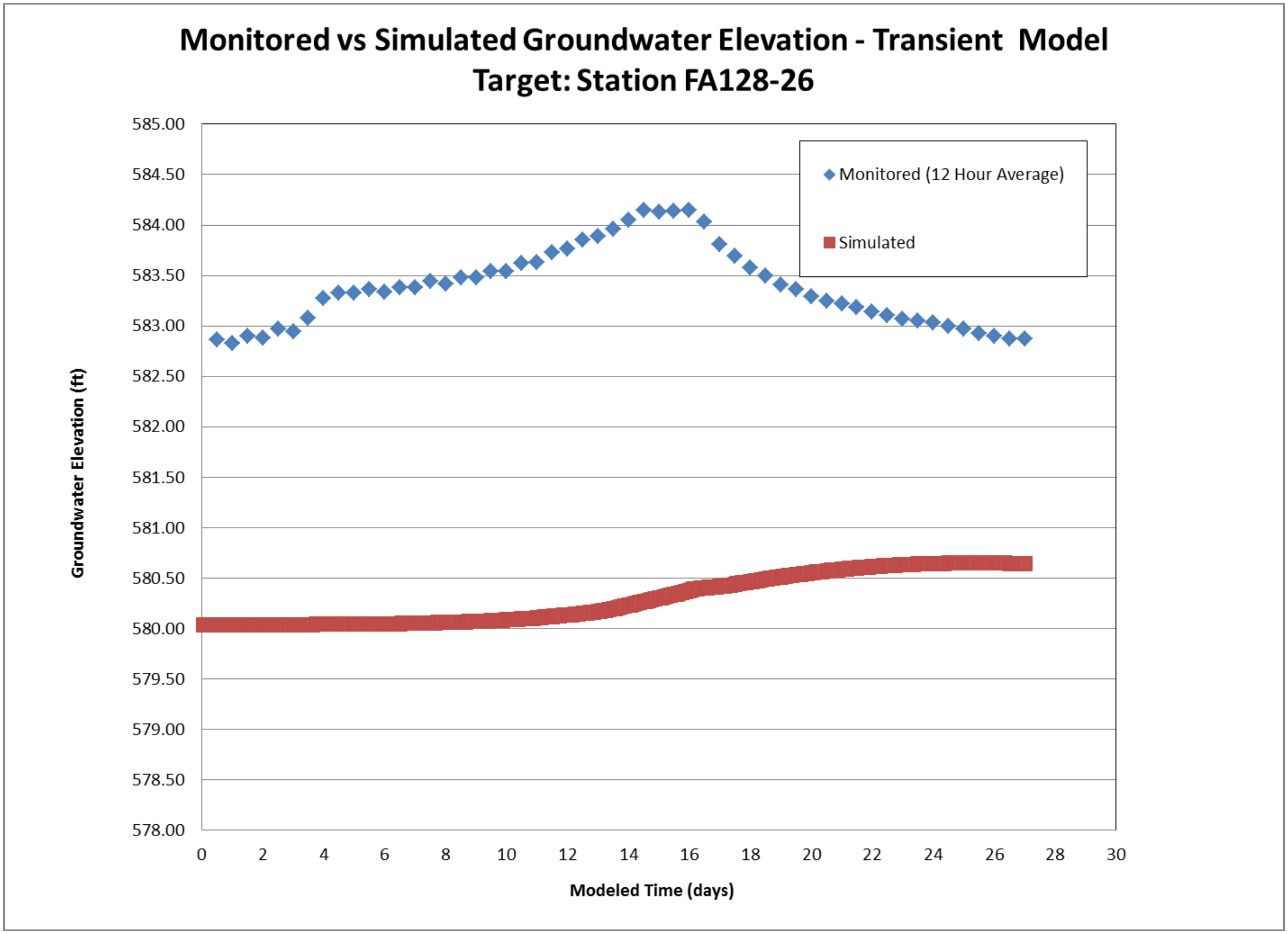


Figure B1-14. Monitored vs. Simulated Groundwater Elevation – Transient Model at Target Station FA128-26.

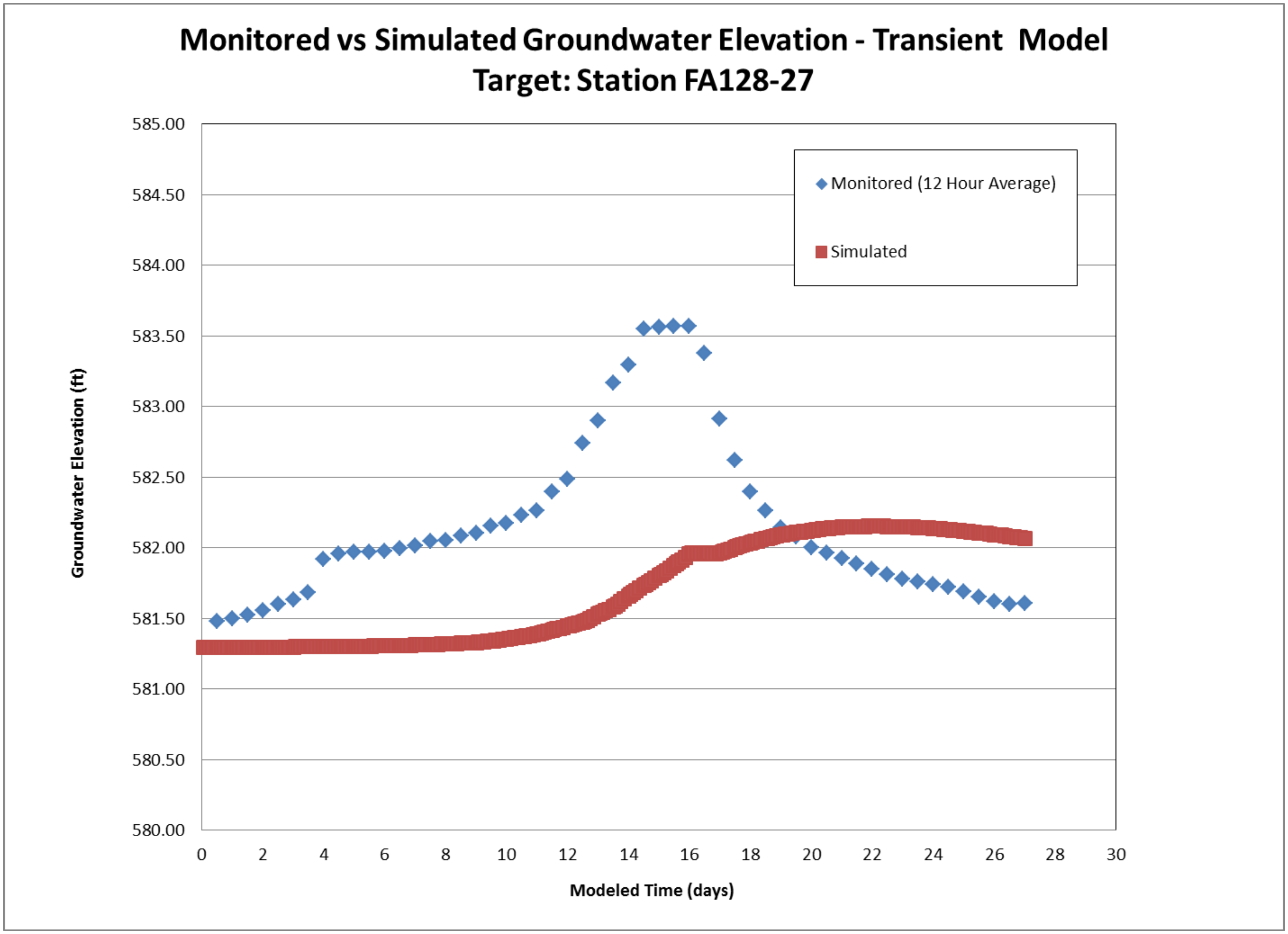


Figure B1-15. Monitored vs. Simulated Groundwater Elevation – Transient Model at Target Station FA128-27.