RECLAMATION
Managing Water in the West

Coupling Reclamation's Surface Water Model to a Groundwater Model

Research and Development Office
Science and Technology Program
(Final Report) ST-2019-3236-01

U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

Sept. 2019

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public .

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The health of many river ecosystems, particularly gravel bed river systems, depends on the interaction of the river with the underlying fluvial and floodplain aquifer. A better understanding of the interaction between surface water and groundwater in rivers below Reclamation dams is crucial to improve the health of these ecosystems. Of interest is the ability to model the exchange of water between the surface and sub-surface. SHR-2D (Sedimentation and River Hydraulics 2-Dimensional) is Reclamation’s numerical surface water model used to simulate the flow of water in rivers. In 2015, the Bureau of Reclamations Science and Technology Program (S&T) funded a scoping proposal to investigate the feasibility of coupling SRH-2D to a groundwater flow model Kimbrel and Bradley [2015]. Such a coupled model would provide Reclamation with the ability to model the exchange of water between a river and the sub-surface aquifer(s). I collected data on surface water – groundwater interaction at a site on the Trinity River during the spring and summer high flow and used those data to develop a</td></tr>
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coupled surface water – groundwater model by configuring SRH-2D as a MODFLOW package. Full implementation within the project budget was not possible due to unforeseen issues with the mechanism for adding water to SRH-2D from the aquifer.

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Coupling Reclamation's Surface Water Model to a Groundwater Model

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Executive Summary

The health of many river ecosystems, particularly gravel bed river systems, depends on the interaction of the river with the underlying fluvial and floodplain aquifer [*Hauer et al.*, 2016]. River water flowing into the sub-surface carries with it dissolved oxygen and organic matter needed by microbes and aquatic insects living in the subsurface [*Pepin and Hauer*, 2002]. Water returning to the river from the sub-surface carries bio-available nutrients that nourish the base of the aquatic food web [*Valett et al.*, 2014; *Wyatt et al.*, 2008]. Water returning to the river from the subsurface moderates river temperatures, particularly in summer [*Wyatt et al.*, 2008], and may provide the majority of summer baseflow [*Burns et al.*, 1998]. For these and many other reasons, a better understanding of the interaction between surface water and groundwater in river's below Reclamation dams is crucial to improve the health of these ecosystems. Of particular interest is the ability to model the exchange of water between the surface and sub-surface.

SHR-2D (Sedimentation and River Hydraulics 2-Dimensional) is Reclamation's numerical surface water model used to simulate the flow of water in rivers. SRH-2D simulates river flow by solving the depth-averaged St. Venant equations (also known as the dynamic wave equations) [*Lai*, 2008]. In 2015, the Bureau of Reclamations Science and Technology Program (S&T) funded a scoping proposal to investigate the feasibility of coupling SRH-2D to a groundwater flow model *Kimbrel and Bradley* [2015]. Such a coupled model would provide Reclamation with the ability to model the exchange of water between a river and the sub-surface aquifer(s).

I collected data on surface water – groundwater interaction at a site on the Trinity River during the spring and summer high flow and used those data to develop a coupled surface water – groundwater model. I integrated SRH-2D with MODFLOW, a popular groundwater flow model developed by the U.S. Geological Survey [*Harbaugh*, 2005] by converting SRH-2D to MODFLOW package. The approach I used appears to be sound, but there are problems with the mechanism for adding water to SRH-2D from the aquifer. Characterizing the problems and identifying a workaround ultimately consumed most of the remaining project budget and I was not able to complete a full implementation of the model integration. However, the monitoring data collected on the Trinity River hints at more complex interaction between the river and the fluvial aquifer than I initially expected and could be used in the future to test a full implementation of the coupled model.

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Introduction

The health of many river ecosystems, particularly gravel bed river systems, depends on the interaction of the river with the underlying fluvial and floodplain aquifer [*Hauer et al.*, 2016]. River water flowing into the sub-surface carries with it dissolved oxygen and organic matter needed by microbes and aquatic insects living in the subsurface [*Pepin and Hauer*, 2002]. Water returning to the river from the sub-surface carries bio-available nutrients that nourish the base of the aquatic food web [*Valett et al.*, 2014; *Wyatt et al.*, 2008]. Water returning to the river from the subsurface moderates river temperatures, particularly in summer [*Wyatt et al.*, 2008], and may provide the majority of summer baseflow [*Burns et al.*, 1998]. For these and many other reasons, a better understanding of the interaction between surface water and groundwater in river's below Reclamation dams is crucial to improve the health of these ecosystems. Of particular interest is the ability to model the exchange of water between the surface and sub-surface.

SHR-2D (Sedimentation and River Hydraulics – Two-Dimension) is Reclamation's numerical surface water model used to simulate the flow of water in rivers. SRH-2D simulates river flow by solving the depth-averaged St. Venant equations (also known as the dynamic wave equations) [*Lai*, 2008]. In 2015, the Bureau of Reclamations Science and Technology Program (S&T) funded a scoping proposal to investigate the feasibility of coupling SRH-2D to a groundwater flow model *Kimbrel and Bradley* [2015]. Such a coupled model would provide Reclamation with the ability to model the exchange of water between a river and the sub-surface aquifer(s). After consultation with scientists at the U.S. Geological Survey (USGS), Sean Kimbrel and I decided to integrate SRH-2D with GSFLOW [*Markstrom et al.*, 2008], a software package developed by the USGS that links models of surface and near-surface processes to MODFLOW [*Harbaugh*, 2005]. MOFLOW is a commonly used 3-dimesional finite difference groundwater flow model. On further reflection, I decided that GSFLOW was unnecessarily complicated and it would be better to integrate only with MODFLOW. SRH-2D would be integrated as a MODFLOW-2005 package following the example of the Stream Flow Routing package (SFR2) [*Niswonger and Prudic*, 2005]. SFR2 is a 1-dimensional flow routing package that includes water exchange with the sub-surface but lacks the capabilities inherent in a 2-dimesional model like SRH-2D, such as automatic determination of wetted width and laterally varying water depth.

A site on the Trinity River was selected to develop the coupled model. The surface water model needs high-resolution bathymetry and topography, as well as information about river discharge, water surface elevation, and channel roughness. The groundwater model needs topography, information about the stratigraphy of the sub-surface, and wells to monitor water levels to provide model validation data. I chose a site on the Trinity River in Northern California because Reclamation has a recent hydraulic model of the river and there are numerous sites with monitoring wells that were drilled as a part of restoration projects by the Trinity River Restoration Program (TRRP).

Methods

Field Data Collection

With assistance from TRRP staff, I installed surface and groundwater stage monitoring pressure loggers deployed at two reaches along the Trinity River in Northern California on April 22 and 23, 2016 (Figure 1). HOBO pressure loggers (HOBO) from Onset Computer Corporation record pressure and temperature to estimate the depth of the water above the sensor [*ONSET*, 2017]. Fifteen loggers were installed at the Sheridan Creek site in 13 wells and 2 river stage gages. Nine loggers were deployed at the Lowden Ranch site in 7 wells and 2 river stage gages. The locations of the sites are shown in Figure 1. Ultimately, the Sheridan Creek site was selected for the integrated model, so only data from that site are presented in this report. The locations of the Sheridan wells and river stage loggers are shown in Figure 2.

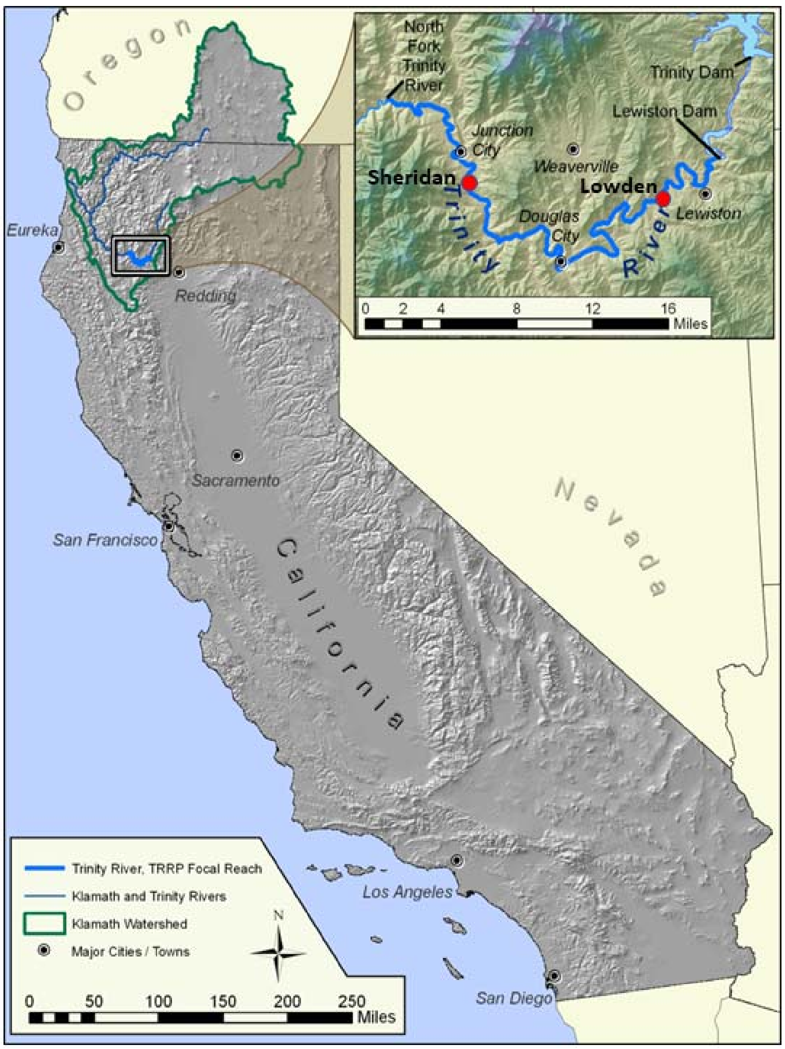

Figure 1. The Trinity River in Northern California. The monitoring sites are indicated with red dots in the inset map of the river.

HOBO pressure loggers were deployed in wells by hanging them from the well head (a PVC pipe) with a metal chain. We measured distance between the well head and the pressure sensor at the tip of the HOBO a tape measure. The well head elevations were known from previous surveys. These measurements were combined to yield a sensor tip elevation. Before installing each HOBO, we measured the water level in the well with well tape. A well tape is a tape measure with a water sensing tip that sounds an alarm when it encounters the water surface. A HOBO pressure logger and one of the Lowden wells is shown in Figure 3.

We installed river stage gages the upstream and downstream end of each site. The stage gages consist of a HOBO pressure logger suspended by chain inside of a protective PVC pipe that is open at the bottom and vented at the top. The pipe is secured with hose clamps to a t-post driven into the stream bed. The HOBO tip rests on a bolt through the pipe near the bottom. We surveyed the elevation of the stream bed below the logger with a high precision real-time kinematic global positioning system (RTK GPS) and measured the distance from the stream bed to the bolt to yield an elevation of the pressure logger sensor. The downstream river stage gage at Lowden and schematic of the gage is shown in Figure 4.

Two HOBOs were deployed at two locations in nearby Weaverville, CA to measure fluctuations in atmospheric pressure. A record of atmospheric pressure is necessary to convert the pressure and temperature timeseries collected by the well and river stage loggers to water depths.

The water levels in Lowden wells and in the right bank wells at Sheridan were measured manually with a well tape from May 9-13, 2016 during the spring high flow. Left bank wells at Sheridan are not accessible by car. The Trinity River peaked at about 11,000 cfs on May 10 and May 14, 2016. The hydrograph from the Junction City gage (USGS 11526250), located about 2 miles downstream of the Sheridan site, is shown in Figure 5. These measurements were later used to verify the water surface elevations derived from the pressure loggers.

With the assistance of Yurok Tribe staff, I recovered the river and well stage loggers on July 21-22, 2016. The atmospheric pressure loggers were retrieved at about the same time and all loggers were shipped back to Denver. I downloaded and processed the data from the loggers using HOBOware Pro 3.7.7. The temperature and pressure records were converted to water depths using the standard procedure detailed in the HOBOware User Manual [*ONSET*, 2019].

The water depths computed by HOBOware had to be adjusted to compensate for the 100 m increase in elevation between at the HOBOs measuring atmospheric pressure. I followed a procedure developed by Eric Peterson of the TRRP (personal communication). The mean elevation of the Sheridan site is 450.5 m, 146.5 m lower than the atmospheric logger in Weaverville that was installed at the lowest elevation. At low elevations, atmospheric pressure decreases by 1.2 kPa per 100 m of altitude increase. The elevation difference between Weaverville and the Sheridan site corresponds to a 1.2 kPa/100m * 146.5 m = 1.76 kPa *increase* in atmospheric pressure at Sheridan relative to Weaverville. Standard barometric pressure of 101.3 kPa corresponds to a water column 10.3 meters high, therefore 1 kPa corresponds to ~10 cm of elevation change. A change of 1.76 kPa corresponds to an elevation change of 17.6 cm. Because the atmospheric pressure at Sheridan is higher than in Weaverville, the water depth computed from the Sheridan loggers is deeper than the water really is. To correct the Sheridan water depths, I subtracted 18 cm or 0.6 ft.

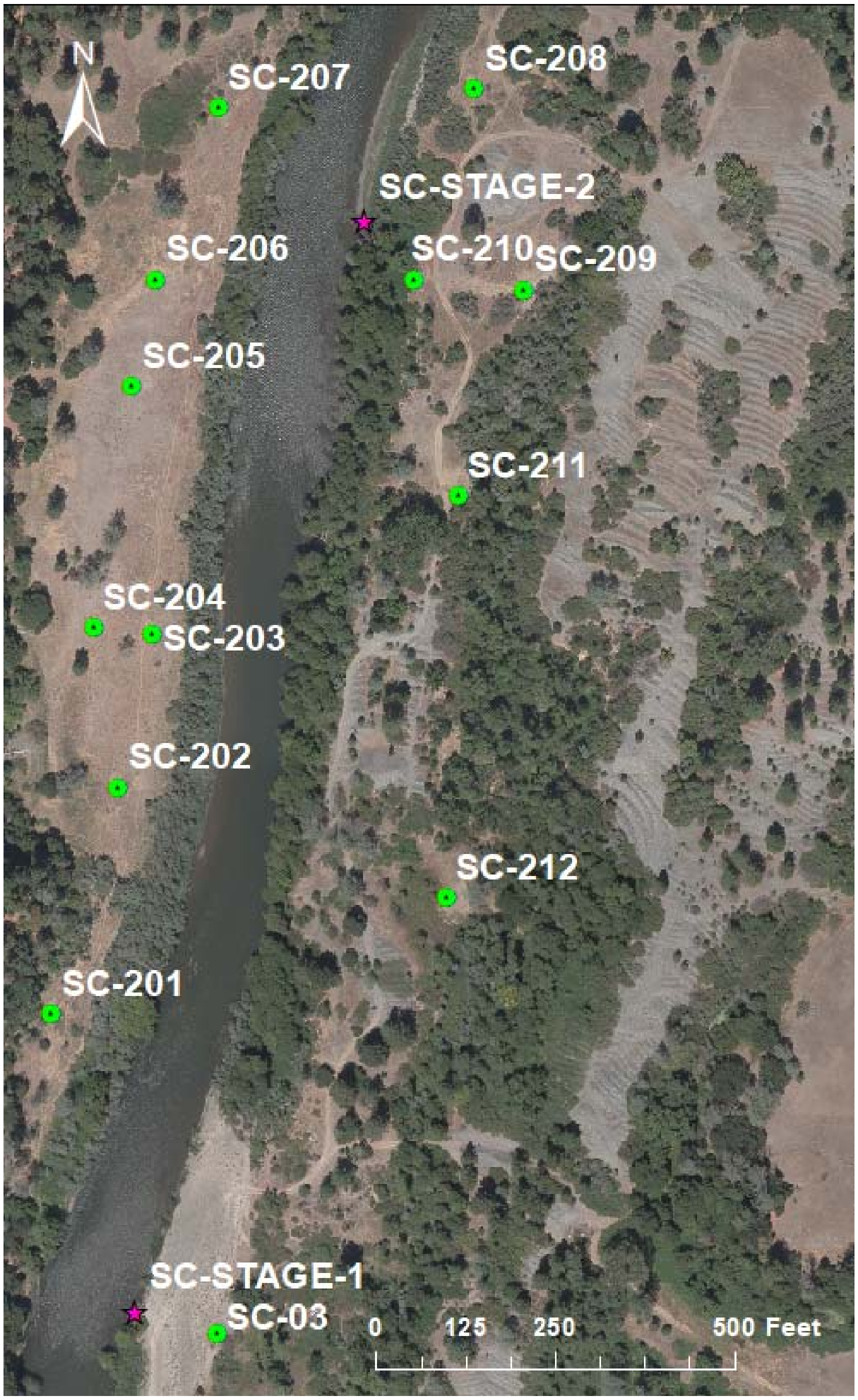

Figure 2. Well and river stage monitoring sites at the Sheridan Creek site. Flow is from bottom to top. The green circles represent groundwater wells and the pink stars represent river stage gages.

Figure 3. An uncapped well head at Lowden Ranch (center) and a picture of the Onset HOBO pressure loggers used in this study.

Figure 4. The downstream stage gage at Lowden. The inset white box at right shows a schematic of the stage gage design.

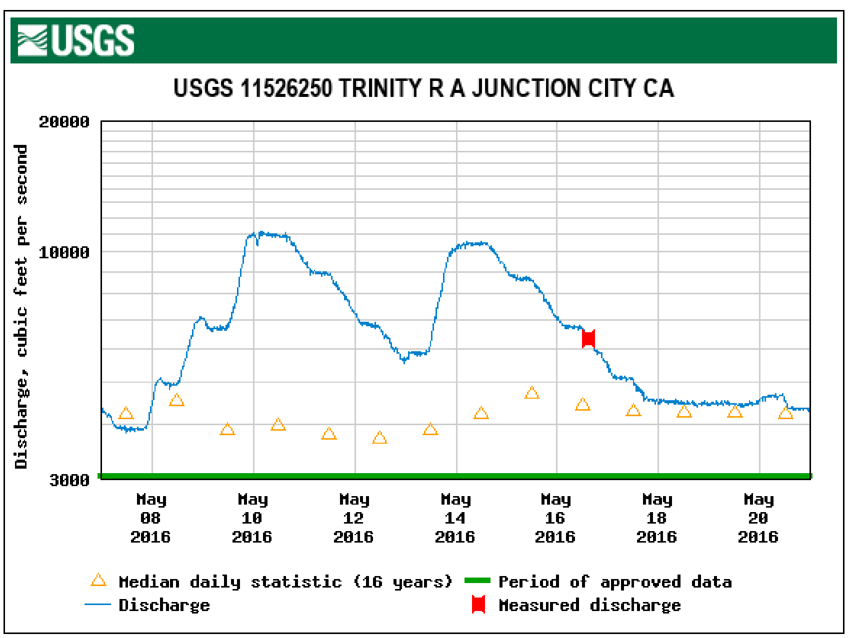

Figure 5. Discharge measured by the USGS gage at Junction City during the spring 2016 high flow.

Surface Water Model Development

The SRH-2D surface water model was based on the 2017 Trinity River 40 Mile hydraulic model that extends from Lewiston Dam to the confluence with the North Fork Trinity River [*Bradley*; 2018]. That model used topography and bathymetry from a 2016 LiDAR and bathymetric survey and channel roughness based a map of the 84^{th} percentile (D_{84}) of bed grain size developed by the Trinity River Habitat Assessment Team in 2014 [*Alvarez et al.*]. I clipped the Sheridan site from this 40 Mile mesh and coarsened the mesh resolution to decrease model run times during development. The mesh extent is shown in Figure 6. The upstream boundary of the mesh is about 3000 ft upstream of the most upstream well (SC-03) and downstream about 3000 ft from the downstream stage gage, SC-Stage-2. The median floodplain element area is about 375 ft^2. The median channel element is about 230 ft^2, or about 20' long and 15' wide. The distributions of mesh element size are shown in Figure 7. The model boundary conditions were derived from the Junction City gage (Figure 5) and a rating curve at the outlet developed from the 2017 40 Mile model (Figure 8).

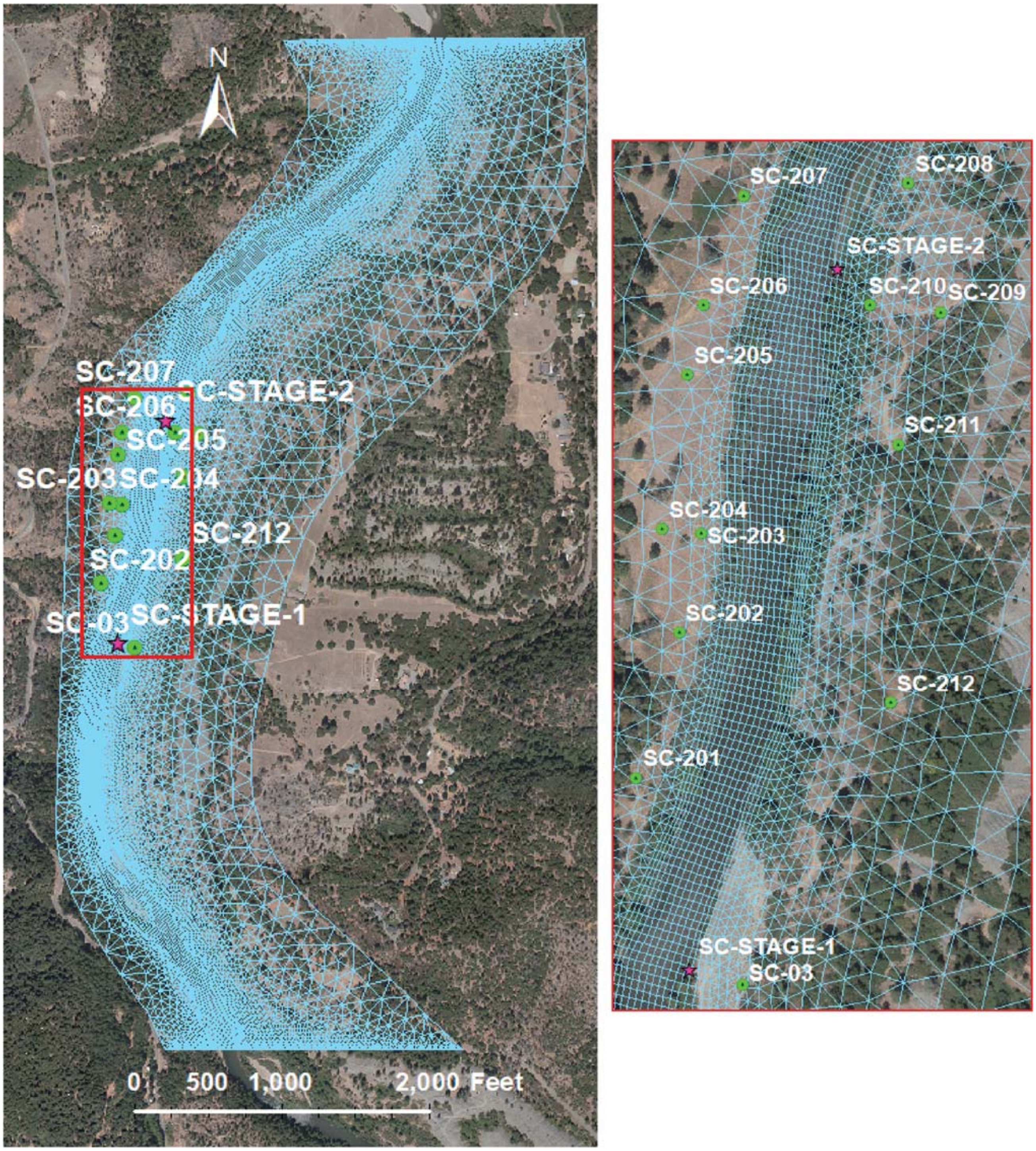

Figure 6. The full Sheridan surface water model mesh (left) and a detailed view of the area outlined in red (right). The green circles represent groundwater wells and the pink stars represent river stage gages.

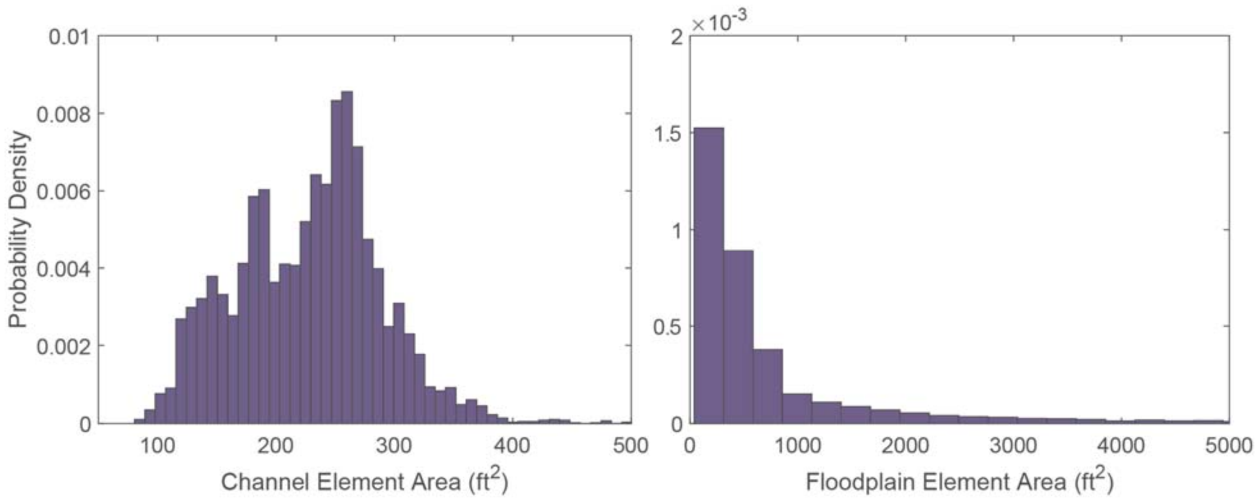

Figure 7. The probability distributions of channel element area (left) and floodplain element area (right) for the Sheridan SRH-2D model.

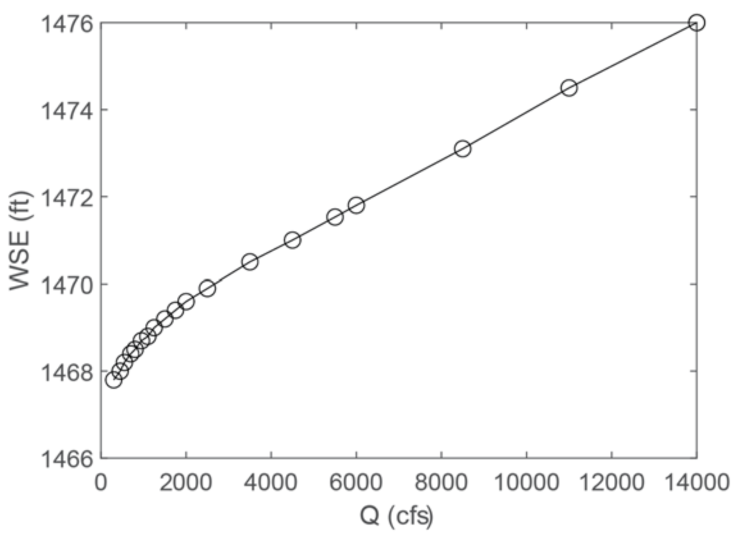

Figure 8. The rating curve derived from the Trinity 40 Mile model used to generate the outlet boundary condition.

Groundwater Model Development

MODFLOW is 3-dimensional, layered flow model. In an attempt to develop a realistic layering scheme, I compiled stratigraphic information from the test pit logging reported by [*Sherer*, 2011] (see Table A1), but the resulting layering model generated by the Groundwater Modeling System (GMS 10.2) software [*Aquaveo*, 2019] was unusable. Even using the simplified layer types listed in

Table A1 resulted in a layering scheme that was indefensibly complex and not spatially coherent. To simply the analysis, I opted for a two-layer model of alluvium on bedrock. Each layer was assigned uniform hydraulic conductivity, with higher conductivity in the alluvium and very low conductivity in the bed rock, appropriate for studying short term interactions between the river and fluvial aquifer. If the goal of a study was to understand longer term water exchange between a river and a surrounding bedrock aquifer, the bedrock hydraulic conductivity would need more careful consideration.

Using the GMS software, I created a MODFLOW grid with 100 rows (the north-south direction), 66 columns (the east west direction), and 2 layers (vertical). This results in MODFLOW cells that are 77 ft long (north-south) and 42.6 ft wide (east-west). The surface of the grid is shown in plan view in Figure 9. The top layer represents alluvium 1450 ft deep. Layer 2 represents bedrock that is not intended to participate in the flow model. The top of the bedrock layer is at 1450 ft and the bottom is at an elevation of 1400 ft. A cross section through the grid is shown in Figure 10.

The minimum channel elevation through the site is 1456.7 ft, which means that there is at least 5.7 ft of alluvium below the channel bottom. Bedrock is exposed on the left bank at the downstream end of the site at Sheridan Hole, so this is a reasonable alluvial thickness under the channel and floodplain. However, it creates artificially thick alluvium under the hillslopes where the bedrock is near the surface. A more realistic model might mimic the topographic surface on the top of the bed rock layer.

Initial hydraulic conductivity values were assigned to optimize SRH-2D and MODFLOW stability. I assigned the alluvium layer an initial horizontal hydraulic conductivity of 0.06 ft/s. Vertical hydraulic conductivity was set 0.02 ft/s. These values are low for a fluvial aquifer, corresponding to very fine sand [*Bear*, 2013], but were chosen with the idea that lower rates of water exchange would be less likely to result in numerical instability in SRH-2D and MODFLOW. I assigned the bedrock layer a horizontal hydraulic conductivity of 10^{-7} ft/s. Vertical hydraulic conductivity was set to 3.3 x 10^{-8}. These are low values chosen to minimize the role of the bed rock layer in the flow process. Specific storage for both layers was set to 10^{-4} ft^{-1} and specific yield was set to 0.25. I expected to adjust these initial values as a part of the model calibration process.

I defined the downstream boundary model as a general head boundary (GHB package) with a hydraulic conductance (the flow rate per unit head of driving force) set to an arbitrary initial value of 0.00006 ft^2/s/ft. Water is driven across the downstream boundary according to the upstream head. The eastern and western edges were no-flow boundaries. I defined the model inlet at the upstream end of the domain as a time-variant specified head boundary (CHD package). The method I used to assign the head at the boundary at each stress period is discussed in the Model Integration section below.

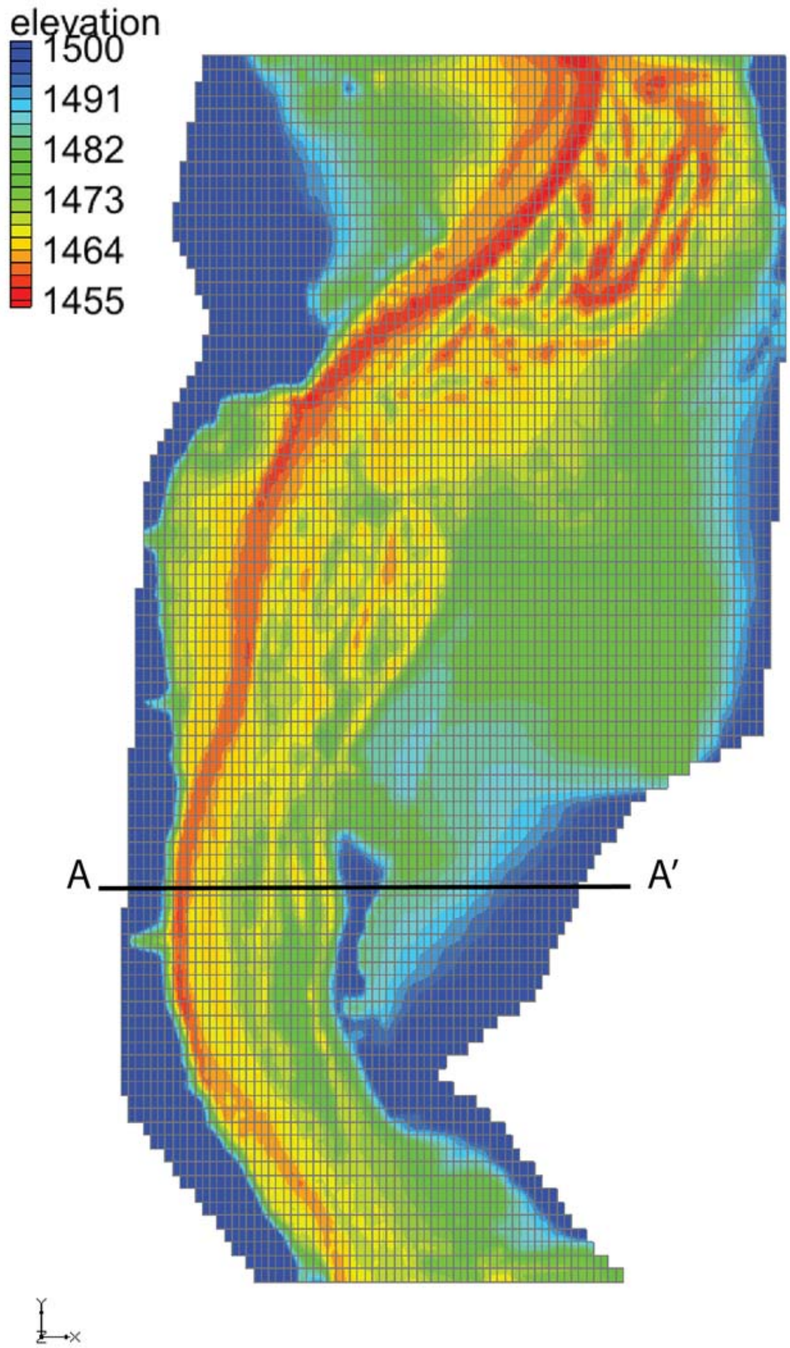

Figure 9. The MODFLOW grid in plan view. Inactive MODFLOW cells are not shown. Elevations shown are the land surface. North is up. Cross section A-A' is shown in Figure 10

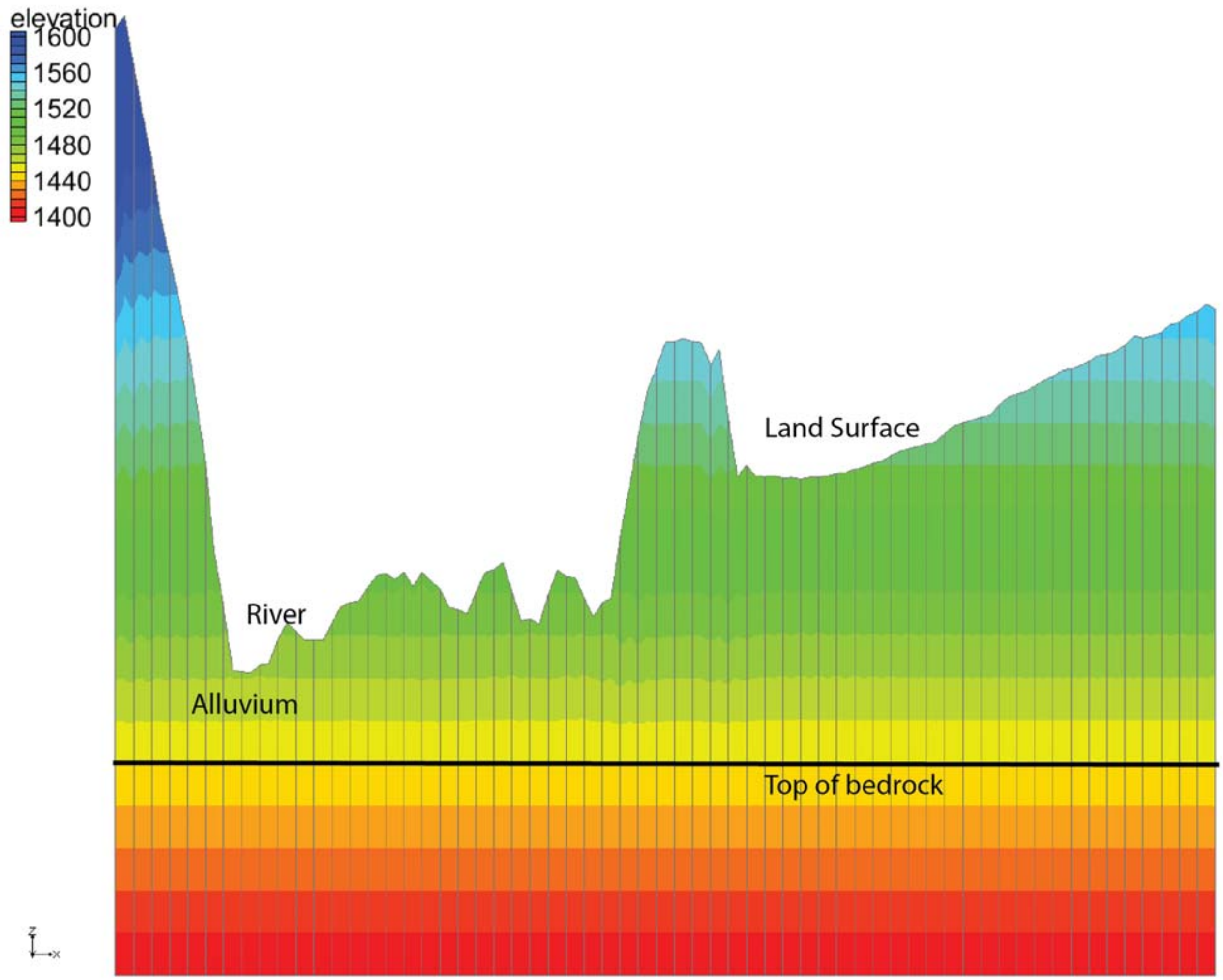

Figure 10. A cross section through The MODFLOW grid along A-A' shown in Figure 9.

Model Integration

I integrated the SRH-2D surface water model with MODFLOW by converting SRH-2D to a MODFLOW package [*Harbaugh*, 2005]. I used the MODFLOW-NWT (Newtonian formulation) version of MODFLOW-2005 [*Niswonger et al.*, 2011]. The technical details of integrating the SRH-2D Fortran source code into MODFLOW Fortran source code are not described in detail here. Essentially, the two source trees are compiled together and the MODFLOW code is modified to include calls to the SRH-2D code at various stages in the MODFLOW execution. SRH integration closely followed the example of the SFR2 streamflow routing package integration in the MODFLOW source code.

MODFLOW model runs are governed by stress periods, which are intervals of steady MODFLOW boundary conditions. Each MODFLOW package executes once for each stress period and computes its contribution to the groundwater flow. Flow routing packages such as the

SFR2 or SRH-2D have their own internal time stepping mechanism that executes during each stress period. Figure 11 shows the flow of the execution process.

Water is exchanged between the aquifer and SRH-2D via the momentum-less mass source/sink (MMSS) mechanism in SRH-2D [*Lai*, 2008] and by adding water to or subtracting water from the grid cell arrays that MODFLOW uses to keep track of the flow of water.

The rate of water exchange between an SRH-2D river cell and the underlying MODFLOW groundwater cell is governed by two equations adapted from the SFR2 package [*Niswonger and Prudic*, 2005]. If the aquifer head (the elevation of the top of the water table) is above elevation the stream bed, the flux Q_m into (or out of) the m^{th} SRH-2D river cell is given by Equation 1.

Equation 1

$$Q_m = -\frac{K_m A_m \left(WSE_m - H_{ij}\right)}{\Delta Z_m}$$

In Equation 1, K_m is the hydraulic conductivity (L/T) of the stream bed below cell m, A_m is the area (L^2) of cell m, WSE_m is the water surface elevation in cell m, H_{ij} is the aquifer head (L) in the MODFLOW grid cell i, j that underlies the m^{th} SRH cell, and ΔZ_m is the bed thickness (L) in cell m. If Q_m is positive, flow is to the river from the aquifer. If Q_m is negative, flow is out of the river into the aquifer.

If the aquifer head is below the elevation of the stream bed, stream bed elevation in cell m, $BedZ_m$, replaces the aquifer head term in Equation 1 and flow is governed by Equation 2.

Equation 2

$$Q_m = -\frac{K_m A_m (WSE_m - BedZ_m)}{\Delta Z_m}$$

I defined a MMSS for each SRH-2D cell and mapped each river cell to the underlying aquifer grid cell. Because river cells will generally be much smaller than aquifer cells, many river cells are mapped to each aquifer cell. The total flow to the aquifer cell i, j from the N cells that are mapped to it is given by Equation 3. The Sheridan SRH-2D river mesh superimposed on the MODFLOW aquifer grid is shown in Figure 12. The mapping is defined in an input file and is described below.

Equation 3

$$Q_{ij} = \sum_{m=1}^{N} -Q_m$$

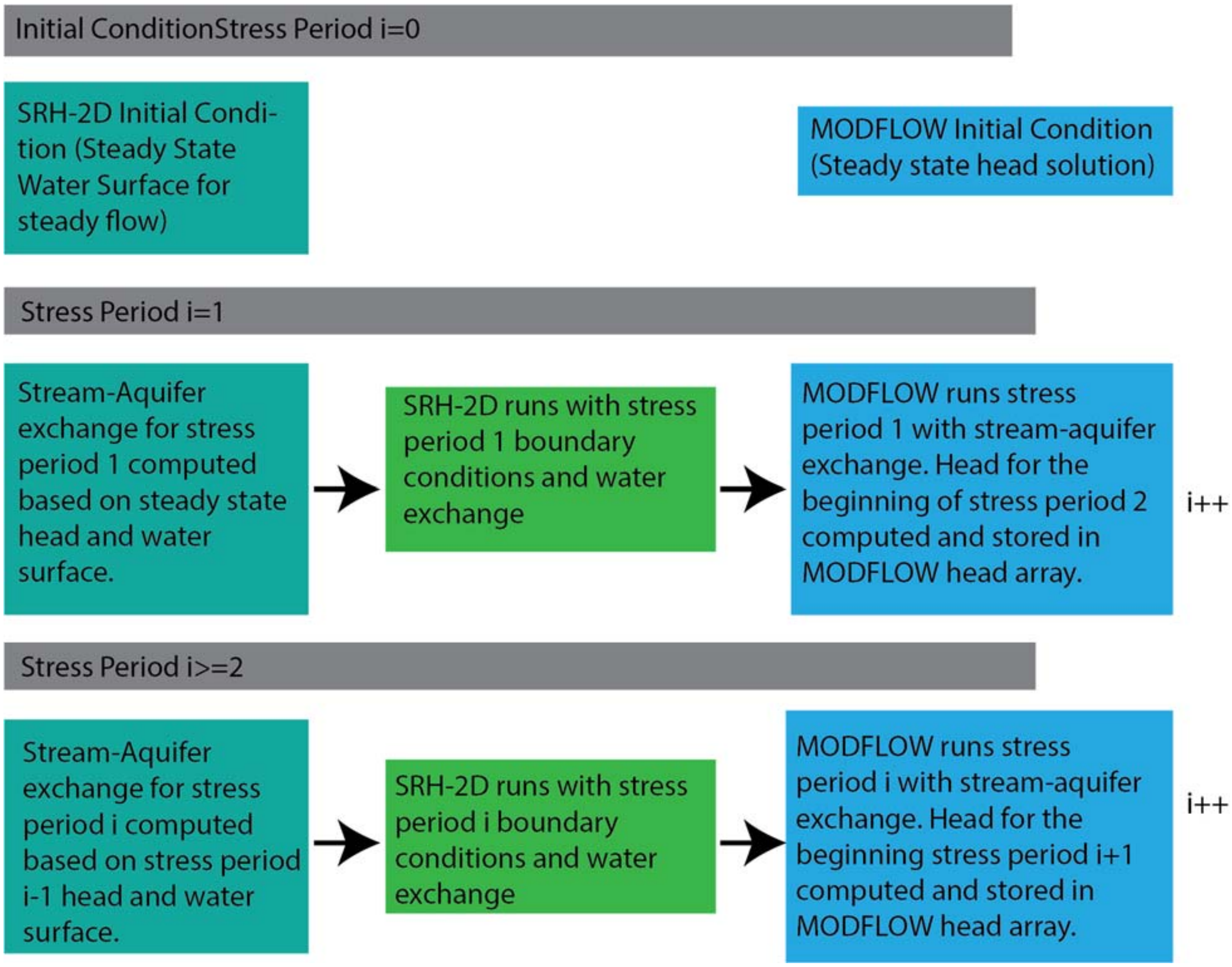

Figure 11. Flow chart defining the MODFLOW to SRH-2D interaction during MODFLOW stress periods.

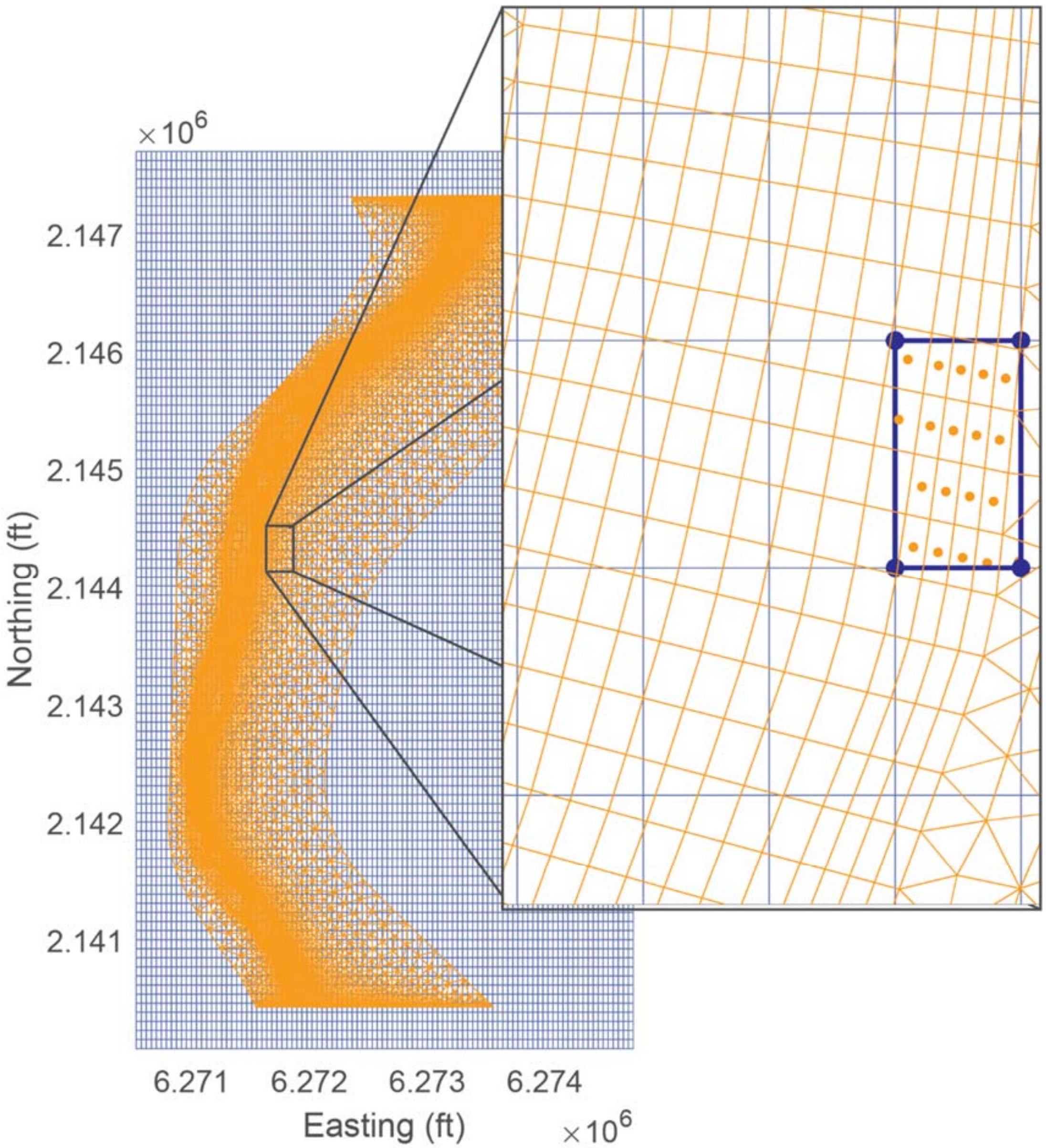

Figure 12. The Sheridan SRH-2D model mesh (orange) mapped onto the underlying MODFLOW grid (blue)

Model Setup

The first step in creating a transient integrated surface water – groundwater model is to set up SRH-2D and MODFLOW models with appropriate boundary conditions to serve as the initial condition of the subsequent transient coupled model.

A SRH-2D model simulation is required to establish initial conditions (river water surface and groundwater head) for the coupled model. The initial conditions SRH-2D run should be an unsteady, constant inlet discharge model. The run time of the initial conditions model defines the duration of model runs inside of the MODFLOW time loop so the model duration must be chosen carefully. It must be long enough for the model to come into equilibrium with the new boundary conditions, so advanced knowledge of the transient simulation boundary conditions is necessary. The model discharge was set to the approximate flow measured at the Junction City gage on April 21, 2016, 675 cfs and the model duration was 2 hours. This was considered an adequate run time for the model to adjust to changing boundary conditions because water moving at a conservative average velocity of 2 ft/s will travel 14,400 ft in 2 hours, almost twice the length of the Sheridan model domain, approximately 8,000 river feet.

The initial condition MODFLOW model should be a steady state simulation with the constant head boundary at the upstream end of the model set to the inlet water surface elevation from the SRH-2D model. The SFR2 package should be active and routing the same amount of flow as the initial condition SRH-2D model. I created an SFR2 river boundary condition that follows the channel centerline and had spatially uniform channel width, channel bed roughness, bed thickness, and bed hydraulic conductivity. The upstream and downstream water surface elevations were assigned based on the SRH-2D initial condition run. The water exchange between the SFR2 stream to the aquifer established the groundwater head in the MODFLOW model that served as the initial condition of the transient coupled simulation. The starting head from this simulation is shown in Figure 13.

In the coupled transient simulation, SRH-2D runs within the MODFLOW package. To activate the SRH-2D code, a variable "SRH" is added to the MODFLOW name file in the "Flow Process" section. The value of this variable is the path to SRH package configuration file. The SRH package configuration file defines the paths to six files that define values for the variables in the equations governing water exchange between the river and the aquifer (Equation 1 and Equation 2). Those variables are:

1. MESH – The path to the .2d SRH-2D model mesh
2. HCOND – A file that defines the bed hydraulic conductivity for each mesh cell in the same order cells are listed in the mesh file.
3. BEDTH – The river bed sediment thickness for each mesh cell in the same order cells are listed in the mesh file.
4. MESH2GRID – A list of the row, column, and layer indices of the MODFLOW grid cell that each SRH-2D mesh cell contributes water to in the same order cells are listed in the mesh file. The indices must be space delimited and in i,j,k order.
5. DAT – The SRH-2D .DAT file from the initial condition run.

6. BOUNDARY – The path to the inlet and outlet SRH boundary conditions for each MODFLOW stress period. The first line of this file is the number of stress periods. The following lines Stress Period Number, Seconds, Hours, Inle tQ, and outlet water surface elevation for each stress period on a tab delimited line.

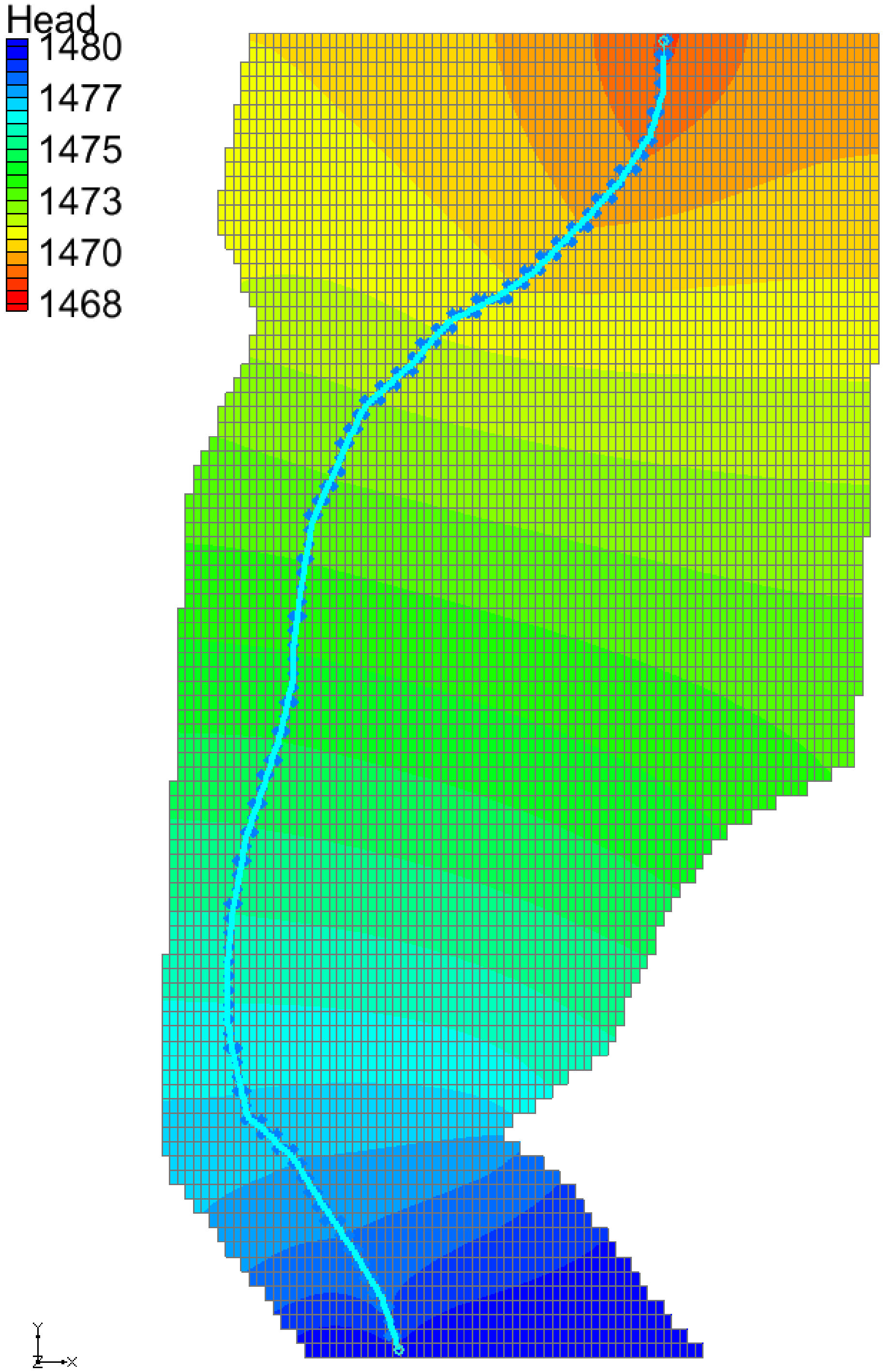

Figure 13. The MODFLOW starting head determined by the initial condition steady state run. The teal colored line is the SFR2 1-dimensional river.

The SRH-2D inlet boundary conditions for the transient coupled simulation were derived from the 2016 high flow hydrograph at the Junction City gage and down sampled from 15-minute intervals to 4-hour intervals to match the MODFLOW stress periods. The original hydrograph and the down sampled hydrograph are shown in Figure 14. The changes in flow during the spring of 2016 generally happened on a timescale longer than 4 hours, so little detail is lost in the down sampling process. The outlet boundary condition (water surface elevation) was derived from a rating curve developed from the 2017 40 Mile hydraulic model, shown in Figure 8. Similarly, the timeseries of upstream boundary head for MODFLOW (defined in the *.chd flow process file) was extracted from a rating curve developed from the 2017 40 Mile hydraulic model.

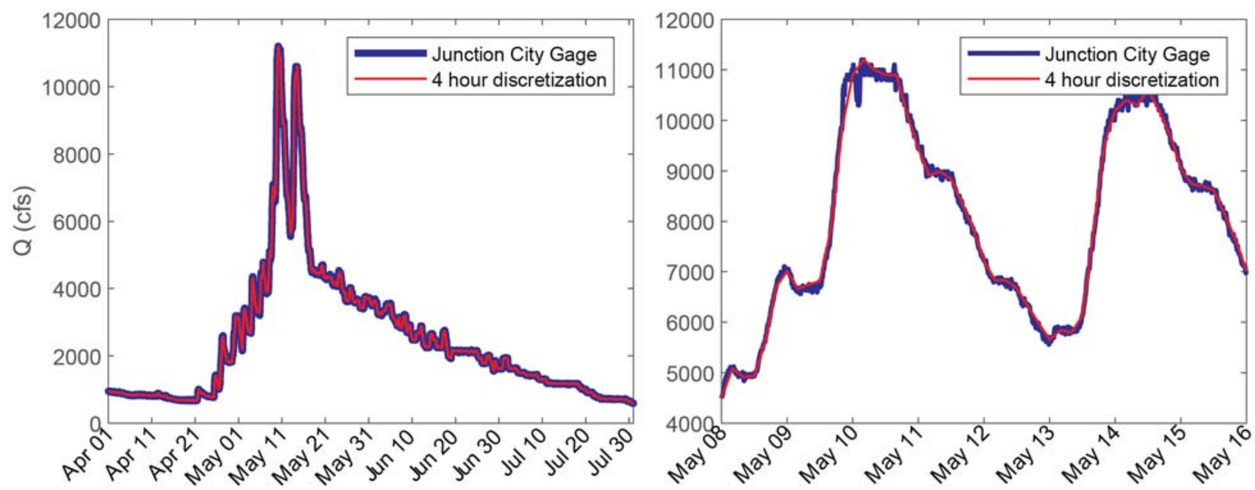

Figure 14. The 2016 high flow hydrograph at the Junction City gage and 4 hour discretized model boundary conditions (left). The right panel shows the two timeseries during the flow peaks.

Results

River and Well Monitoring

The water surface elevations derived from the Sheridan river stage loggers are shown in Figure 15. The fluctuations mimic the discharge changes at the Junction City gage and show that there is consistently about 3 ft of water surface elevation drop through the site, for a water surface slope of about 0.002. The top panel of Figure 16 shows water surface elevations were manually measured in the right bank wells and compared to the pressure logger derived elevations. The bottom panel shows that the elevations are within +/- 0.1 ft in four wells and within 0.2 ft at a fifth well (SC-212). One right bank Sheridan logger, SC-211 did not record any data during the monitoring period. Figure 17 shows the water surface elevations for all instrumented wells for the full monitoring period.

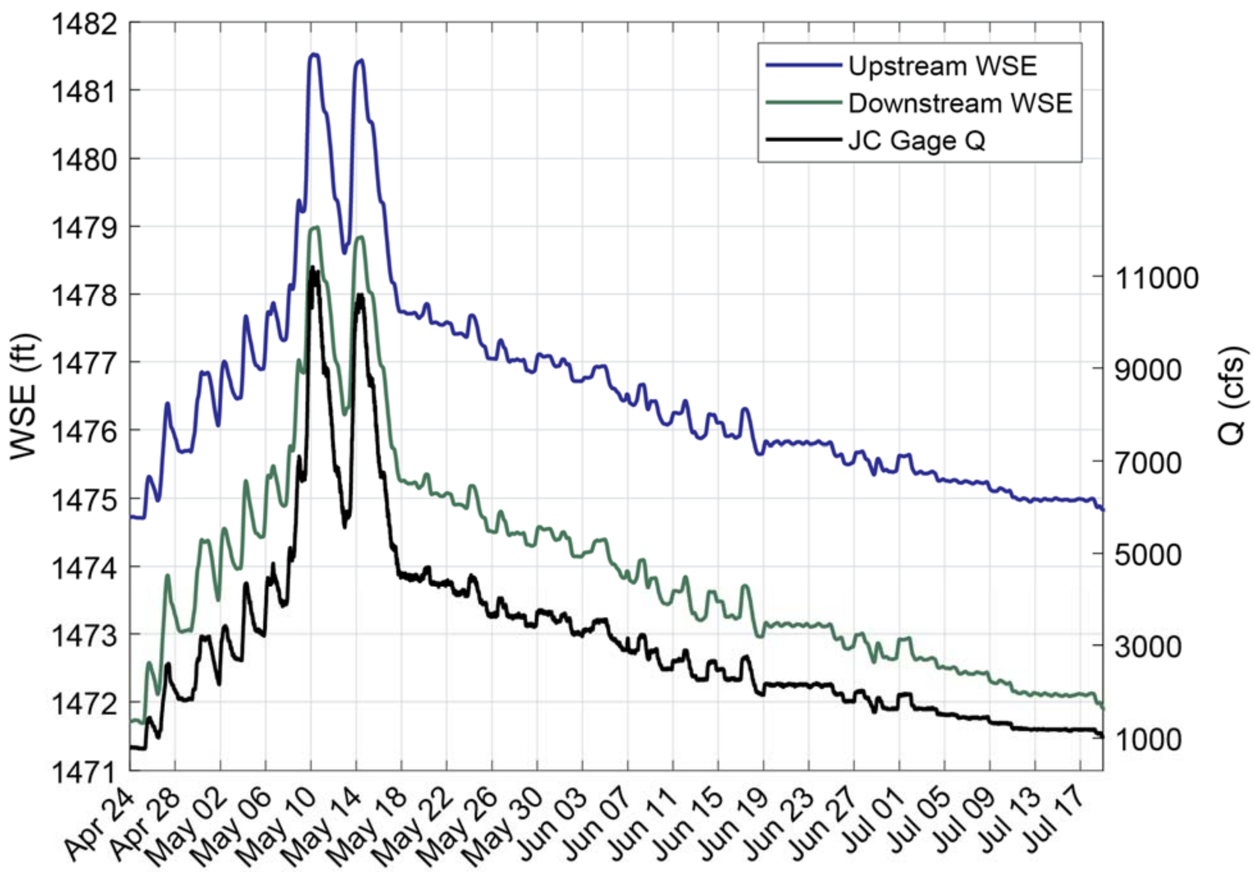

Figure 15. The water surface elevation measured at the Sheridan river stage gages (blue and green lines) plotted with the Junction City gage hydrograph (USGS 11526250)

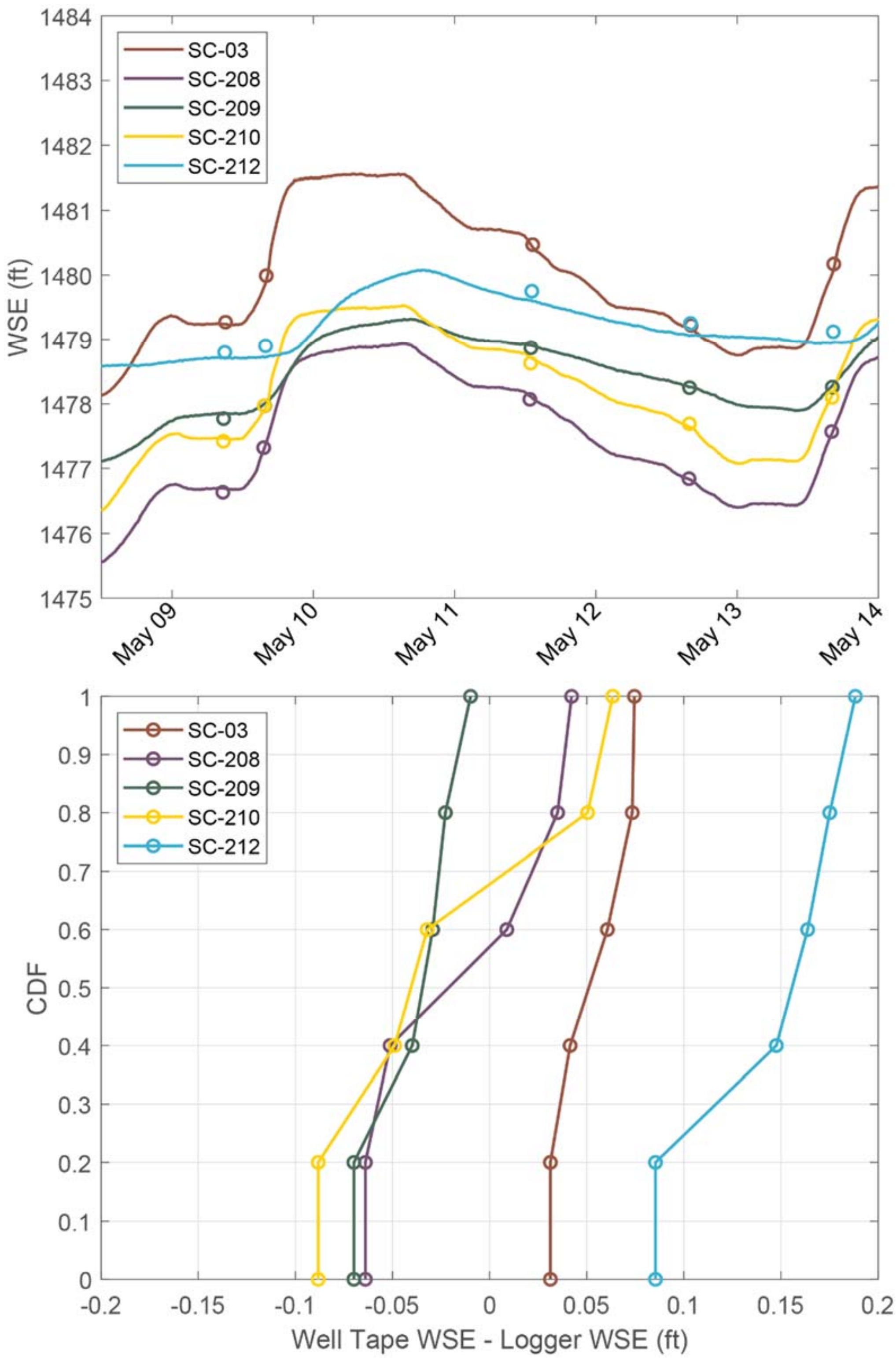

Figure 16. The Sheridan right bank WSE's measured by well loggers compare to the manual well tape measurements (top) and the distribution of WSE residuals (bottom).

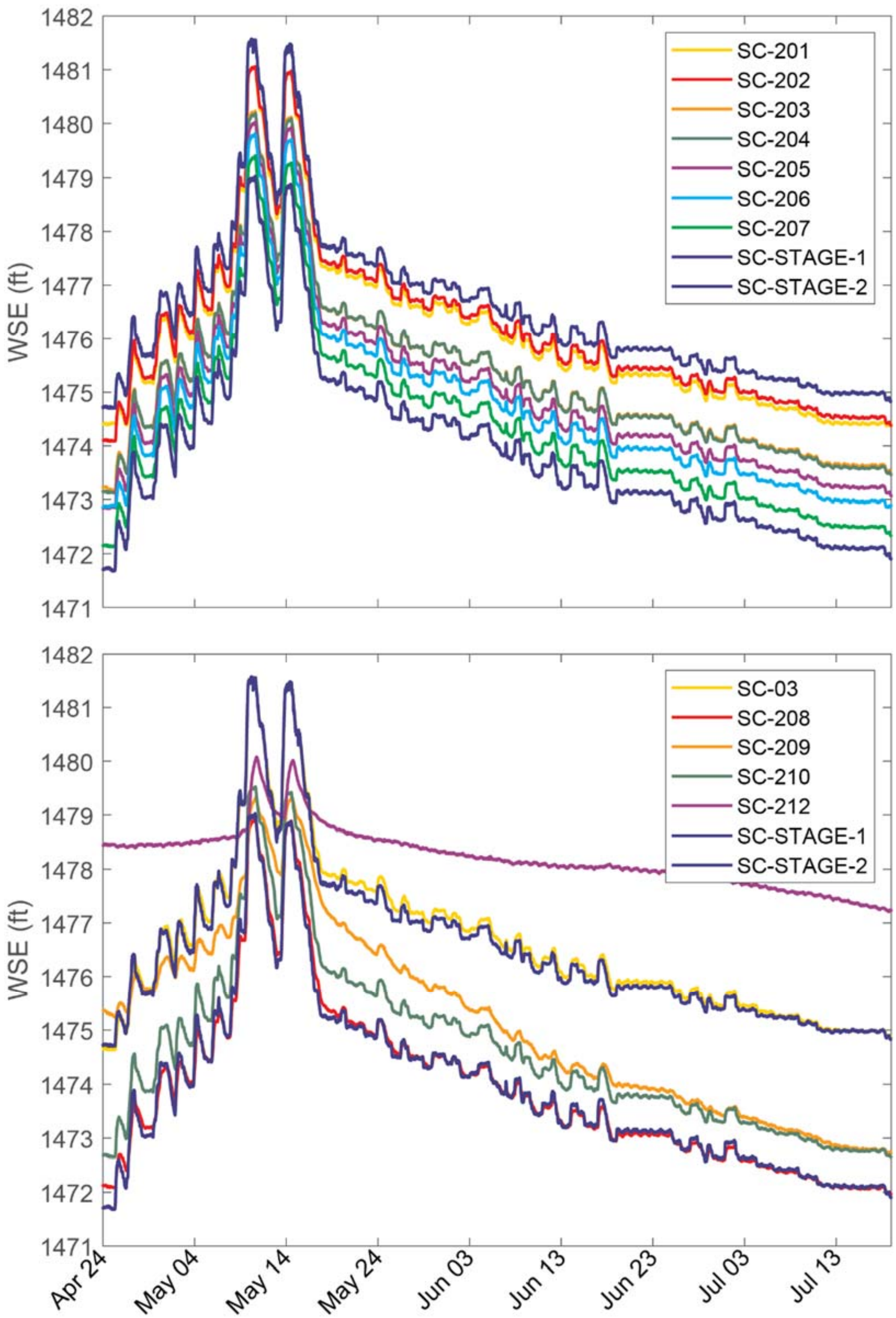

Figure 17. Well and river WSE's for the Sheridan left bank (top) and right bank (bottom). Well SC-212 in the bottom panel is thought to have a hillslope groundwater influence.

Surface Water – Groundwater Model Integration

Water exchange between SRH-2D and MODFLOW caused SRH-2D to behave abnormally. Troubleshooting this abnormal behavior consumed an enormous amount of time and most of the remaining project budget. Extensive experimentation with coupled model led me to conclude that the momentumless mass source/sink mechanism that I used to exchange water with SRH-2D has shortcomings. I explored a wide range of rates of water exchange between MODFLOW and the SRH-2D package by varying the hydraulic conductivity of the channel bed. SRH-2D would sometimes unambiguously indicate numerical instability. At other times, the water would simply disappear from the model, though not because all flow was being lost to the sub-surface. I knew in advance that the MMSS mechanism would not add water to dry model cells and I eventually concluded that the abnormal behavior occurred when aquifer water was added to river cells that with water shallower than some threshold depth. Trial and error indicated that this threshold depth was about 1 ft for the Sheridan coupled model but could be different for a different model configuration.

To attempt to solve this problem, I developed the following workaround. When the flow equations indicated that water was flowing from an aquifer grid cell to a river cell, I summed the flow from the aquifer cell to all the river cells above it (see Figure 12), identified the cells in that group where the water depth exceeded the stability threshold, and distributed the net water exchange among those cells. This workaround stabilized SHR-2D. Unfortunately, by the time the problem was identified, and the workaround was developed, the project budget was insufficient to complete the model integration. We recommend applying this methodology for future attempts to integrate these numerical models.

Discussion and Future Work

River and Well Monitoring

The well response to changing river water levels was indistinguishable from an instantaneous response. Figure 18 shows a detailed view of the left bank wells during the rising limb of the hydrograph. The black lines show that the changes in the timeseries are synchronized. This synchronization extends to the time resolution of the pressure loggers (5 minutes). The well head is tightly coupled to the river water level and there is no discernable travel time for water to flow from the river horizontally into the wells. Some mechanism other than horizontal advection of river water is responsible for the tight coupling.

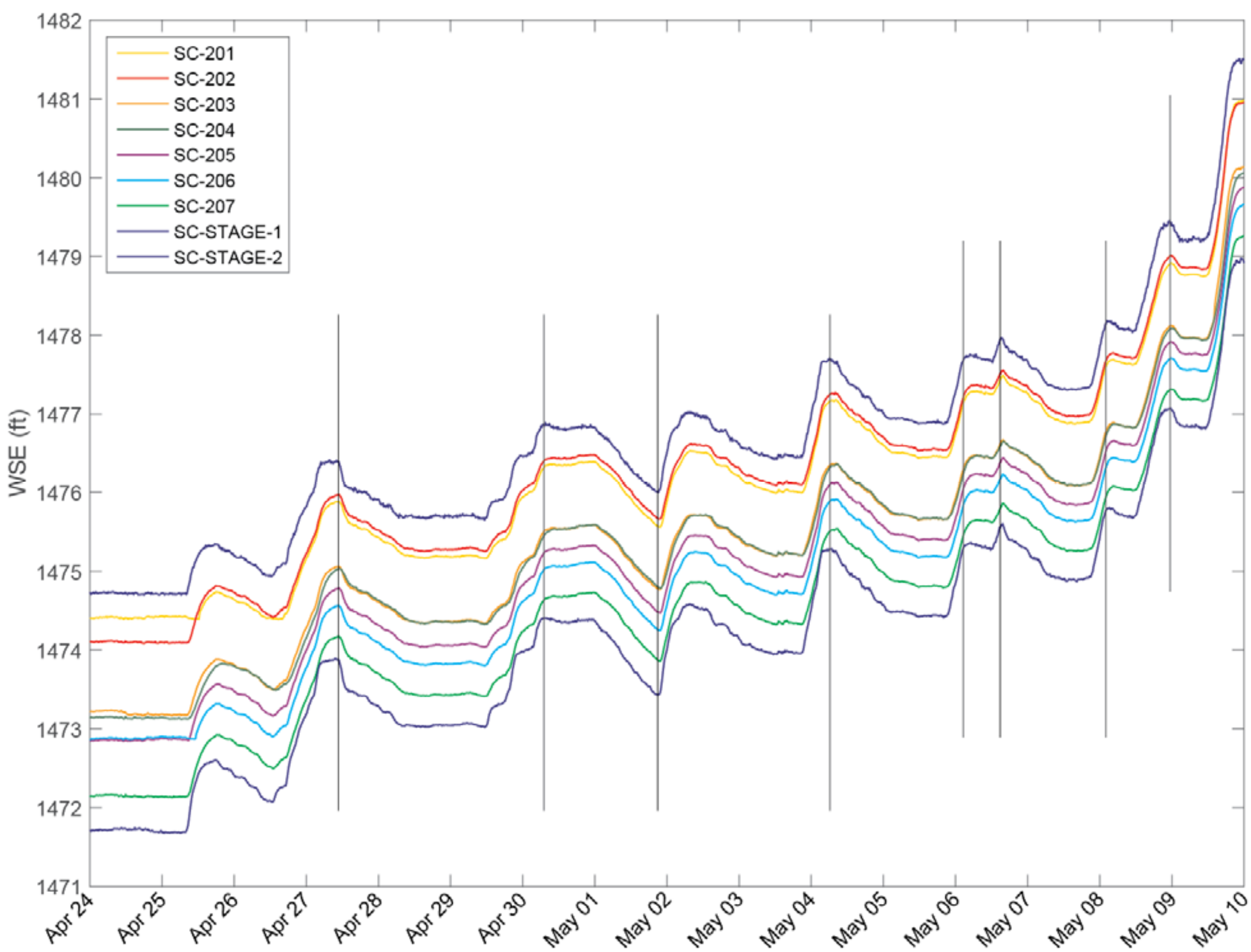

Figure 18. A detailed view of the left bank wells on the rising limb of the hydrograph.

If horizontal movement of water were responsible for the coupling, wells should respond as a function of distance from the river. The simplest case of aquifer response $h(x, t)$ to a change in river head h_0 is 1-dimesional diffusion through the fluvial aquifer, the solution is given in Equation 4 [*De Marsily*, 1986] where $erfc$ is the error function, x is distance, D is the diffusion coefficient, and t is time.

Equation 4

$$h(x, t) = h_0 erfc\left(\frac{x}{\sqrt{4Dt}}\right)$$

Equation 4 is plotted at four different times in the top panel of Figure 19. At time t_0 there is a unit step change in head at x=0. The step change in head diffuses through the aquifer at a finite velocity governed by the diffusivity and the response decays with distance from the well. The curves labeled t_1, t_2, and t_3 show how the head change evolves with time. The bottom panel of Figure 19 shows the change in water level in the Sheridan wells as a function of distance from the channel on 4 different dates during the 2016 high flow. Except for the two most distant wells (SC-209 and SC-212, which Figure 17 shows behave differently), there is almost no variability in the magnitude of well response with distance from the river, contrary to the prediction of Equation 4.

The temperature signals (Figure 20) also indicate that behavior of the wells is not as simple as river water advecting through the banks. If river water were advecting rapidly through the banks, one would expect the water temperatures in the wells to vary in phase with river temperature variations and for all wells to respond similarly.

This is not the case. On the left bank, SC-202, SC-204, and SC-206 are tightly coupled to each other, with temperatures within about a degree over most of the time series. SC-204 and SC-205 are coupled, but their temperatures are more than 1 degree higher than the other left bank wells during most of the timeseries. On the right bank, SC-03, SC-210, and SC-212 are similar, while SC-209 is several degrees warmer.

The well water temperatures are not coupled to the river water temperature. The coolest river water is during the peak flows, roughly May 9-24. The left bank well water temperatures during this time are inversely correlated with the river. Each of them experiences a rise in water temperature as river temperatures start to drop at the beginning of May. Three of the left bank wells (SC-202, SC-204, and SC-206) experience a decrease in temperature starting after the second flow peak on about May 15, while the temperature in two others (SC-205 and SC-206) continues to rise.

On the right bank, the temperature in SC-209 and SC-203 rises as the river temperature drops though the magnitude of the response is different. The temperature in SC-210 decreases slightly (about 0.5 degree C) as the river temperature starts to drop, but then stays roughly constant throughout the rest of the high flow. SC-212 appears to be completely un-coupled from the river temperature, consistent with idea that it is affected by hillslope groundwater.

The river and well stage and temperature suggest that the water rising in the wells is with increased river stage is not "new" river water advected through the banks. I suspect that it is deeper groundwater that is driven upwards by the pore pressure increase caused by the weight of the river water. This is the type of hypothesis that could be tested with a working model of surface water – groundwater interaction.

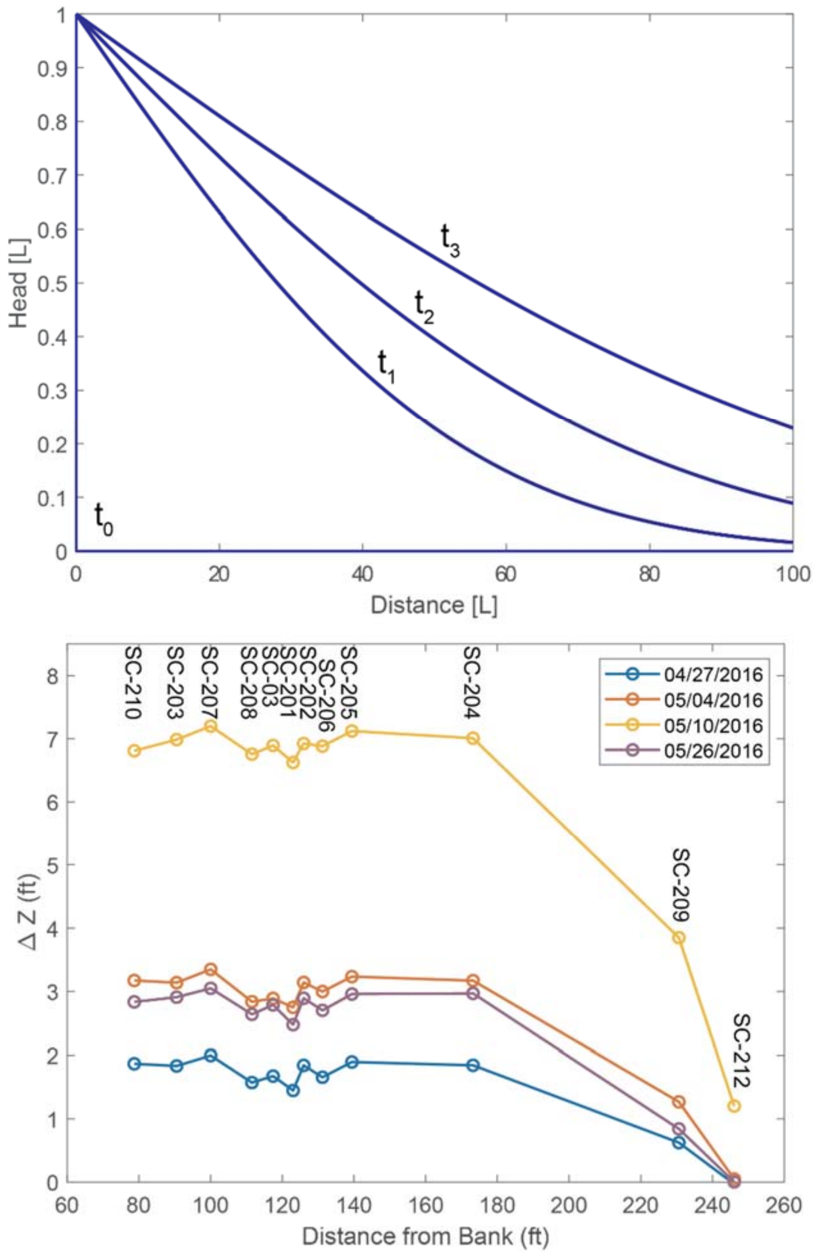

Figure 19. The head response to a change in head predicted by Equation 4 at 4 different times (top). The bottom panel shows the response of the Sheridan wells as a function of distance from the river at 4 different times.

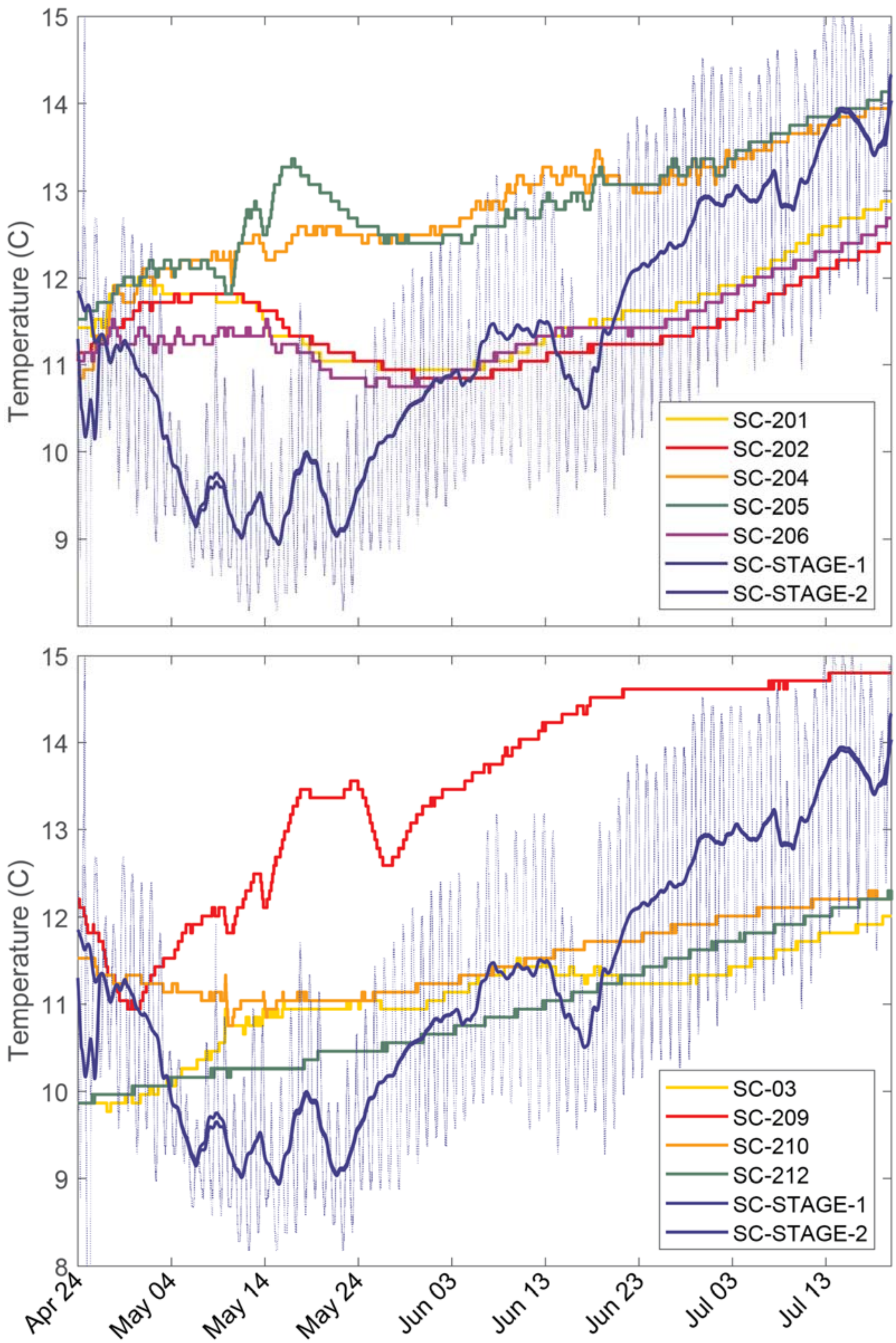

Figure 20. Well and river temperatures for the Sheridan left bank (top) and right bank (bottom). The stage recorder temperature times series is shown as dashed blue lines. The solid blue line are the temperature time series with the diurnal fluctuations removed. Wells affected by overtopping by river water (SC-203, SC-207, and SC-208) are not shown.

Surface Water – Groundwater Model Integration

SRH-2D would work as a MODFLOW package if the mechanism for water exchange with the fluvial aquifer were more robust. There does not seem to be a problem with subtracting water from the river, although if large amounts of water in a simulation were lost, it might cause water velocities in the river to artificially accelerate unless the momentum associated with the lost water was also removed from the model. The bigger problem is the SRH-2D numerical instability and other abnormal behavior created by adding water to the river from the aquifer. I do not know what the root cause of this problem is, but it is associated with a depth threshold. Ideally, the momentumless mass source/sink mechanism in SRH-2D would be updated (or replaced with a mechanism that accounts for momentum) so that water could be added to dry cells to simulate springs and to cells with shallow water. Short of this, the workaround described above would probably work well enough, but additional funding would be needed to complete the integration of SRH-2D as a MODFLOW package. At present, I have no plans to submit a proposal for further work, but I would be happy to support anyone else who is interested in extending the work described in this report

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Appendix A. Compiled Sheridan Test Pit Logs

Table A1. Well stratigraphy derived from Sherer [2011]

Well	Easting (ft)	Northing (ft)	Ground Elev. (ft)	Well Depth (ft)	Layer Top (ft below surface)	Layer Bottom (ft below surface)	Layer Type	Simplified Layer Type
SC-03	6271340.9	2143160.1	1480.1	9.0	0.0	1.0	Silty Sand to Sandy Silt	Sand
					1.0	4.0	Poorly Graded Sand with Silt and Gravel	Sand
					4.0	9.0	Poorly Graded Sand with Silt	Sand
					0.0	0.0	Well Bottom	Well Bottom
SC-201	6271110.6	2143608.0	1481.2	8.1	0.0	2.0	Silty Sand with Gravel	Sand
					2.0	7.0	Poorly Graded Gravel with Silt, Sand, and Cobbles	Gravel
					7.0	0.0	Poorly Graded Gravel with Silt, Sand, and Cobbles	Gravel
					0.0	0.0	Well Bottom	Well Bottom
SC-202	6271204.1	2143924.8	1479.8	8.7	0.0	2.0	Silt with Sand	Silt
					2.0	6.9	Poorly Graded Gravel with Silt, Sand, and Cobbles	Gravel
					6.9	0.0	Poorly Graded Gravel with Silt, Sand, and Cobbles	Gravel
					0.0	0.0	Well Bottom	Well Bottom
SC-203	6271251.2	2144139.2	1478.4	7.7	0.0	1.5	Silt with Sand, Gravel, Cobbles, and Boulders	Silt
					1.5	3.3	Silty Gravel with Sand and Cobbles	Gravel
					3.3	4.0	Poorly Graded Gravel with Silt, Sand, and Cobbles	Gravel

					4.0	5.4	Silty Gravel with Sand and Cobbles	Gravel
					5.4	0.0	Silty Gravel with Sand and Cobbles	Gravel
					0.0	0.0	Well Bottom	Well Bottom
SC-204	6271168.3	2144147.8	1480.7	9.8	0.0	1.0	Silt with Sand and Gravel	Silt
					1.0	4.0	Silty Sand to Silty Gravel	Sand
					4.0	7.5	Poorly Graded Sand with Silt, Gravel, and Cobbles	Sand
					7.5	0.0	Poorly Graded Sand with Silt, Gravel, and Cobbles	Sand
					0.0	0.0	Well Bottom	Well Bottom
SC-205	6271221.8	2144485.4	1482.7	11.0	0.0	0.5	Silt	Silt
					0.5	4.0	Silty Gravel with Sand and Cobbles	Gravel
					4.0	7.0	Silty Sand with Gravel and Cobbles	Sand
					7.0	8.0	Silty Sand with Gravel and Cobbles	Sand
					8.0	10.3	Silty Gravel with Sand and Cobbles	Gravel
					10.3	0.0	Silty Gravel with Sand and Cobbles	Gravel
					0.0		Well Bottom	Well Bottom
SC-206	6271255.7	2144635.0	1482.1	10.3	0.0	2.2	Silt with Sand	Silt
					2.2	9.4	Silty Gravel with Sand and Cobbles	Gravel
					9.4	0.0	Silty Gravel with Sand and Cobbles	Gravel
					0.0	0.0	Well Bottom	Well Bottom
SC-207	6271342.8	2144874.7	1478.1	8.0	0.0	0.4	Silt with Sand	Silt

					0.4	6.0	Clayey Gravel with Sand	Gravel
					6.0	0.0	Clayey Gravel with Sand	Gravel
					0.0	0.0	Well Bottom	Well Bottom
SC-208	6271700.7	2144901.3	1477.4	8.1	0.0	1.6	Silt with Sand	Silt
					1.6	4.0	Silty Gravel with Sand and Cobbles	Gravel
					4.0	6.0	Silty Sand with Gravel	Sand
					6.0	0.0	Silty Sand with Gravel	Sand
					0.0	0.0	Well Bottom	Well Bottom
SC-209	6271770.6	2144620.7	1481.1	11.3	0.0	0.7	Silt with Sand	Silt
					0.7	2.0	Silty Gravel with Sand	Gravel
					2.0	4.0	Silty Sand with Gravel	Sand
					4.0	5.0	Silty Sand	Sand
					5.0	8.5	Silty Sand with Gravel	Sand
					8.5	9.8	Silty Sand	Sand
					9.8	0.0	Silty Sand	Sand
					0.0	0.0	Well Bottom	Well Bottom
SC-210	6271616.5	2144635.1	1478.3	7.8	0.0	2.5	Silt with Sand	Silt
					2.5	6.5	Silty Gravel with Sand	Gravel
					6.5	0.0	Silty Gravel with Sand	Gravel
					0.0	0.0	Well Bottom	Well Bottom
SC-211	6271678.8	2144332.4	1484.6	14.9	0.0	0.3	Silt with Sand	Silt
					0.3	14.5	Silty Sand	Sand

					14.5	0.0	Silty Sand	Sand
					0.0	0.0	Well Bottom	Well Bottom
SC-212	6271661.2	2143770.6	1488.7	16.4	0.0	2.0	Silty Sand	Sand
					2.0	10.0	Silty Sand with Gravel and Cobbles	Sand
					10.0	14.6	Silty Gravel with Sand, Cobbles, and Boulders	Gravel
					14.6	0.0	Silty Gravel with Sand, Cobbles, and Boulders	Gravel
					0.0	0.0	Well Bottom	Well Bottom