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Using MODFLOW to Assess Groundwater Storage Enhancement via a Floodplain Infiltration Basin

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USING MODFLOW TO ASSESS GROUNDWATER STORAGE ENHANCEMENT VIA A FLOODPLAIN INFILTRATION BASIN

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by

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ABSTRACT

USING MODFLOW TO ASSESS GROUNDWATER STORAGE ENHANCEMENT VIA A FLOODPLAIN INFILTRATION BASIN

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Delaying groundwater discharge into rivers until it is critically needed during baseflow conditions provides promise for lowering elevated stream temperatures and improving habitat for aquatic species. Increasing groundwater storage may accomplish this in locations where excess spring runoff can be captured and allowed to infiltrate into the subsurface for later beneficial use, a process known as Managed Aquifer Recharge (MAR). Here, MAR via an infiltration basin is considered at a site along the Teanaway River in central Washington State. The effects of simulated ephemeral ponds of sizes varying from 554 m^3 to 2430 m^3 (0.449 acre-feet to 1.97 acre-feet) on the existing groundwater flow regime are investigated using a transient MODFLOW groundwater flow model.

The groundwater flow model is calibrated against 217 groundwater head observations at the site over a span of 2 years. Secondary calibration is performed by comparing the MODFLOW model to an analytic water balance developed by idealizing the water table with a least-squares plane of best-fit to determine the change in groundwater storage from water table fluctuations. Both the transient groundwater flow model and the analytic water balance model employ specific yield in the calculation of groundwater storage. Coupling of the two models produces a weighted average of specific yield at the site for the shallow alluvial aquifer and upper 10 m of sandstone bedrock of 0.12.

Comparison of head elevations and mass balances between the calibrated groundwater flow model and the different ephemeral pond scenarios indicates that increased infiltration contributes to an increased overall volume of the system in the short term, with the additional water returning to baseline levels by September following the drying up of the pond at the end of April. The maximum increase in groundwater elevation is 0.76 m. The total increase in volume of the system is offset by increased discharge across the downgradient boundary of the site and to the river, with a modest increase in evapotranspiration. For the storage and hydraulic conductivity conditions of the shallow alluvial aquifer at the site, MAR in the spring would not have lasting effects into summer when increased baseflow is desired.

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Lastly, this is for Kristi. I did it, my friend!

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

Chapter Page

LIST OF TABLES

LIST OF TABLES (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

CHAPTER I

INTRODUCTION

Overview and Purpose

In Kittitas County in central Washington State, the Teanaway River flows from the eastern slopes of the Cascade Range to the Yakima River (Figure 1). Elevated water temperatures (Creech, 2003) and anthropogenic channel alterations (Schanz et al., 2019) are contributing to the decline in numbers of anadromous fish and other aquatic species in the Teanaway River (Snyder and Stanford, 2001). The State of Washington, the Yakama Nation, and several conservation groups are actively seeking ways to restore aquatic habitat in the Teanaway River and its tributaries. Since groundwater seepage into rivers is known to reduce stream temperature, enhanced groundwater storage and increased seepage are promising habitat restoration practices.

A possible method for enhancing groundwater storage is managed aquifer recharge (MAR). MAR is the "purposeful recharge of an aquifer for subsequent recovery or environmental benefits" (Ringleb et al., 2016). Zhang et al. (2020) detail the historical development of MAR from ancient agrarian practices to the coining of the term in the early 21st century. MAR is accomplished in a variety of ways, including by injection of water into an aquifer through wells, infiltration via ponds, ditches, and surface spreading, in-channel and bank modifications of streams, and rooftop rainwater harvesting.

The Teanaway River watershed contains a conservation district known as the Teanaway Community Forest (TCF), which is land co-managed by the Washington State Department of Fish and Wildlife (WDFW) and the Washington State Department of Natural Resources (DNR) and set aside with goals of maintaining 5 key elements: watershed protection, forestry and grazing, recreation, fish and wildlife habitat, and community partnerships. Within the TCF, a

215-acre property known as the Teanaway Valley Family Farm (TVFF) is situated at the base of steep uplands adjacent to the Teanaway River. The site's available land in the floodplain and the seasonal water supply from nearby upland runoff make it a site suitable for potential MAR infiltration techniques.

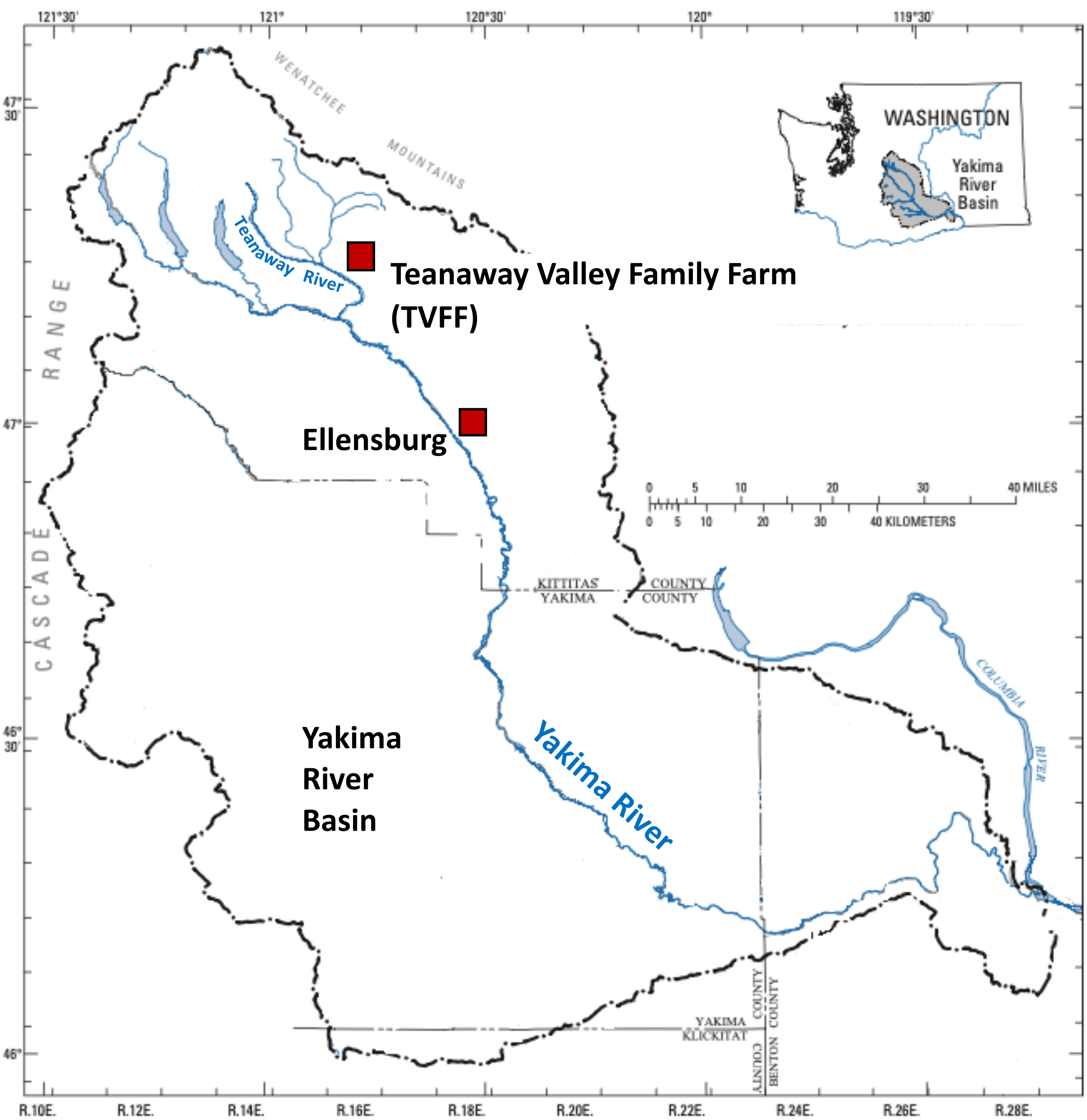


Figure 1. General location of the Teanaway River. The research site, Teanaway Valley Family Farm (TVFF), is shown. Adapted from Vaccaro et al., 2009.

The purpose of this research is to investigate the potential benefits of small infiltration ponds in floodplain sites on shallow aquifer recharge by modeling this type of infiltration pond at TVFF. A groundwater flow model was created using the United States Geological Survey (USGS) numerical modeling code MODFLOW and calibrated with observed physical parameters. A theoretical pond was then added to the calibrated model to evaluate its influence on the existing groundwater regime.

Site Description

The TVFF research site borders an approximately 1800 m reach of the Teanaway River located 13 river kilometers upstream of the confluence of the Teanaway and Yakima Rivers (Figure 1). Land use at the site was conventional hay farming until 2016. In 2017, the property was acquired by WDFW for floodplain and meadow restoration. As part of this conservation effort, 10 groundwater monitoring wells were installed by Mid-Columbia Fisheries Enhancement Group in 2018 (Gazis, 2020). The well locations are shown in Figure 2. Wells numbered 2 through 10, located in the floodplain, are utilized in this research.

The northern border of the study area is the Teanaway Road, which inhibits surface water runoff from the uplands to the north except through limited culverts passing beneath the road. The culverts transmit the flow of ephemeral creeks to the floodplain. An unnamed drainage contributes runoff that is captured by a ditch on private property on the south side of the road at the western end of the site. The ditch prevents runoff from flooding a field used for alfalfa farming. A creek on the eastern end of the site, named Freds Creek, flows into the TVFF property. Freds Creek was anthropogenically channelized in the past for agricultural practices,

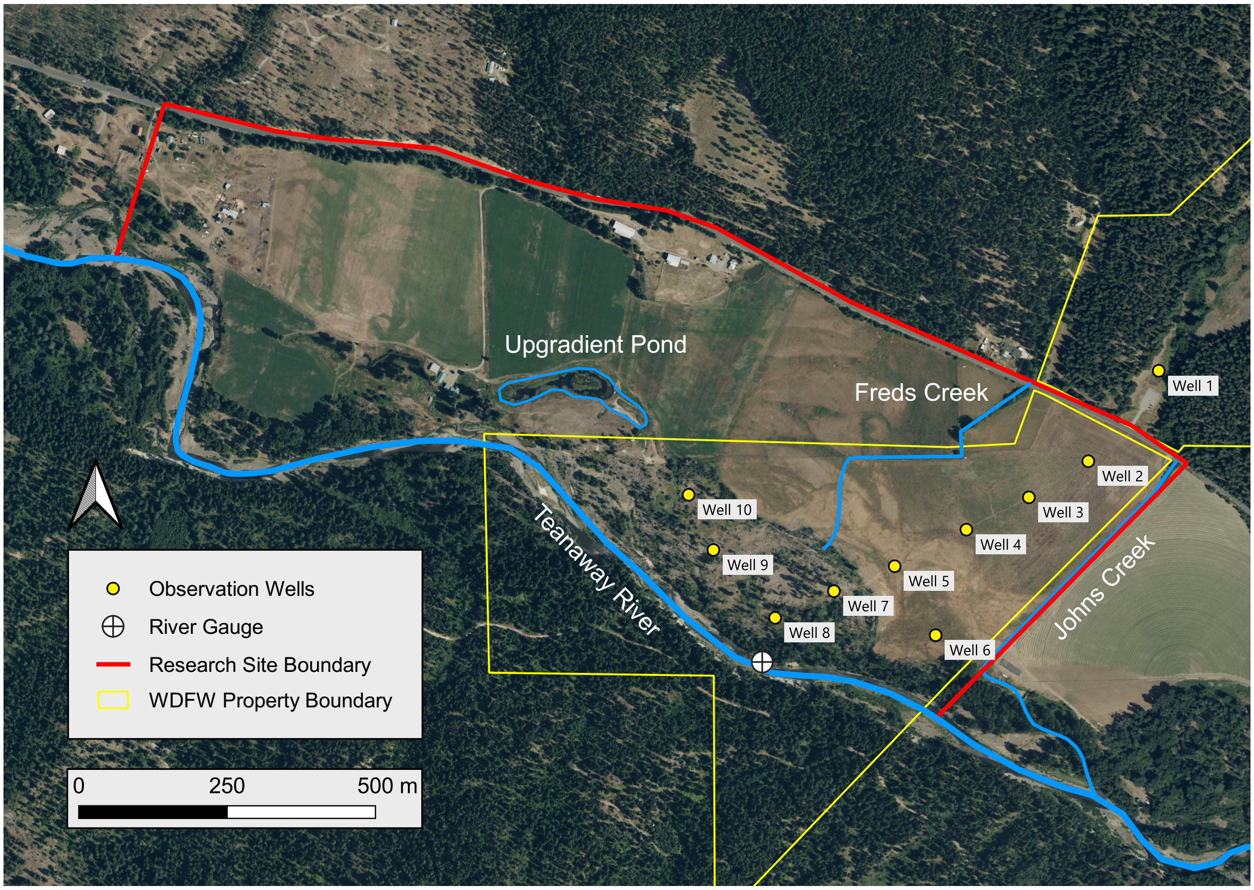


Figure 2. Teanaway Valley Family Farm Site Map. TVFF is located along the Teanaway River. Blue lines indicate streams and ponds. The red perimeter indicates the extent of the groundwater flow model. The yellow boundary delineates property owned by the Washington Department of Fish and Wildlife for floodplain and meadow restoration.

but now, as part of the TCF, is a candidate for restoration. Another ephemeral creek, called Johns Creek, flows on private property along the eastern boundary of TVFF. Interconnected ponds west of the TVFF property are collectively known as the Upgradient Pond. The Upgradient Pond is an abandoned channel of the Teanaway River that remains full perennially. Water from the Upgradient Pond is pumped for irrigation of the nearby alfalfa field.

Discharge in the Teanaway River has been described as “flashy,” with high and variable flows in the spring and after precipitation events. Low flows in the late summer adversely affect aquatic life in the river, and efforts have been made to enhance instream flows, that is, “keep water in the river" through water rights management, improved irrigation efficiency, restorative plantings, large wood emplacement, and beaver dam analogs. Capturing excess tributary runoff when it is available in the spring, allowing it to infiltrate into the shallow alluvial aquifer that underlies the floodplain, and delaying its discharge into the Teanaway River may provide additional instream flows at a more critical time. The TVFF site is well situated to provide this type of MAR. Abundant spring runoff in Freds Creek withheld in an infiltration pond could potentially discharge as groundwater into the Teanaway River in the summer and fall and supplement low flows.

Managed Aquifer Recharge Background

MAR techniques for infiltrating water include infiltration ponds and basins, flooding, ditches, furrows, and drains, and irrigation (Ringleb et al., 2016), and are used worldwide in both large-scale and small-scale applications (Zhang et al., 2020). An example where similar "flashy" runoff is captured is in the country of India, where small reservoirs, called percolation tanks, are sited in strategic locations to retain monsoonal rains and infiltrate water slowly, recharging shallow aquifer systems to provide a water supply for agriculture (Massuel et al., 2014). Nearer to the Teanaway River, MAR is used to enhance streamflow in the Walla Walla Basin in northeastern Oregon and southeastern Washington (Scherberg et al., 2014). MAR was implemented there in 2004 and now has 17 infiltration galleries which recharge the basin aquifers and supplement flow in hydraulically connected streams. On a smaller scale, infiltration techniques for recycling stormwater and delaying runoff are a common practice in stormwater management.

Numerical modeling is often used to assess MAR site suitability for water storage and extraction, determine a feasible water balance, and weigh risk, such as flooding downstream property (Maples et al., 2019, Russo et al., 2014). Scherberg et al. (2014) used a numerical groundwater model to test different management scenarios for the Walla Walla Basin MAR program, showing that MAR contributes more to enhanced surface flows, which is a benefit to aquatic habitat, than to increased groundwater storage.

Regional Groundwater Studies and Models

Regionally, prior groundwater studies in the greater Yakima Basin were undertaken by the USGS not to assess MAR, but because of concerns about the impacts of groundwater withdrawal on surface water rights. Notably these include the hydrogeologic frameworks by Vaccaro et al. (2009) and Gendaszek et al. (2014). These studies detail the hydrogeologic units in the basin and their hydraulic properties, report groundwater hydrochemistry, quantify water use, and provide water budgets for the Yakima basin as a whole and the Upper Kittitas County subbasin, respectively.

A comprehensive groundwater flow model for the entire Yakima Basin was published by Ely et al. (2011). The model simulated stresses on the Yakima Basin groundwater system for different scenarios, including the effects of increased pumping withdrawals in the basin. It also attempted to forecast conditions up to the year 2025. This model is extensive but coarse, having 24 subsurface layers and a discretized grid of 600 cells by 600 cells, approximately 300 meters per side, covering the 16,000 km^2 areal extent of the entire basin. Futornick (2015) refined the Yakima Basin model in Upper Kittitas County, consolidating the 24 subsurface layers into 5, discretizing the smaller 2,200 km^2 area with a 246 by 195 cell grid, including more tributary streams, and using an updated numerical solver. The Upper Kittitas County model studied the effects of varied pumping and decreased recharge on surface water flows.

This thesis presents a high-resolution site-scale numerical groundwater flow model to investigate the potential for enhanced groundwater seepage into the Teanaway River by simulating MAR in the form of delayed infiltration of surface water runoff in an ephemeral creek. The model domain is discretized into a grid of 182 by 91 10-meter by 10-meter cells and 10 subsurface layers. The work seeks to characterize the exchange of water between the Teanaway River and the shallow alluvial aquifer in the floodplain adjacent to the river.

MODFLOW

Introduction to MODFLOW

MODFLOW, which is short for "Modular three-dimensional finite-difference ground-water flow," is a numerical groundwater modeling code from the USGS. The first version was released in 1984 and continues to be the industry standard in groundwater modeling (USGS, 2020). MODFLOW operates with "packages" that handle individual aspects of the numerical simulation. For example, calculations for the hydraulic connection between a river and an aquifer are performed using the "RIV" package. Packages make a groundwater flow model customizable according to the physical conditions being modeled. The commercial product Visual MODFLOW Flex 7.0 (Waterloo Hydrogeologic, 2021) is employed here as the graphical user interface for processing the MODFLOW code.

MODFLOW simulates groundwater flow by iteratively solving the groundwater flow equation on a small control volume. The entire three-dimensional space of the model is composed of these small control volumes, or "cells." The cells are generated by discretizing the land surface with a grid and the subsurface with vertical layers. Cells can be any volumetric prism; they do not have to be cubes.

The groundwater flow equation is a combination of conservation of mass through a volume, that is,

$$\textit{Inflows} - \textit{Outflows} = \textit{Change in Storage}, \tag{1}$$

and Darcy's Law, Equation (2). Darcy's Law was established from experiments performed by French engineer Henri Darcy in the 1850's. He investigated the flux of water through a sample of porous material and determined:

$$Q = -KA\left(\frac{dh}{dl}\right), \tag{2}$$

where Q is the flow rate (the units for Q are length cubed divided by time, i.e., L^3/T), K is hydraulic conductivity (L/T), A is the cross-sectional area of the sample (L^2), dh is the change in height between ends of the sample (L), and dL is the change in length of the sample (L).

Taken together in three dimensions, Equations (1) and (2) yield the following partial-differential equation for groundwater flow:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) + Q_s^{'} = S_s\frac{\partial h}{\partial t}. \tag{3}$$

Here, K_{xx}, K_{yy}, and K_{zz} are the values of hydraulic conductivity along the x, y, and z axes ($L{\cdot}T^{-1}$), h is the potentiometric head (L), Q'_s is a volumetric flux per unit volume (T^{-1}), S_s is the specific storage of the porous material (L^{-1}), and t is time (T). Equation (3) is solved for hydraulic head as a function of space and time. It requires the specification of flow conditions (positive Q'_s for flow into the system and negative Q'_s for flow out of the system), aquifer characteristics (permeabilities, porosity, specific storage), head conditions at the boundaries of the aquifer system, and initial head conditions. MODFLOW numerical models are calibrated by comparing measured hydraulic head with simulated values.

Unconfined, Variably Saturated Flow

Equation (3) governs transient groundwater flow in saturated, confined conditions. However, groundwater flow near the surface is unconfined and may not be fully saturated. To account for this, the saturated thickness of the unconfined zone can be taken to be the hydraulic head above bottom of the unconfined aquifer. This difference makes equation (4) more appropriate for these conditions:

$$\frac{\partial}{\partial x}K_x\left(h\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}K_y\left(h\frac{\partial h}{\partial y}\right) = S_y\frac{\partial h}{\partial t} \tag{4}$$

where K_x and K_y are again hydraulic conductivity in the x and y directions ($L{\cdot}T^{-1}$), h is the head (L), S_y is the specific yield of the porous material (L^{-1}), and t is time (T). Because head varies, note that h is required to be inside of the derivative and specific yield, S_y, is used instead of specific storage. Equation (4) is for two-dimensional flow under unconfined, transient, anisotropic, and heterogeneous conditions (Woessner and Poeter, 2020).

Different versions of MODFLOW computer code exist for solving Equations (3) or (4). MODFLOW-NWT (Niswonger et al., 2011) is used in this research because of its ability to solve (4) under conditions where the model cells go dry (that is, the head drops below the bottom of a cell) and then rewet, which occurs in the transient, unconfined simulations in this model. MODFLOW-NWT employs the Newton-Raphson method for solving the groundwater flow equation. Like the traditional Newton's method for finding the root of a mathematical function, MODFLOW-NWT uses a linear approximation technique to find the solution to the non-linear groundwater flow equation such as (4).

Boundary Conditions Overview

Boundary conditions are critical components of a MODFLOW model. They are locations where water is exchanged between the model domain and its surroundings. Examples include recharge, evapotranspiration, rivers, lakes, and pumping wells. Boundary conditions fall into 3 categories in MODFLOW: 1) specified head, 2) specified flux, and 3) head dependent flux. Specified head boundaries, also known as constant head boundaries, require a fixed head value at their location, thus providing an infinite source or an infinite sink of water in the exchange between the system and its surroundings. Specified flux boundary conditions, such as recharge or pumping wells, represent a flow of water as a function of time that enters or exits the model domain. The no-flow boundary condition is a specified flux of zero. In the head dependent flux boundary condition, the flow rate of water into or out of the boundary control volume cell is proportional to the head in the cell. The evapotranspiration boundary condition is one such head dependent flux boundary condition: the rate of water leaving a cell assigned this boundary condition is a maximum when the head is at a high level in the cell but drops to zero via linear interpolation when the head in the boundary cell falls below a specified level known as the extinction depth. When boundary conditions change with time, the model is known as *transient*. Periods of time between the changes in boundary conditions are called *stress periods*. When boundary conditions do not change with time, the model is *steady state* and the resulting change in storage is zero. Boundary conditions are defined conceptually and then implemented in the MODFLOW code using the aforementioned packages.

CHAPTER II

GEOLOGIC SETTING

The Teanaway Watershed

The Teanaway River originates high in the central Cascade mountains in Washington State, terminating at its confluence with the Yakima River near Cle Elum, Washington. Three branches, the West Fork, Middle Fork, and North Fork, comprise the upper reaches of the river. These 3 tributaries drain steep uplands before converging into the mainstem Teanaway River. Here the topography transitions into a northwest-to-southeast trending valley generally 0.5 to 0.7 kilometers wide. The valley is bounded by the Wenatchee Mountains on the north and northeast, Sasse Ridge on the west, Cle Elum Ridge on the southwest, and Lookout Mountain on the south. The Teanaway River watershed drains 543 km^2 and is part of the greater Yakima Basin, with relief from 2190 m above sea level at Navajo Peak to 555 m above sea level at the confluence with the Yakima River. Lying in the orographic shadow of the Cascade mountains, the climate is primarily continental Mediterranean with precipitation amounts ranging from 1800 mm annually in the uplands, mostly falling as snow, to 617 mm in the lower valley (PRISM, 2022).

The geologic setting for the Teanaway River watershed has been strongly influenced by 3 important episodes: 1) the Eocene deposition of non-marine sediments in fault-bounded basins, 2) deformation resulting from ongoing uplift of the Cascade Range, and 3) the Pleistocene advance and retreat of valley glaciers. To a lesser extent, Miocene Columbia River Basalt flows also impacted the geologic history of the Teanaway drainage.

Bedrock

Bedrock formations in the Teanaway watershed are Eocene sedimentary and volcanic rocks. Generally speaking, the steep uplands are comprised of the older Swauk and Teanaway

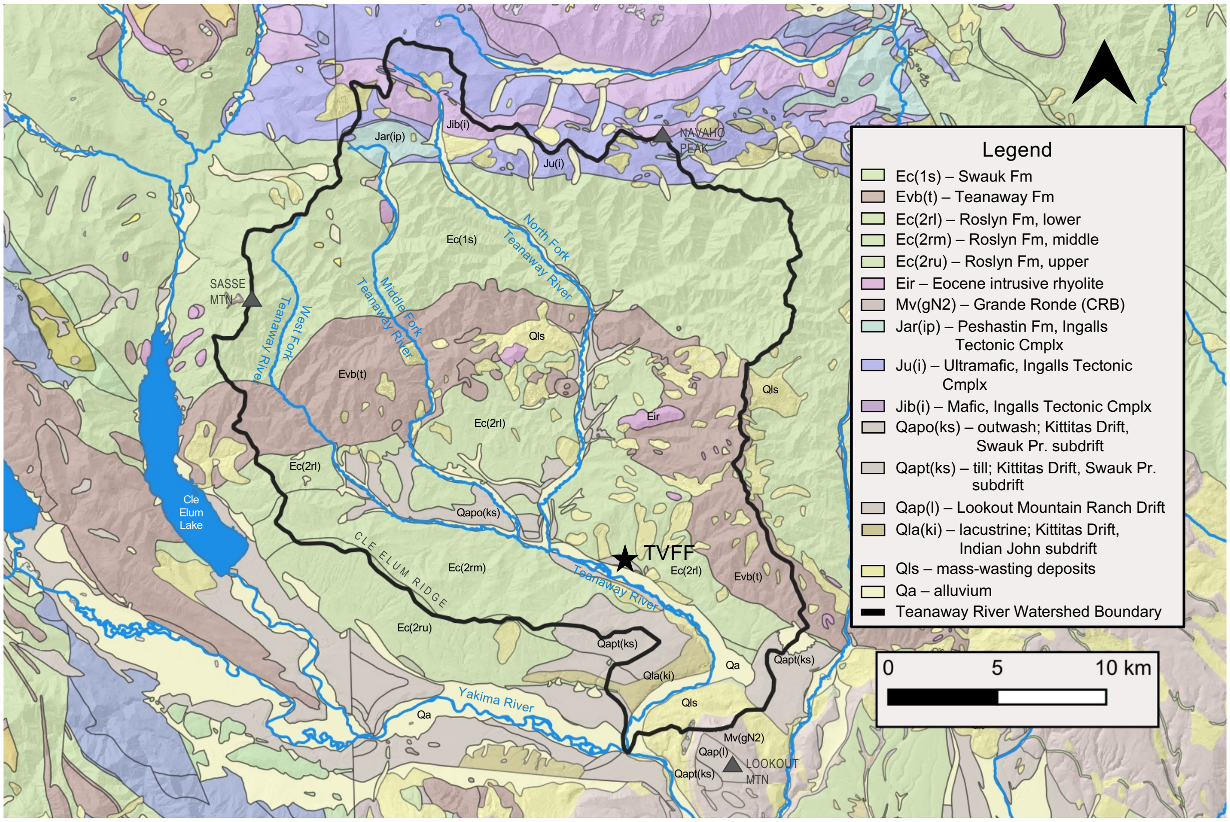


Figure 3. Geologic Map of the Teanaway River Watershed. Data set is from Washington Division of Geology and Earth Resources (2016).

Formations, while lower elevations are comprised of the younger Roslyn Formation. Alluvial deposits cover the Roslyn in the valley. Metamorphic and plutonic rocks of the North Cascades crystalline core are exposed north of the watershed. These include the Mesozoic granodiorite of the Mount Stuart batholith and the ophiolitic Ingalls Complex (Tabor et al., 1984, Miller et al., 2022). Early Cretaceous blueschist of the Easton terrane can be found to the west (Haugerud and Tabor, 2009).

The Swauk Formation

The Swauk Formation found in the Teanaway watershed highlands unconformably overlies the North Cascade crystalline basement rocks. It is a dark-colored feldspathic sandstone interbedded with dark carbonaceous siltstone and shale and containing pebbly sandstone and conglomerate throughout (Tabor et al., 1982). The formation is as much as 4800 m thick (Tabor et al., 1984), and was deposited between ≤59.9 and >49.9 Ma in the ancient non-marine sedimentary Swauk Basin (Eddy et al., 2016). Different hypotheses exist regarding the depositional history of the Swauk Formation, including: 1) that it was deposited locally in a subsiding strike-slip basin (Johnson, 1985), 2) that the Swauk and other area basins are erosional remnants of the same regional depositional system (Cheney and Hayman, 2009), 3) that the basins were a regional system deposited during a period of extension, later partitioned by strike-slip faults (Evans, 1994), and 4) that the Swauk is an erosional remnant of a regional depositional system that includes the Chuckanut and Manastash Formations, but is temporally distinct from the nearby Chumstick Formation to the east (Eddy et al., 2016). The consensus is that the Swauk Formation is fluvial material sourced from eastern mountains, and it is bounded by the Straight Creek-Fraser Fault on the west and the Leavenworth Fault on the east. Approximately 51 Ma the Swauk was folded and uplifted, attributed to collision by the Siletzia terrane with continental North America (Miller et al., 2022).

The Teanaway Formation

Following the collision of Siletzia, the Teanaway Formation volcanics erupted and are located unconformably on the Swauk Formation. Several of the rugged upland peaks in the Teanaway watershed are Teanaway Formation. Commonly referred to as the Teanaway Basalts, the formation ranges in composition from basalt to rhyolite and contains basaltic and andesitic tuff and breccia (Tabor et al., 1984). The thickness of the Teanaway Formation is estimated to be less than 10 m in its eastern extent to at least 2500 m near Lake Kachess in the west (Tabor et al., 1984). Related to the Teanaway Formation is the Teanaway dike swarm, which intruded the

Swauk Formation, Mount Stuart batholith and Ingalls Complex approximately 49.3 Ma (Miller et al., 2022).

The Roslyn Formation

The youngest bedrock layer in the Teanaway watershed is the Roslyn Formation, which lies conformably over the Teanaway Formation. The Roslyn Formation is a thick-bedded, non-marine arkosic sandstone that is described by Tabor et al. (1982) as "conspicuously white, weathering yellow." Its deposition indicates renewed sedimentation by westward-flowing rivers from ancestral mountains to the east. Bressler, in his 1951 PhD thesis (Bressler, 1951), divided the formation into 3 stratigraphic members based on grain size: the lower, middle, and upper. Grain size decreases upward through all three members, and the presence of shale and coal increases. The lower member is located north and east of the Teanaway River and is estimated to be 1000 m thick. It is interbedded with rhyolite flows and tuffs in its lower extents, and then consists of sandstone that grades from tuffaceous to arkosic with medium to coarse grain sizes and some conglomerate (Walker, 1980). The middle member extends northwest to southeast between Cle Elum Ridge and the Teanaway River. It is also approximately 1000 m thick, thinning toward the northwest. It is predominantly medium-grained sandstone with minor amounts of pebbly sandstone, siltstone, shale, and some coal toward the top (Walker, 1980). The upper member is fine grained sandstone and is coal-bearing; it was called the "coal measures" by Bressler. This member was extensively mined to support the railroad between 1882 and 1963 and was the economic mainstay for the town of Roslyn, near Cle Elum (Walker, 1980). This upper member may be as thick as 800 m. It is located on the southern slope of Cle Elum Ridge, bounded by the Yakima and Cle Elum Rivers to the south and west. Eddy et al. (2016) provide maximum depositional ages for the Roslyn of 48.8 Ma for the lower member and 47.6 Ma for the upper member, and the 49 Ma Teanaway dikes do not cut through the formation (Miller et al., 2022).

Regional Deformation

Regional deformation during the Eocene occurred coincident with the accretion of the Siletzia Terrane at the continental margin (Miller et al., 2022). This deformation includes the uplift of the Cascades core, strike-slip fault activation, intrusion of dike swarms, basin subsidence with sediment accumulation, and development of a WNW-trending fold-and-thrust belt (Haugerud et al., 1991, Miller et al., 2016, Eddy et al., 2016). As a result, the Swauk Formation steeply dips to the south and southwest on the northern and eastern sides of the Teanaway River watershed (Tabor et al., 1982). The Teanaway Formation was emplaced following the uplift of the Swauk (Eddy et al., 2016), and the Teanaway dikes cut the Swauk nearly perpendicular to its fold axes (Miller et al., 2022). The dikes were tilted after emplacement as a result of a younger SE-plunging syncline and were largely influenced by the strain field of the Straight Creek-Fraser Fault and possibly (to a lesser extent) by the Leavenworth Fault (Miller et al., 2022). The Teanaway and Roslyn Formations are tightly folded near the Straight Creek-Fraser Fault; folds become more gentle moving east away from the fault (Johnson, 1985). Movement on the Straight Creek-Fraser Fault continued until 35-30 Ma (Eddy et al., 2016), further deforming the Teanaway and Roslyn Formations, although not to the extent of the Swauk.

Columbia River Basalt

In the Miocene, flood basalts of the Columbia River Basalt Group (CRBG) encroached on the southern margin of the Teanaway River watershed. Lookout Mountain, comprised of the Grande Ronde Basalt member of the CRBG (Tabor et al., 1982), sits at the southern limit of the watershed. The Teanaway River makes an abrupt turn to the southwest at this location, flowing along the north side Lookout Mountain toward the Yakima River. Saunders (1914) hypothesized that the Teanaway River originally flowed along the east side of Lookout Mountain into the area known as Swauk Prairie, in the channel now occupied by Swauk Creek, and that Swauk Creek was a tributary of the Teanaway River. Saunders proposed a sequence of stream captures that resulted in the present courses of the Teanaway River and Swauk Creek as separate tributaries to the Yakima River. Waitt (1979) constrains the stream capture events for streams sourcing material from the Teanaway Basalts and Swauk Formation, specifically First Creek and Swauk Creek, to between the deposition of the Pliocene Thorp Gravel and Pleistocene Kittitas Drift. Pleistocene glacial advances mapped by Porter (1976) show evidence that a terminal moraine extending to the east side of Swauk Prairie may have altered the course of the Teanaway River.

Glacial Advances and Drift Deposition

Glaciers in the Teanaway River watershed existed locally in the uplands, and ice advances from the west shaped the topography of the lower Teanaway River valley through a series of ice-marginal lakes. During Pleistocene glacial maxima, individual valley glaciers in the Cascade mountains merged and flowed southeast from the present-day Puget Sound area over Snoqualmie Pass and into the upper Yakima River drainage (Porter, 1976). Episodes of ice advance and subsequent drift deposition that impacted the Teanaway River drainage include, chronologically from oldest to youngest, the Thorp, Lookout Mountain Ranch, Kittitas, and Lakedale Drifts (Porter, 1976, Waitt, 1979).

The Thorp glacial advance was to approximately 65 km east of the present Cascade divide, the extent being the west wall of Horse Canyon, the south slope of Lookout Mountain, and north to Hex Mountain. The drift has been extensively eroded and subsequently covered by later advances. Pronounced weathering of Thorp drift demonstrates a long interval of time passed between the retreat of the Thorp glaciers and the advance of Lookout Mountain Ranch ice (Porter, 1976, Waitt, 1979).

Lookout Mountain Ranch drift dates to approximately 750,000 years BP (Waitt, 1979) and is exposed at the top of Lookout Mountain and in Horse Canyon. Its exposure is at a higher elevation than that of the next glaciation, the Swauk Prairie subdrift of the Kittitas Drift.

The older of two Kittitas subdrifts, the Swauk Prairie subdrift, approximately 600,000 years old (Porter, 1976), also extended north to Hex Mountain, and east and south to Swauk and Thorp Prairies in two lobes of ice. The presence of clasts of Teanaway Basalt in the lower Teanaway River drainage basin indicates that Swauk Prairie ice flowed over a saddle at Cle Elum Ridge and into the Teanaway Valley. However, glacial landforms are lacking in the valley and till is not exposed due to coverage by colluvium (Porter, 1976). A readvance of Kittitas ice at 300,000 years BP terminated at Indian John Hill, for which it is named, its eastern limit being the lower Teanaway River valley opposite Lookout Mountain. A lateral moraine is evident on the south slope of Cle Elum Ridge, marking the northern extent of Indian John Hill subdrift. The glacier did not overtop the ridge. Landslides cover moraines along the west base of Lookout Mountain.

Ice-marginal lakes were impounded by Kittitas ice and drift in the lower Teanaway valley on at least three occasions (Tabor et al., 1982). Advancing Swauk Prairie ice dammed the Swauk and Teanaway valleys, later progressing into the lake it created. Flat surfaces of sand and gravel extend north to the three forks of the Teanaway River, indicating the presence of a long-lived lake following the retreat of the Swauk Prairie glacier (Tabor et al., 1982). Lacustrine sediments and dropstones found west to Cle Elum Ridge provide evidence of a lake associated with the

Indian John glacial retreat. This lake was larger than any of the 3 present lakes, Keechelus, Kachess, or Cle Elum, estimated to be 15 km long, 3 to 5 km wide, and 275 m deep (Porter, 1976).

The most recent period of ice advances, the Lakedale Drift, was divided into 4 subdrifts by Porter (1976): the Bullfrog, Ronald, Domerie, and Hyak. Terminal moraines for Lakedale subdrifts lie west of Cle Elum and do not directly influence the geologic setting of the Teanaway River Valley. Lakedale loess does, however, blanket areas downvalley from the Domerie moraines, which are the dams of present day Keechelus, Kachess, and Cle Elum Lakes, and is prominent at the southern end of the Teanaway River watershed between Swauk Prairie and the town of Easton. Small alpine glaciers were present during the Lakedale period in the vicinity of the North Fork Teanaway River (Tabor et al., 1982).

The Teanaway River valley floor is covered by shallow deposits of Quaternary alluvium and other glacial and more recent sedimentary deposits that overlie the lower member of the Roslyn Formation sandstone bedrock. Near the confluence of the North, Middle, and West Forks of the Teanaway River, well logs indicate the alluvium is <5 m thick. These unconsolidated deposits are comprised of alpine glacial deposits, Kittitas loess, sands and gravels of streams, some older terrace deposits, and mass-wasting deposits from valley side walls (Haugerud and Tabor, 2009, Porter, 1976). The sandstone bedrock is exposed in locations in the upper valley floor and is prominent in the riverbed. The Teanaway River is described by Collins et al. (2016) as a "rapidly incising river in a region with slow rock uplift and no known active faulting."

CHAPTER III

SITE CHARACTERISTICS

Overview

The hydrogeologic setting for TVFF is influenced by its location in a synclinal basin surrounded by steep uplands, by permeable sandstone bedrock on the valley floor, and by alluvial deposits of glacial, fluvial, and mass-wasting origin. The unconsolidated alluvial deposits that form the shallow alluvial aquifer are the focus of this study. The deeper sandstone aquifer has been characterized by Gendaszek et al. (2014), who determined groundwater movement in the regional bedrock is primarily through fractures and zones of secondary porosity. The site receives recharge from rain in the lowlands and melting snowpack from the surrounding highlands. Irrigation return flows also recharge the shallow aquifer. Water levels in observation wells at the site indicate that groundwater tends to flow toward the Teanaway River in the spring when recharge is abundant, and then flows parallel to the river and runs down the valley at other times of the year (Petralia, 2022).

Stratigraphy

From well logs and site observations, the subsurface stratigraphy at TVFF can be divided into 4 hydrogeologic units: an uppermost topsoil unit, a subsurface alluvial unit of silt, sand, and cobbles, a second floodplain unit having lower permeability and composed of clayey silt, and the sandstone bedrock of the middle member of the Roslyn formation (Figure 4). These layers are informally referred to by the names “Soil,” “Cobbles,” “Clay,” and “Sandstone,” respectively.

The Soil unit is approximately 1 m thick across the entire site. This soil is designated Patnish-Mippon-Myzel complex (0 to 3 percent slopes) by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS, 2022). It is, generally

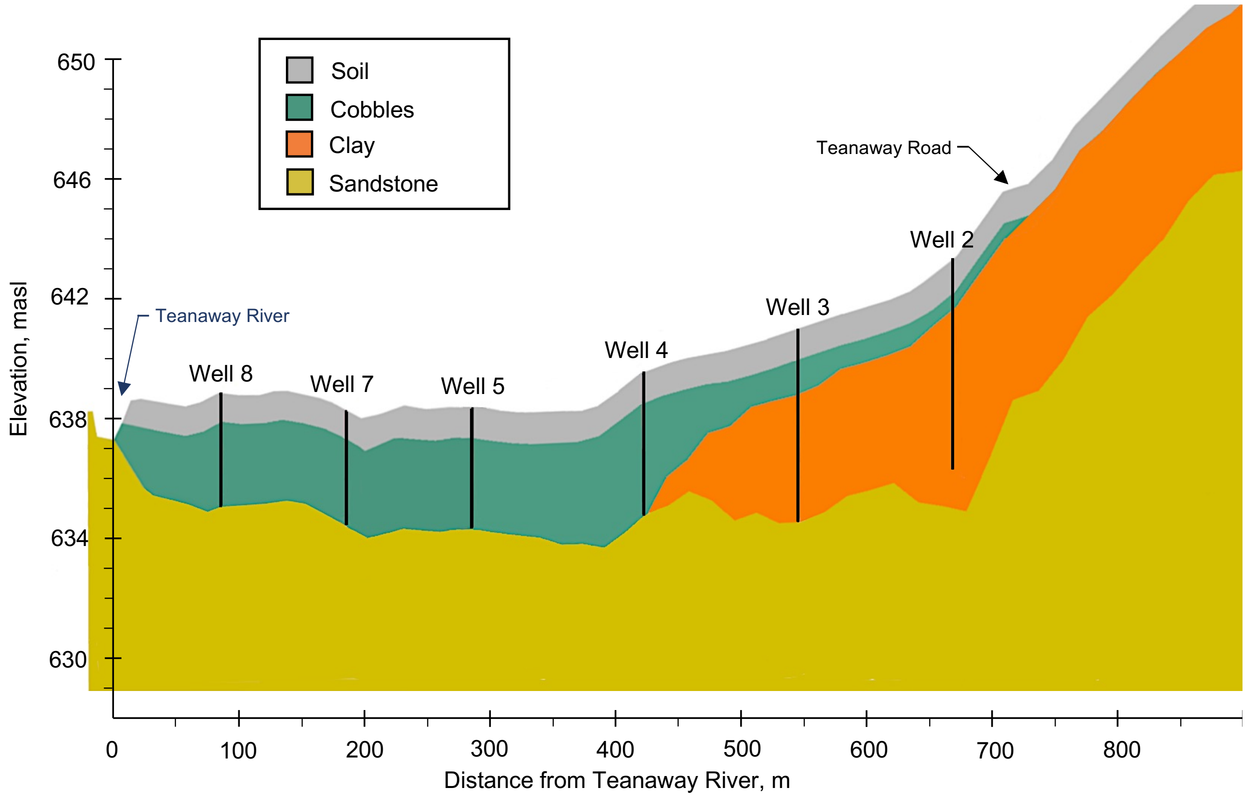


Figure 4. Cross Section of the Hydrogeologic Units at TVFF. The cross section is along the line of Wells 2 through 8. The clay unit terminates between Wells 3 and 4 roughly halfway between Teanaway Road and the Teanaway River. The cross section is generated from DEM surfaces used in the groundwater flow model.

speaking, an ashy loam containing sand to cobbles. The Cobbles unit is immediately below the Soil. It is made up of roughly 10% silt and a 90% mix of subrounded pebbles and cobbles. The unit is approximately 1.5 m thick along the river, deepening to approximately 3.5 m thick moving north from the river, then gently thinning northward on the upper half of the floodplain to depths < 1 m. The horizon of the unit vanishes near Teanaway Road. On the upper half (north side) of the floodplain, the lower permeability Clay unit is prominent with a thickness of up to 5 m toward the northern perimeter of the site. The thickness of the clay diminishes moving upslope, but it is present at varying thicknesses < 5 m for a few hundred meters north of Teanaway Road.

Visible on the valley sides and comprising the valley floor beneath the alluvial units is the middle member of the Roslyn formation, a medium-grained sandstone with minor amounts of pebbly sandstone, siltstone, and shale (Walker, 1980). The bed of the Teanaway River sits on the Sandstone unit and very little alluvial sediments are present in the river. The riverbed has experienced measurable incision due to anthropogenic logging and timber transport practices (Schanz et al., 2019).

A summary of the wells surrounding the site vicinity are tabulated in Table 1. Well logs are catalogued by the Washington State Department of Ecology (Ecology) according to their location in the quarter-quarter section of the Public Land Surveying System. TVFF is located in Township 20 North, Range 16 East, Section 10. Wells downstream (east) of the site are in Section 11, wells in Section 10 are non-project wells in the same section as TVFF, and wells in Sections 9 and 5 are upstream of TVFF. The column "Valley or Slope" indicates whether the well is located in the Teanaway River valley (Valley) or if the well is in the hillslopes north of the river valley (Slope). All wells were completed in sandstone bedrock except wells identified by tag numbers AGM798 and AGM799, which terminated at the base of alluvial river valley deposits/top of the sandstone unit. Well AGM953 was deepened from 36.6 m to 154 m in 2003.

Section 11 wells tend to be in the river valley and terminate in bedrock at depths of 35.7 m to 103 m in what is described as "blue clay" or "soft blue rock." This can be interpreted as low permeability shale. Two of the wells have static water levels 30.5 m below ground surface and two of the wells were artesian on their completion date. Wells upstream (west) of the site are found in Sections 5 and 9 (no wells are located in Section 4). These wells are near the confluence of the North Fork and West Fork Teanaway Rivers with the mainstem Teanaway River. They are located in both the river valley and on the northern side slope at depths of 42.7 m to 141 m,

Table 1.
Information from Ecology Well Logs for Sections Surrounding T20N, R16E

Well ID (Tag Number)	Section	Well Depth (m)	Casing Diameter (cm)	Static Water Level (m, bgs)	Well Completion Date	Valley or Slope
Unknown	11	35.7	2.36	3.05	10/25/83	Valley
AFE357	11	103	2.36	Artesian	9/13/00	Valley
Unknown	11	97.5	2.36	30.5	8/1/89	Valley
ABL090	11	61.0	2.36	Artesian	5/25/94	Valley
Unknown	11	68.6	2.36	30.5	6/30/78	Slope
AGM798	10	3.66	18.9	2.74	10/22/03	Valley
AGM953	10	154	2.36	7.01	12/15/03	Slope
Unknown	10	91.4	2.36	21.3	10/4/90	Slope
Unknown	10	36.6	2.36	6.10	6/3/90	Slope
AGM799	10	3.66	18.9	2.74	10/22/03	Valley
AKW772	10	122	2.36	59.4	10/7/03	Slope
Unknown	9	42.7	2.36	24.4	4/29/88	Valley
ACL105	5	67.1	2.36	1.83	9/17/96	Valley
ABL625	5	61.0	2.36	2.74	11/6/95	Valley
BCF664	5	105	2.36	7.62	8/15/12	Slope
Unknown	5	48.8	2.36	1.52	7/27/90	Slope
BAP329	5	141	2.36	5.18	8/17/08	Valley
ACL861	5	62.5	3.94	3.35	10/2/97	Slope
ABX135	5	91.4	2.36	11.6	6/7/95	Slope
ACE814	5	67.1	3.94	6.10	6/10/96	Valley
ACL652	5	38.1	2.36	3.35	7/21/98	Valley
ACL106	5	42.7	3.94	9.75	9/18/96	Valley
ACL889	5	32.0	2.36	5.18	5/7/98	Valley

terminating in sandstone described as white. The wells in this section have characteristically high static water levels ranging from 1.52 m to 11.6 m below ground surface. Multiple wells here exhibit lithologies of alternating layers of blue or blue-gray shale and white sandstone, likely the middle member of the Roslyn formation.

Wells used for domestic supply and irrigation are listed for Section 10 (the site) in Table 1. In this section, domestic supply wells are finished in sandstone bedrock at depths of 36.6 m to 154 m while irrigation wells are only 3.66 m deep and terminate at the top of the contact with sandstone. Domestic wells have static water levels ranging from 6.10 m to 59.4 m below ground surface. The irrigation wells have static water levels of 2.74 m below ground surface. One well,

Well Tag ID AGM953, was deepened from 54.9 m to 154 m, presumably because the well yield had diminished below a useful supply. These wells demonstrate that domestic supply is sourced from the deeper sandstone aquifer, and irrigation supply is sourced from the shallow alluvial aquifer.

Recharge

Recharge to the shallow alluvial aquifer comes from local precipitation events (Figure 5) and the Teanaway River bordering the southern edge of the site. Situated in the orographic shadow of the Cascade Mountain crest, TVFF receives around 800 mm of precipitation per year: the 30-year normal (1991 – 2020) median precipitation is 835 $mm \cdot yr^{-1}$, and the median amount in the 5 years of this study is 749 $mm \cdot yr^{-1}$ (PRISM, 2022). Melting snowpack from the uplands north of the site provides runoff to Freds Creek and an unnamed creek at the west end of the site, which flow from January through the end of April. This runoff is conveyed through 2 culverts under Teanaway Road and reaches the site via Freds Creek and an irrigation ditch. Neither ephemeral stream reaches the Teanaway River on the surface. Ponding leakage serves to recharge the alluvial aquifer. Irrigation returns also provide recharge, but in a neutral sense because water from the onsite Upgradient Pond is pumped to provide the irrigation. The amount of recharge to the alluvial aquifer provided by the Teanaway River is indefinite for this reach. Groundwater elevations indicate that the water flows parallel to the river for much of the year suggesting that it is neither gaining nor losing. During and immediately after recharge, groundwater flows toward the river. A 2011 seepage study (Gendaszek et al., 2014) using water temperature as a tracer assessed reaches of the North Fork Teanaway River and West Fork Teanaway River upstream of the study site, and the mainstem Teanaway River downstream of the study site. The North and West Fork Teanaway River reaches were gaining and the mainstem Teanaway River

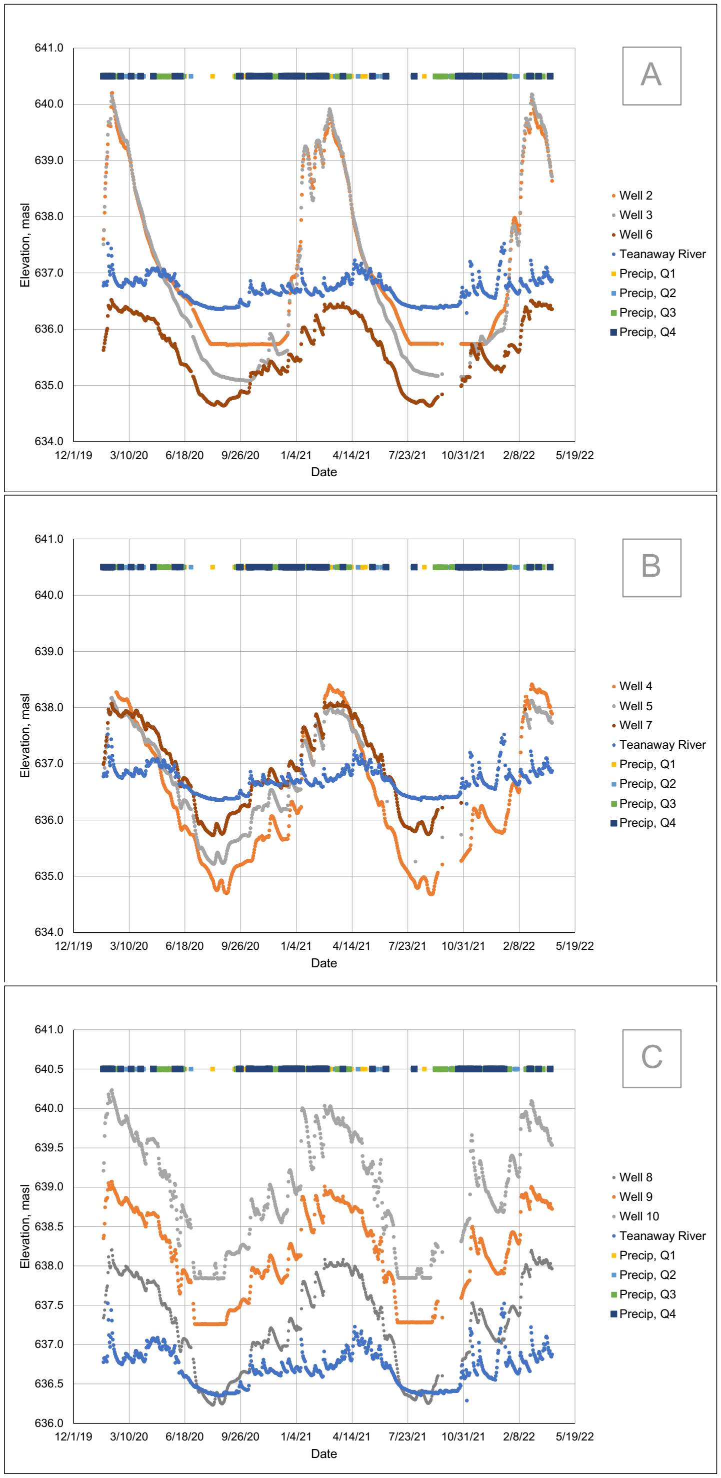


Figure 5. Precipitation, River Stage, and Observation Well Levels. (A) shows Wells 2, 3, and 6, (B) shows Wells 4, 5, and 7, and (C) shows Wells 8, 9, and 10 for the period of January 24, 2020, to April 7, 2022. Precipitation amounts were grouped by quartile according to increasing magnitude. Water levels in both the river and the wells are responsive to individual precipitation events regardless of magnitude, demonstrating the occurrence of local recharge to the shallow alluvial aquifer.

reach was neutral. Overall, the river system in the Teanaway River watershed appears to behave as a drain for groundwater discharge, not as a source of recharge for the shallow alluvial aquifer.

CHAPTER IV

FIELD METHODS

Overview of Field Measurements

Parameters in the groundwater flow model were informed by field data collected at the study site, including water level measurements, hydraulic conductivity tests, and sediment samples. Pressure transducers in wells located at the site provided continuous water level monitoring over the course of the study. Site visits were conducted every 6 weeks in which manual water level measurements were taken and the water surface elevation in the Teanaway River was observed. Groundwater samples from each well and surface water samples from the Teanaway River and ephemeral creeks were also obtained during each site visit but were not used in this study. Slug tests were performed on site at various wells to estimate in-situ hydraulic conductivity in the Cobbles and Clay subsurface layers. Porosity of the alluvial material was approximated in laboratory experiments from the sediment samples obtained at the site.

Site Description and Monitoring

The groundwater monitoring wells located in the floodplain, Wells 2 through 10 (Figure 2), were utilized for this research. The floodplain wells tap the shallow alluvial aquifer at depths ranging from 3.2 to 6.9 meters. Except for Well 2, each monitoring well terminates at the contact with the Roslyn sandstone bedrock (Figure 4). Well 2 is 6.9 m deep but does not encounter bedrock at depth. All wells were constructed of 5-cm diameter schedule 40 PVC pipe, screened in the bottom 1.5 to 3 meters depending on overall depth, packed with silica sand, and sealed with bentonite clay and a concrete monument. In addition to the wells, water level gauges to monitor stage were also installed in the Teanaway River and a nearby pond. The well and gauge locations were surveyed in July 2019.

In August 2019, the wells were instrumented with Onset pressure transducers (U20-001-04 HOBO Freshwater Water Level Data Logger) and an on-site barometer was placed in the top casing of Well 1 (Petralia, 2022). The transducers logged pressure readings at 15-minute intervals and provide a near-continuous record of water levels in the monitoring wells from August 2019 to present. The raw pressure transducer data was processed with HOBOware Pro software (Onset, 2019) to determine water level, and the program R was used to compute daily averages from the 15-minute data. Manual water level measurements were also taken at each well on a 6-week frequency from August 2019 to April 2022. Manual measurements and logged water levels were compared each time and found to be in agreement within a few centimeters. A data gap for all on-site wells exists from September 15, 2021, to October 27, 2021, when the available memory to store data on each logger was exceeded. Individual, short-term data gaps exist for Wells 4, 5, and 7 due to suspension cable repair, battery failure, and data exceeding memory storage capacity, respectively. The most complete, uninterrupted record of water level data for Wells 2 through 9 is from January 24, 2020, to April 8, 2022. End-of-month water elevations during this period were used to calibrate the groundwater flow model, with a total of 217 water-level calibration points from Wells 2 to 9 over this two-year time span.

Water surface elevations in the Teanaway River were observed during each 6-week site visit at the gauge installed in the river near the southeast corner of the site. The gauge is a simple ruler-style measure affixed to a rock in the river, having a surveyed location of 47.23628 °N, 120.83000 °W and a base elevation of 636.0 meters above sea level (masl). Observed water surface elevations were correlated with discharge information from the USDA monitoring station approximately 2 river kilometers upstream of the site (Teanaway River at Forks near Cle Elum, Station ID 12480000; 47.25 °N, 120.86 °W). River stage inputs for the groundwater flow model were determined from the rating curve based on site observations and discharge data.

Slug Tests

Slug tests were performed to approximate hydraulic conductivity in the Clay and Cobbles subsurface layers. Tests were conducted in all wells except Wells 7, 9, and 10, which were excluded because of equipment failure. Tests in Wells 2, 3, 6, and 8 were performed in April 2022 by the study author. Tests in Wells 4 and 5 were performed by 3 different GEOL 545 Hydrogeology classes at Central Washington University (CWU) in the Winter 2020, 2021, and 2022 terms. The study author was a member of the Winter 2021 class and was a guest attendee for the slug test performed by the Winter 2022 class. The only slug test presented here that the author was not present for was the slug test performed in Well 5 by the Winter 2020 class. The author obtained the data for this test from the class instructor and performed the data analysis presented in this work.

For each slug test, a temporary data logger was securely suspended into the water column in the well below the water surface, above the bottom of the well and within the screened portion of the well casing. The data logger was set to record at 1-second intervals. The static water level was measured and then a "slug" was introduced into the well. In the tests performed by the CWU classes, the slug was 2 liters of water quickly poured into the well. In the tests performed by the study author, the slug was an 0.215-liter cylinder filled with sand. In each case, a falling-head slug test was performed. Water levels were recorded for an amount of time sufficient enough for the head in the well to return to the static level. The temporal water level data was analyzed using the Hvorslev method as described in Fetter (2001), which is appropriate for the site conditions and well construction. Slug test analyses are in Appendix A, and Table 2 summarizes the hydraulic conductivities that were measured. The computed hydraulic conductivities are consistent with those given in Freeze and Cherry (1979) for unconsolidated deposits.

Table 2.
Hydraulic Conductivities from Slug Tests at TVFF

Well	Date	Hydraulic Conductivity ($m \cdot s^{-1}$)	Description	Average Hydraulic Conductivity ($m \cdot s^{-1}$)
Well 1[c]	2/26/20 6/16/21	6.28×10^{-9} 1.04×10^{-8}	Silty sand[a] Clay[b]	8.34×10^{-9}
Well 2	4/8/22	6.94×10^{-5} 7.38×10^{-5}	Silt, silty sand & gravel[a] Mostly clay; thin layer angular gravel[b]	7.16×10^{-5}
Well 3	4/8/22	6.78×10^{-4}	Silt, silty sand & gravel[a] Clay rich w/ some cobbles & pebbles[b]	6.78×10^{-4}
Well 4	2/2/21 2/22/22	9.18×10^{-5} 1.41×10^{-4}	Silt, silty sand & gravel[a] Mostly cobbles & pebbles[b]	1.16×10^{-4}
Well 5	2/27/20	1.25×10^{-4}	Silt, sand & gravel[a] Sandy soil; pebbles to small cobbles[b]	1.25×10^{-4}
Well 6	4/8/22	4.16×10^{-4}	Silty sand, sand & gravel[a] Pebbles & cobbles increasing in size with depth[b]	4.16×10^{-4}
Well 7		Not Available	Sand, gravel, cobbles[a] Cobbles; some clay[b]	
Well 8	4/8/22	4.59×10^{-4}	Cobbles, sand & gravel[a] Cobbles and pebbles[b]	4.59×10^{-4}
Well 9		Not Available	Cobbles, sand & gravel[a] Cobbles grading to pebbles below[b]	
Well 10		Not Available	Sand & gravel; river rock[a] Sand-silt soil; cobbles & pebbles below[b]	

[a]Description from well log. [b]Site observation by Central Washington University. [c]Well 1 is outside of the groundwater model domain. Hydraulic conductivity was measured at this location, but not used in this study.

Porosity Tests

Laboratory testing was performed on soil samples from the study site to determine porosity by the Winter 2021 GEOL 545 Hydrogeology class (Appendix A). Both volumetric and gravimetric methods were used. The porosity ranged from 40 – 44% ± 5% for the silty soil and 43 – 49% ± 3.5% for the clayey soil. Inputs into the groundwater flow model were generalized to 43% for the effective porosity.

CHAPTER V

WATER BALANCE ANALYTICAL MODEL

Steady-State Analysis

A steady-state water balance was developed to inform the inputs to the groundwater flow model as well as validate the model once it produced results. The water balance was calculated for each month by conservation of mass, Equation (1), through a control volume. Inflows in the water balance are the monthly volumes of precipitation, upland runoff, leakage from the Teanaway River into the surficial aquifer, and irrigation return flows. Outflows from the control volume are the monthly volumes of evapotranspiration, baseflow, and the volume of water necessary to refill the Upgradient Pond during irrigation season. The east and west boundaries of the site are not natural hydrologic no-flow boundaries, so the exchange with surficial aquifers adjacent to the site is also accounted for.

Change in Storage

The right-hand-side of Equation (1), the change in storage, ΔS, is computed monthly by

$$\Delta S = S_y A \Delta h, \tag{5}$$

where S_y is the average specific yield of the control volume (dimensionless), A is the area of the plane representing the water table (m^2), equivalent to the area of the site, and Δh (m) is the monthly change in the average elevation of the water table. This is illustrated conceptually in Figure 6. Monthly changes in storage can be positive or negative depending on hydrologic conditions, but the annual change in storage is zero under the steady-state assumption.

$$(P + U + L + I) - (ET + B + T) + N = \Delta S, \text{ where } \Delta S = S_y A \Delta h:$$

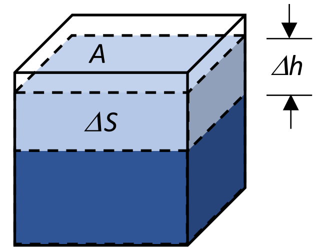


Figure 6. Conceptual Control Volume Illustrating Change in Storage. For the analytical water balance model, a control volume that is approximately the size of the entire site of the site was used. The water table is the plane with area *A*, and the monthly change in height of the water table is Δh. The monthly change in storage is the product $S_y A \Delta h$, given the average specific yield of the entire site, S_y. Inflows into the control volume are the monthly volumes of precipitation, *P*, upland runoff, *U*, leakage from the Teanaway River into the surficial aquifer, *L*, and irrigation return flows, *I*. Outflows from the control volume are the monthly volumes of evapotranspiration, *ET*, baseflow, *B*, and the volume of water necessary to refill the Upgradient Pond during irrigation season, *T*. The term *N* represents the net exchange with the surficial aquifers adjacent to the site.

Idealized Water Table: Least-Squares Plane of Best Fit

The control volume for the water balance is approximately the entire site, and the top surface of the volume is the water table. The water table is idealized as the least-squares plane of best fit through the average monthly water surface elevations in each of the wells, developed according to Equation (6):

$$\begin{bmatrix} \sum_{i=1}^{n} x_i^2 & \sum_{i=1}^{n} x_i y_i & \sum_{i=1}^{n} x_i \\ \sum_{i=1}^{n} x_i y_i & \sum_{i=1}^{n} y_i^2 & \sum_{i=1}^{n} y_i \\ \sum_{i=1}^{n} x_i & \sum_{i=1}^{n} y_i & n \end{bmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix} = \begin{bmatrix} \sum_{i=1}^{n} x_i z_i \\ \sum_{i=1}^{n} y_i z_i \\ \sum_{i=1}^{n} z_i \end{bmatrix}. \tag{6}$$

In (6), the number of wells, *n*, are discretized as points (x_i, y_i, z_i) where x_i and y_i are the UTM easting and northing coordinates of the i^{th} well, respectively, and z_i is the average monthly water surface elevation from pressure transducer measurements taken at the i^{th} well. The plane parameters a, b, and c are solved for on a monthly basis by Equation (6) to determine the equation of the best-fit plane, z = ax + by + c, which represents the water table for that month.

The extent of the best-fit plane was the research site, and its corners are given by the UTM coordinates in Table 3. The centroid of the plane was determined geometrically and the area of the plane was the area of the site, 8.88×10^5 m^2. Once the plane parameters a, b, and c for the monthly best-fit planes were obtained, the equation z = ax + by + c was used to calculate the elevation of the centroid of the water table idealized by the best-fit plane. The change in height of the water table month-to-month, Δh, follows $\Delta h = z_k - z_{k-1}$, where z_k is the elevation of the water table centroid in the present month and z_{k-1} is the elevation of the water table centroid in the prior month. Figure 7 illustrates the planes and Δh for the months of December 2020 and January 2021.

Table 3.
Universal Trans Mercator (UTM) Coordinates of the Corners and Center of Mass of the Research Site

Corner	UTM Easting	UTM Northing
SW	663153	5234456
SE	664539	5233632
NE	664943	5234048
NW	663230	5234636
Centroid	664090	5234139

Average Specific Yield

The average specific yield for the site used in the computation of ΔS by Equation (5) was determined by computing a weighted average by volume according to

$$S_y = \frac{(S_y)_s \cdot V_s + (S_y)_c \cdot V_c + (S_y)_{cl} \cdot V_{cl} + (S_y)_{ss} \cdot V_{ss}}{V_{Total}} \quad (7)$$

where $(S_y)_s$, $(S_y)_c$, $(S_y)_{cl}$, and $(S_y)_{ss}$ are the specific yields of the individual layers of Soil, Cobbles,

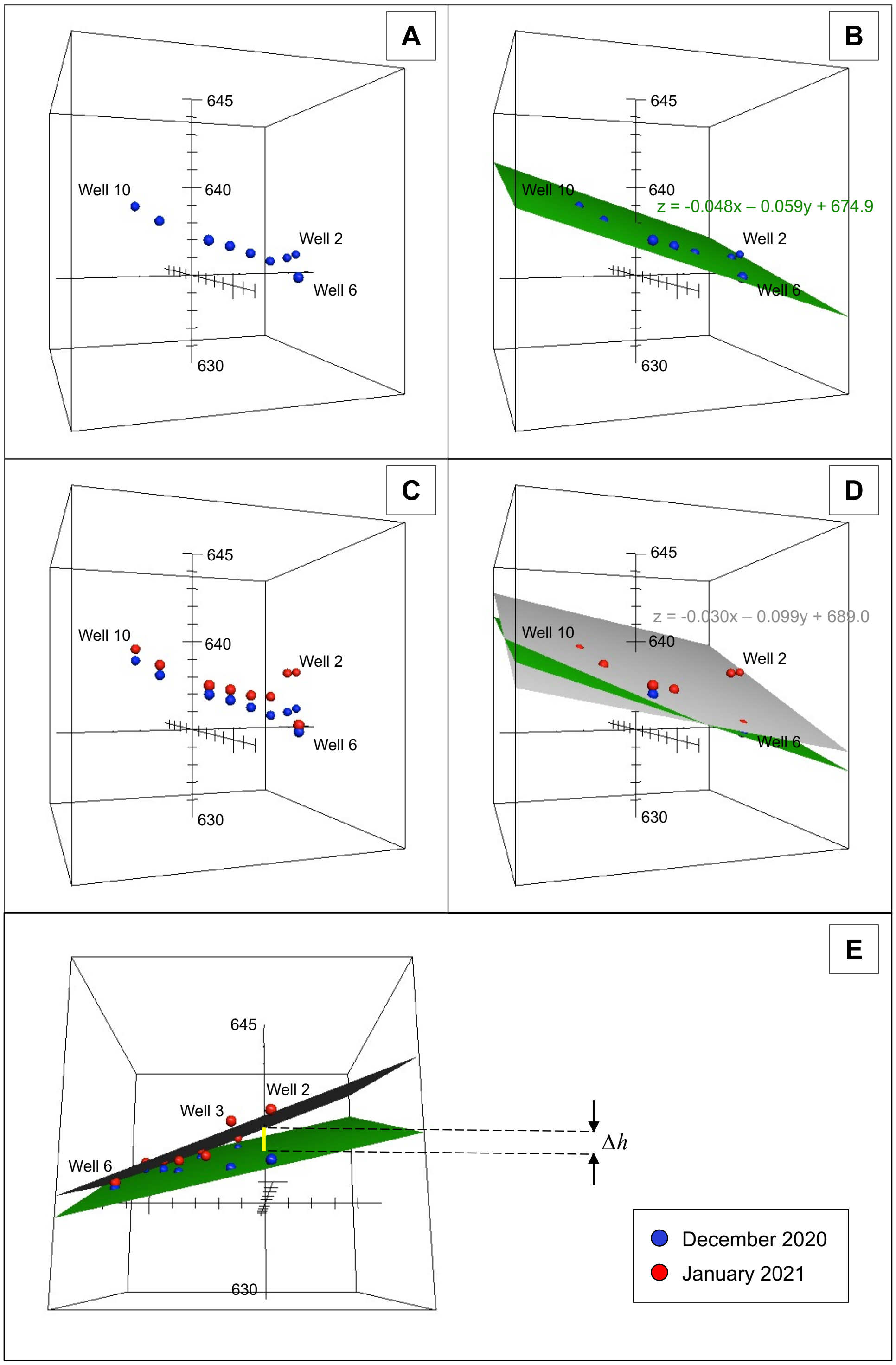


Figure 7. Graphical Illustration of the Water Table Best-Fit Plane. The concept was used to generate an idealized water table. (A) shows water table elevations in the floodplain wells in December 2020 (blue spheres). (B) shows the best-fit plane in December 2020. (C) includes water table elevations in January 2021 (red spheres). (D) adds the best-fit plane for January 2021 (the intersection of the planes occurs outside of the study area). (E) is a rotated view to show the change in height at the centroid, which is approximately the vertical axis. Elevations, in masl, are noted on the vertical axis.

Clay, and Sandstone, respectively, and V_s, V_c, V_{cl}, and V_{ss} are the volumes, respectively, of these same layers. The volumes were calculated by taking the difference in height between the corresponding nodes of the top and bottom Digital Elevation Models (DEMs) of each layer and multiplying by 100 m^2 (since each DEM has 10 m resolution). V_{Total} is the sum of V_s, V_c, V_{cl}, and V_{ss}. Table 4 records the specific yields and volumes of each layer. The values of specific yield for each unit represent final values which were updated after model calibration. By Equation (7), the values in Table 4 give an average specific yield of 0.12 for the study area.

Table 4.
Values of Specific Yield and Computed Volumes of the Different Model Layers

Layer	Specific Yield (dimensionless)	Volume m^3
Soil	0.19	898,000
Cobbles	0.23	1,680,000
Clay	0.07	1,180,000
Sandstone	0.10	9,010,000

Note: Values of S_y represent the final values, updated after model calibration.

Precipitation, Evapotranspiration, and Upgradient Pond Exchange

The water balance uses the 5-year average monthly precipitation and evapotranspiration amounts over the period from 2017 to 2022. Precipitation and evapotranspiration data are from PRISM (2022) and MODIS (Running et al., 2021), respectively. Runoff from the uplands north of the site is calculated so that the timing of the runoff mirrors the hydrograph of the Teanaway River. The amount of runoff is determined from catchment precipitation and evapotranspiration and the channel geometry of the ditches that convey the runoff to the site. Inflows from irrigation are assumed to be an average monthly amount of 80 mm applied to the area of the onsite field for the months of May through September. Leakage from the Teanaway River into the surficial alluvial aquifer is determined from streamflow data, as is baseflow.

Water from the on-site pond, the Upgradient Pond, is pumped to irrigate a nearby field. The pond refills with groundwater seepage from the shallow alluvial aquifer, so the water extracted for irrigation constitutes an outflow from the aquifer. Assuming that 80 mm of irrigation meets the needs of the crop and the irrigated area is 154,000 m^2, and if the sprinkler irrigation system is 85% efficient, then approximately 14,500 m^3 of water is extracted from the aquifer for each of the months of irrigation, May through September.

Baseflow and River Leakage

River flow data from two gauges, Teanaway River at Forks near Cle Elum (12480000), upstream of the site, and Teanaway River Red Bridge (39D110), downstream of the site, were analyzed to determine the timing of baseflow and quantify the amount. Baseflow exiting the aquifers of the lower Teanaway River valley into the Teanaway River was computed from baseflow recession curves for the hydrographs at the two locations. The hydrographs are shown in Figure 8. They indicate that baseflow recession begins approximately June 1 each year and ends at the end of September.

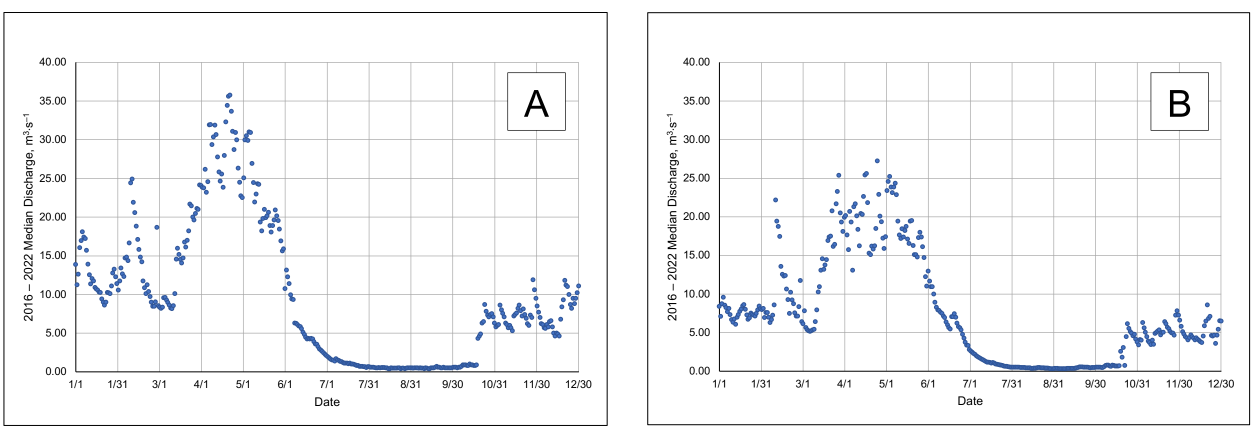


Figure 8. Teanaway River Hydrographs. The hydrographs display the Teanaway River median discharge, in m^3·s^{-1}, for the period of 2016 – 2022. The Forks gauge (A) is approximately 9.58 km upstream of the Red Bridge gauge (B). Baseflow occurs from June 1 though September 30 each year.

Baseflow recession curves of the form $Q = Q_0 e^{-\alpha t}$ are found by regression analysis for the period of June 1 to September 30 for each hydrograph (Figure 9). Here, Q_0 is the initial discharge in $m^3 \cdot s^{-1}$, α is the decay rate, t is the time since baseflow recession begins, in days, and Q is the discharge at time t. The upstream Forks gauge has a smaller contributing catchment area and a recession curve given by $Q = 5.65e^{-0.029t}$. The downstream Red Bridge gauge encompasses the entire Teanaway River drainage and includes the catchment area contributing to the Forks gauge. Its baseflow recession curve is $Q = 7.77e^{-0.035t}$. For each catchment, the volume of water released from storage, V_B, in m^3, can be obtained by integrating the baseflow recession curve, Q, over the timeframe of baseflow recession (Hall, 1968). With conceptual limits of integration, this is

$$V_B = \int_{\text{June 1}}^{\text{September 30}} Q\, dt. \tag{8}$$

The difference between the evaluated integrals for each gauge yields the volume of baseflow downstream of the Forks gauge. The Forks gauge is approximately 9580 m upstream of the Red

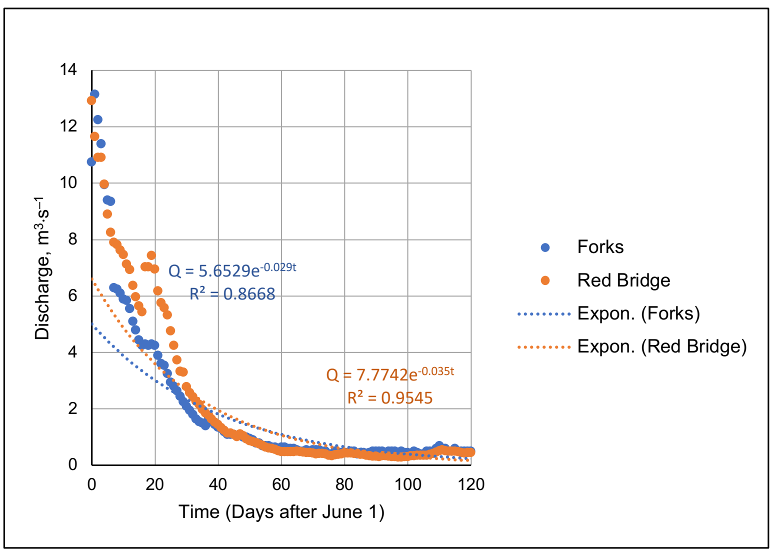


Figure 9. Teanaway River Baseflow Recession Hydrograph. Portions of the hydrographs give the Teanaway River discharge, in $m^3 \cdot s^{-1}$, during baseflow recession from June 1 though September 30 each year. Regression equations and their best-fit lines display the baseflow recession curves for the upstream Forks gauge and the downstream Red Bridge gauge.

Bridge gauge, and the length of the reach along the perimeter of TVFF is 1800 m. The volume of baseflow for TVFF was assumed to be proportional to the baseflow for the area downstream of the Forks gauge with the constant of proportionality being the ratio of the length of the TVFF reach to the distance between the gauges. The resultant volume over the 121-day period from June 1 to September 30 was divided into monthly amounts for the water balance.

The Teanaway River was assumed to recharge the shallow alluvial aquifer during the months of October through May when the hydrograph exhibited the variability indicative of non-baseflow conditions. Similar to baseflow, river leakage into the aquifer was estimated from the gauged streamflow data, detailed in Equation (9). The difference in discharge between the upstream Forks gauge and the downstream Red Bridge was found. This difference was multiplied by the same constant of proportionality used for baseflow: the ratio of the length of the TVFF reach to the distance between the gauges.

$$\text{Daily River Leakage, } L = C\frac{1.80\text{ km}}{9.58\text{ km}}\left(Q_{\text{Forks}} - Q_{\text{Rd Bg}}\right) \times 86400\text{ s}\cdot\text{d}^{-1} \tag{9}$$

C is an empirical adjustment factor for the percentage of water that actually recharges the shallow alluvial aquifer. For C = 3.46%, the yearly volumes of baseflow and leakage are equivalent. In the water balance, C = 2.5% was assumed because it replicated conditions where the total volume of baseflow for the year slightly exceeds the total volume of yearly recharge from the river.

Net Boundary Exchange

The final term of the water balance is the net exchange of water occurring in the shallow alluvial aquifer at the eastern and western extents of the site. These limits are not natural hydrologic boundaries, and it can be assumed that groundwater flows into the site at the upstream (west) end and that flow exits the site at the downstream (east) end. The net exchange was computed monthly by rearranging the equation in Figure 6.

$$N = \Delta S - (P + U + L + I) + (ET + B + T) \tag{10}$$

The total yearly net exchange follows the assumption that for steady-state conditions, the amount of storage in the alluvial aquifer is zero. Thus, net exchange for the site is an outflow in the water balance, as more groundwater exits though the eastern downstream boundary than enters through the upstream western boundary.

Tabulated volumetric amounts for the TVFF annual water balance, in thousands of m^3, are shown in Table 5. Table 6 presents the inflows and outflows of the water balance in millimeters over the TVFF site.

Table 5.
Volumetric Amounts for the Annual Steady-State Water Balance

	Inflows (1000 m^3)				Outflows (1000 m^3)					
	Precipitation	Upland Contribution	River Leakage	Irrigation	ET	Baseflow	Pond Refill	Net Exchange	Avg Water Table Elevation (masl)	Change In Storage (1000 m^3)
January	120.6	61.5	58.6		12.9			75	641.3	152
February	91.8	61.5	45.3		18.7			135	641.7	45
March	46.9	61.5	18.5		25.6			127	641.5	-26
April	38.7	120.4	111		27.1			306	640.9	-63
May	29.9		44.9	12.3	57.8		14.5	83	640.2	-68
June	18.1			12.3	71.9	120	14.5	-121	639.7	-55
July	2.30			12.3	68.3	124	14.5	-75	638.6	-117
August	5.39			12.3	52.8	124	14.5	-164.6	638.5	-8.9
September	25.0			12.3	32.8	120	14.5	-189	639.1	59
October	82.9		15.0		15.0			65.5	639.2	17
November	90.8		27.3		12.9			55	639.7	50
December	111.7		32.3		10.09			119.0	639.8	15.0
TOTALS	664	304.9	353	61.6	406	488	72	417	ΔS =	0

Table 6.
Yearly Steady-State Inflows and Outflows from the Site

Inflows	Amount ($mm \cdot m^{-2} \cdot yr^{-1}$)	Data Source
Precipitation	748	PRISM (2022)
Upland Runoff	343	Percentage of Net Precipitation × Catchment Area
River Recharge (Leakage)	397	Calculated from Teanaway River Gauge discharge data
Irrigation Return Flow	69.3*	Informed by Efetha et al. (2009) and Vaccaro and Olsen (2007)
Total Inflows = 1558		
Outflows		
Evapotranspiration	457	MODIS (Running et al., 2021)
Baseflow	549	Calculated from Teanaway River Gauge discharge data
Upgradient Pond Refill	82	Irrigation ÷ 85% efficiency
Net Boundary Exchange	470	Calculated assuming zero change in storage, $\Delta S = 0$
Total Outflows = 1558		

*The amount shown is the average depth over the entire area of the site (the model domain) over the span of 1 year. 400 $mm \cdot m^{-2} \cdot yr^{-1}$ is the amount assumed over the irrigated field only.

CHAPTER VI

GROUNDWATER FLOW MODEL FRAMEWORK AND CALIBRATION

TVFF Groundwater Flow Model

A transient groundwater flow model was constructed by representing the physical characteristics of the TVFF site mathematically, choosing a temporal scale, and applying boundary conditions to control inputs and outputs of water to the system. The time frame for this model is 5 years and 1 month, commencing on March 1, 2017, and ending on March 31, 2022. Complete records of monthly inputs for precipitation and river stage were available for the entire 5 years, and evaporation records were available for years 2017 to 2021. Water level observations in the on-site wells overlap the last 2 years of this period.

The numerical code used for the model was MODFLOW-2005, with MODFLOW-NWT as the solver, both freely available from the USGS. Visual MODFLOW Flex 7.0 from Waterloo Hydrogeologic (2021) was employed as the graphical user interface (GUI).

Model Domain and Finite Difference Grid

The model domain is comprised of the floodplain between the Teanaway Road and the Teanaway River, extending northwest to southeast from private property to the WDFW property boundary at the ephemeral creek known as Johns Creek (Figure 2). For the numerical representation of the physical location, the area is discretized horizontally into 10-meter by 10-meter cells, resulting in a 182 × 91 grid (Figure 10).

Surface topography for the model is constructed from a 1/3 arc-second digital elevation model (DEM) data from the USGS National Map 3D Elevation Program, 3DEP (USGS, 2017) and provides approximately 10-meter spatial resolution. Subsurface horizons are established by subtracting a prescribed depth from the surface elevation. This depth varies across the site and is

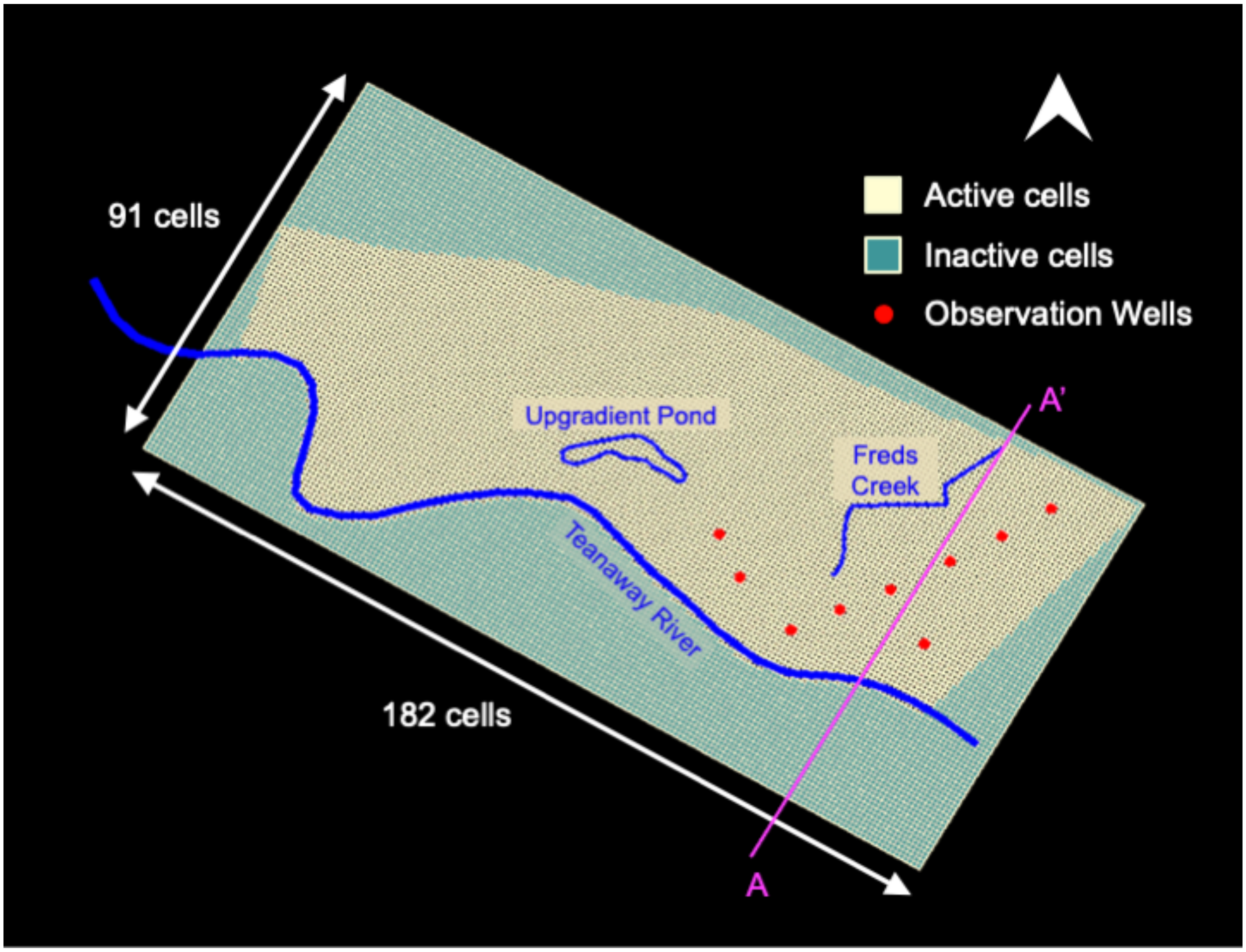


Figure 10. Horizontal Grid for the Model Domain. The horizontal discretization of the model domain is 182 × 91 cells, and each cell is 10 meters by 10 meters. Cells within the model domain are active; cells outside of the model domain are inactive. The vertical discretization of the model is shown in Figure 11 for the cross-section A-A', which corresponds to Row 150.

informed by well logs from wells on and adjacent to the site and by the USDA NRCS Web Soil Survey (NRCS, 2022). Three subsurface horizons divide the model domain into 4 vertical layers according to lithology (Figure 4). As mentioned previously, these layers are informally referred to by the names "Soil," "Cobbles," "Clay," and "Sandstone." The Cobbles and Clay layers are each further subdivided into 2 layers, and the sandstone is subdivided into 5 layers, for an overall vertical discretization of 10 total layers of varying depth. Refinement of the vertical discretization is employed to accommodate the bed elevations of the surface water features more

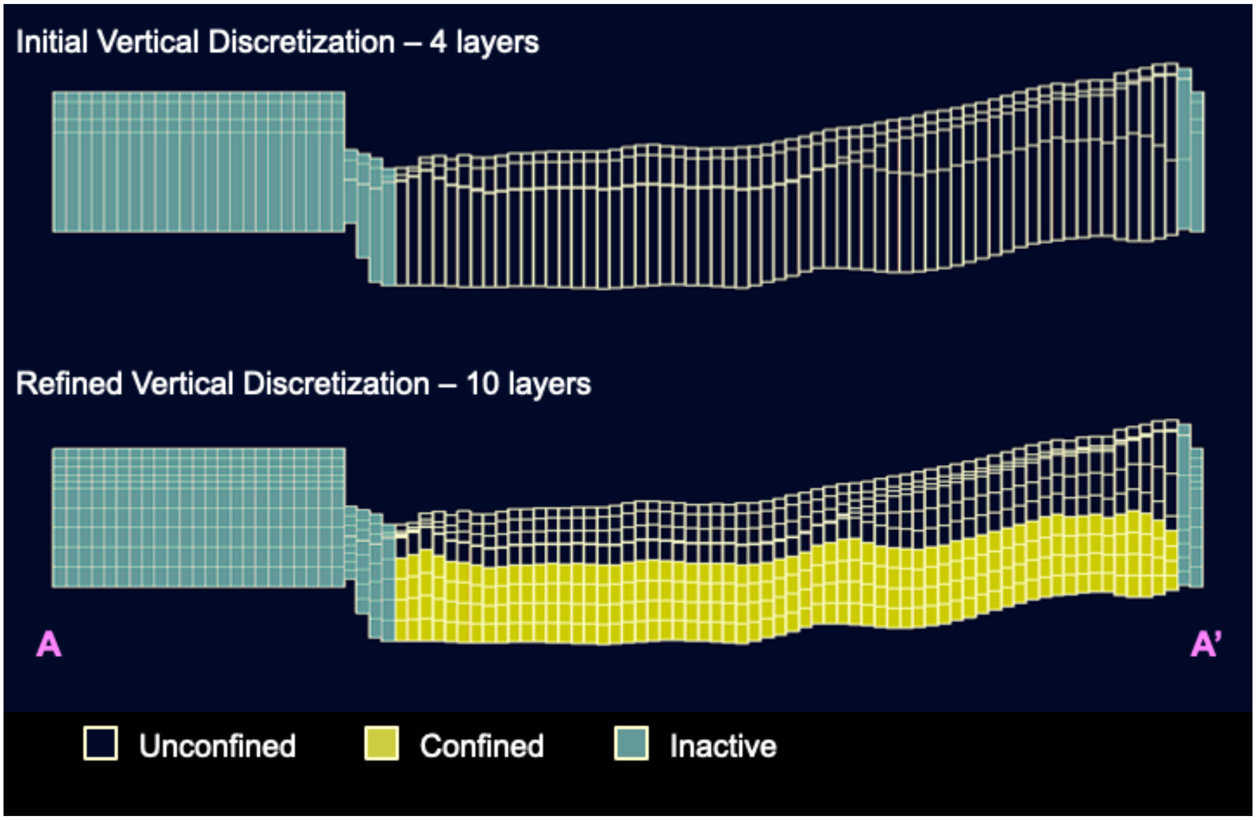


Figure 11. Representative Cross-Section for the Vertical Discretization of the Model Grid. Cross-section A-A’ is at Row 150 in the model. The initial vertical discretization corresponds to the 4 stratigraphic units: Soil, Cobbles, Clay, and Sandstone (Figure 4). The refined vertical discretization divides the Cobbles and Clay units into 2 layers and the Sandstone unit into 5 layers. The upper 6 layers are unconfined, and the bottom 4 layers of Sandstone are confined.

accurately, i.e., the Teanaway River and the Upgradient Pond. The vertical model grid is shown in Figure 11. The horizontal datum for the model is the North American Datum of 1983 (NAD 83). Elevations, in meters, reference the North American Vertical Datum of 1988 (NAVD88). The coordinate reference system is Universal Trans Mercator (UTM) Zone 10 North.

Initial Conditions

The start date of the model (March 1) and initial heads for the transient simulation were selected based on the transducer observations of water level data. For the period of observed record, it was noted that the average maximum water level in the wells occurred around February 24, and the average maximum water surface elevation was approximately 0.74 meters below ground surface if Well 2 is disregarded (0.98 m if Well 2 is included). For the date of March 1, the average water surface elevation was 0.90 m below ground surface without Well 2 and 1.16 m with Well 2 included. MODFLOW requires that cells do not begin dry, so the initial heads must be within the top model layer. In this case the top layer of the model is the soil layer, which has a 1 m depth, therefore initial heads of 0.75 m below ground surface were used.

Flow and Storage Parameters

Hydraulic Conductivity

Hydraulic conductivity inputs for the Cobbles and Clay units in the groundwater flow model were obtained from slug tests performed in 7 of the site observation wells. For the Cobbles layers, the first approximation of hydraulic conductivity is the average hydraulic conductivity from slug tests in Wells 4, 5, 6, and 8. For the Clay layers, the average hydraulic conductivity from the Well 2 slug tests is used. The hydraulic conductivity determined by the slug test for Well 3 was not used in the initial groundwater model run because the test did not have enough reliable data points and the resulting hydraulic conductivity appeared high for the Clay unit. In the initial model run, horizontal and vertical hydraulic conductivity were taken to be equivalent and no anisotropy was assumed ($K_x = K_y = K_z$). Subsequent model runs adopt a modeling rule of thumb that the vertical hydraulic conductivity is an order of magnitude less than the horizontal hydraulic conductivity: $K_z = 0.1K_x$.

Hydraulic conductivity was not measured for the Soil or Sandstone units, instead, values from literature were used. For the Soil unit, NRCS (2022) lists values of saturated hydraulic conductivity, K_{sat}, for Patnish and Mippon soils in the range of 4.02×10^{-6} to 1.40×10^{-5} $m \cdot s^{-1}$, and 1.41×10^{-6} to 4.02×10^{-6} $m \cdot s^{-1}$ for Myzel soils. An intermediate value of 1×10^{-5} $m \cdot s^{-1}$ was selected for the initial trial of the groundwater flow model. From bailer test information contained in the well log, Gendaszek et al. (2014) found the horizontal hydraulic conductivity in a well open to the upper Roslyn sandstone to be 5.64×10^{-6} m·s^{-1}. This value was used here to approximate the hydraulic conductivity of the Sandstone in the initial run of the groundwater model.

Specific Yield

The specific yield, S_y, of a porous medium is the ratio of the volume of water that would drain by gravity from the medium to its total volume. In the context of an unconfined aquifer, specific yield is the amount of water released from storage per unit surface area of aquifer for a unit decline in the water table. Assessment of the volume of storage in an unconfined aquifer depends on specific yield. To determine starting parameters for the groundwater flow model in this study, values of specific yield were obtained from a review of literature.

For the Soil unit, NRCS (2022) gives broad ranges of available water supply for the different constituents of the unit: Patnish, Mippon, and Myzel soils. Patnish soils have a low available water supply at approximately 130 mm in 0 to 1.5 m, Mippon very low at 50 mm in 0 to 1.5 m, and Myzel high at 300 mm in 0 to 1.5 m. Lv et al. (2021) compile several groundwater modeling studies and the values of specific yield used in those studies. In their review, S_y for sandy clay loam ranged from 0.05 to 0.29 for various methods. Given this wide range and uncertainty, an upper-midrange value of 0.20 was used as an initial value in the groundwater flow model for the Soil unit. The same value of 0.20 was also used as an initial approximation for the Cobbles unit.

Johnson (1967) gives values of S_y in the range of 0 – 0.05 for clay, 0.08 – 0.19 for silt, and 0.03 – 0.12 for sandy clay. Because the Clay unit shares all of these constituents, a value of 0.10 was selected as an initial value for the groundwater flow model.

Lastly, the S_y for the Sandstone comes from Woodard et al. (2002). They studied the aquifer system in the Denver Basin in Colorado. In their study, the Dawson formation is similar to the Roslyn formation in that it is Eocene, fluvially deposited, arkosic sandstone. For the Dawson, the specific yield was found to vary with depth. In the topmost 10 meters, it was approximately 0.10. That value is used here as an initial approximation in the groundwater flow model.

Specific Storage

Specific storage is applicable for storage in a confined aquifer and is the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head (Freeze and Cherry, 1979). Two comprehensive reviews were consulted to find suitable values of specific storage for the groundwater flow model, Chowdhury et al. (2022) and Kuang et al. (2020). They are compared side-by-side in Table 7. Values from Chowdhury et al. (2022) were ultimately used here because their material descriptions more closely matched those at the study site. In the model, the Sandstone unit is the only confined unit, and so its specific storage is the only parameter used in the model's calculations; the other parameters are required inputs, however.

Table 7.
Comparison of Values of Specific Storage

Hydrogeologic Unit	Value of Specific Storage, S_s, for a given aquifer material (m^{-1})	
	Chowdhury et al. (2022)	Kuang et al. (2020)
Soil	1.0×10^{-4}	1.76×10^{-4}
Cobbles	1.0×10^{-4}	4.20×10^{-5}
Clay	4.3×10^{-5}	1.92×10^{-5}
Sandstone	2.6×10^{-6}	2.08×10^{-6}

Porosity

The porosities of the Soil, Cobbles, and Clay units were determined in the laboratory by the gravimetric and volumetric methods and ranged from 40 – 44% ± 5% for the silty soil samples and 43 – 49% ± 3.5% for clayey soil samples from TVFF (Appendix A). Inputs into the groundwater flow model were generalized to 43% for the effective porosity of the 3 upper units.

The porosity of the Sandstone unit was determined using an equation described in Scherer (1987), who showed the porosity, n_{ss}, of sandstone is dependent upon depth, age, sorting, and quartz content according to the following empirical relationship:

$$n_{ss} = 18.60 + (4.73 \times \ln(quartz)) + (17.37 \div sorting) - (3.8 \times depth \times 10^{-3}) - (4.65 \times \ln(age)),$$

where n_{ss} is in percent, *quartz* is the percent of solid-rock volume, *depth* is in meters, *age* is in million years, and *sorting* is the Trask sorting coefficient. Inputs for the equation are available in literature. Bressler (1951) provides the average composition of the Roslyn sandstone from examination of thin sections, where he details that the detritus is 29% quartz. His description of the middle Roslyn unit is that it is "fairly well-sorted medium grained detritus." The age of the Roslyn is constrained between 48.8 Ma for the lower member and 47.6 Ma for the upper member (Eddy et al., 2016). These characteristics, together with a depth of roughly 7 m, give a porosity of 26% to 30%.

The initial parameters of hydraulic conductivity, specific yield, specific storage, and porosity used in the groundwater flow model are summarized in Table 8.

Boundary Conditions

Six distinct boundary conditions are assigned in the model (Figure 12). They are the river (RIV), recharge (RCH), streamflow-routing (SFR2), evapotranspiration (EVT), general head (GHB), and no-flow boundary conditions. By default in Visual MODFLOW Flex 7.0, a no-flow boundary condition is assigned to model cells along the perimeter of the model domain when no other boundary condition is assigned at that location. For this model, no-flow boundary conditions are applied at the bottom of the sandstone unit and along a portion of Teanaway Road.

Table 8.
Initial Flow and Storage Parameters Used in the Groundwater Flow Model

Model Zone	Well Number	Measured K ($m \cdot s^{-1}$)	Initial Model $K_x = K_z$ ($m \cdot s^{-1}$)	Specific Yield	Specific Storage	Porosity
1 – Soil		1.4×10^{-5} to 4×10^{-6}	1×10^{-5}	0.20	1×10^{-4}	0.43
2 – Cobbles	4	1.16×10^{-4}	3×10^{-4}	0.20	1×10^{-4}	0.43
	5	1.25×10^{-4}				
	6	4.16×10^{-4}				
	8	4.59×10^{-4}				
3 – Clay	2	7.16×10^{-5}	7×10^{-5}	0.10	4.3×10^{-5}	0.43
4 – Sandstone		5.64×10^{-6}	6×10^{-6}	0.10	2.6×10^{-6}	0.26

The no-flow boundary condition along the road is justified because the road acts as a barrier to surface water flow and precipitation recharge, and the direction of the surficial aquifer groundwater flow in this location generally follows the gradient of the surface topography, which is parallel to this boundary.

River Boundary Condition

The Teanaway River flows from northwest to southeast along the south perimeter of the model domain. The river is incised through the Soil and Cobbles layers and has primarily a bedrock channel of the Roslyn sandstone (Schanz et al., 2019). MODFLOW's river boundary condition (RIV) is used to model the Teanaway River. In the RIV boundary condition, groundwater flux moves only through the river bottom; no flow takes place through the sides of the channel (Figure 13). This ideally represents the characteristics of water movement in the Teanaway River at TVFF through the incised bedrock channel and not through the banks of the river.

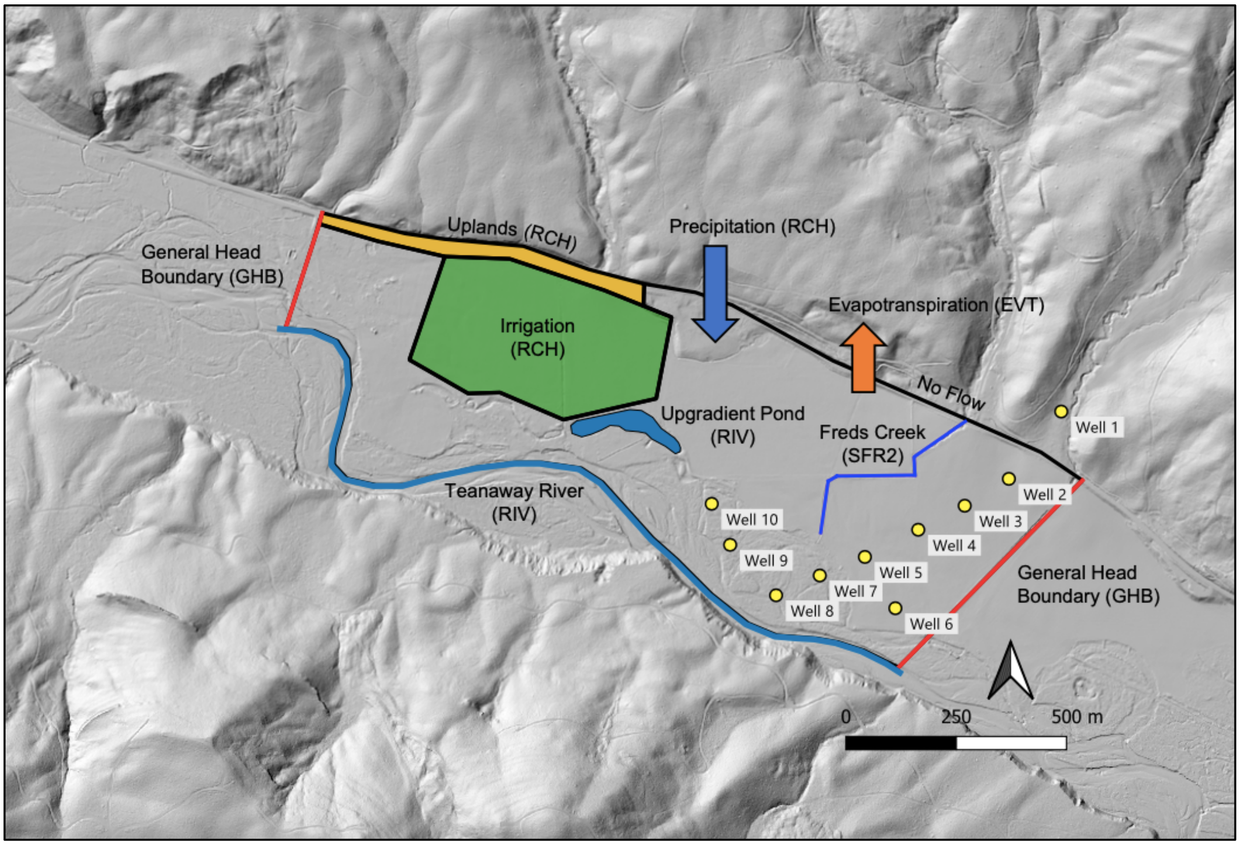


Figure 12. Model Domain and Boundary Conditions. Teanaway Road on the north side of the model domain is a no-flow boundary. General head (GHB) boundary conditions are on the east and west ends of the model domain, and the Teanaway River is a river (RIV) boundary condition on the south perimeter. The Upgradient Pond is also represented by a RIV boundary condition. Recharge (RCH) boundary conditions include the uplands, irrigation, and precipitation, which covers the entire model domain. The evapotranspiration (EVT) boundary condition likewise blankets the model domain. Freds Creek is represented by the streamflow-routing (SFR2) boundary condition.

The required parameters for the RIV boundary condition are the hydraulic conductivity of the clogging layer, K_{riv} ($L \cdot T^{-1}$), the thickness of the clogging layer, d_{riv} (L), the riverbed elevation, B_{riv} (L), the channel width, W (L), and the river stage, H_{riv} (L). Length, L (L), is also an input parameter, and is the calculated length of a reach of river; it is the distance between designated nodes at the start and end points of a reach. For the Teanaway River adjacent to the model domain, the width is fairly uniform and is approximately 30 meters. The thickness of the clogging layer is also estimated to be uniform and is taken to be 0.1 meters. Since the clogging

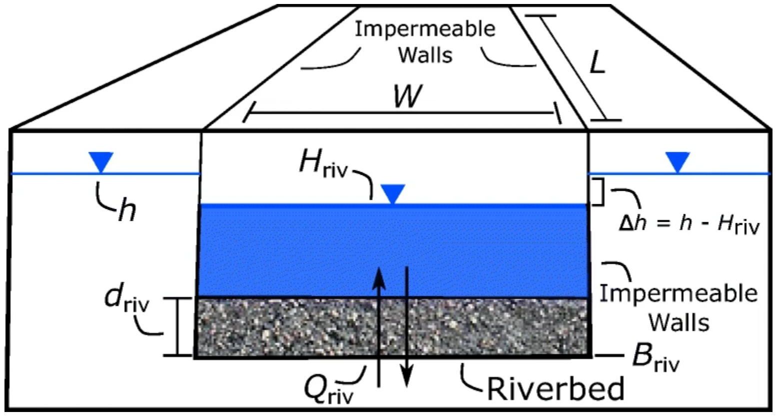


Figure 13. Schematic Diagram of the RIV Boundary Condition. River-aquifer exchange is vertical through the riverbed. Here, Q_{riv} is the flux that is calculated through the bed, B_{riv} is the bed elevation, d_{riv} is the riverbed thickness, also known as the clogging layer, H_{riv} is the stage of the river, W is the width of the river and L is the length (from Ghysels et al., 2019, after McDonald and Harbaugh, 1988). The RIV boundary condition is a head-dependent flux boundary condition.

layer is assumed to be the Cobbles layer immediately above the sandstone of the bedrock channel, the hydraulic conductivity of the Cobbles layer, 3×10^{-4} m·s^{-1}, is used as a first approximation for the riverbed conductivity. The riverbed elevation is extracted from the DEM of the top surface of the sandstone layer at 30 nodes along the length of the reach and is linearly interpolated between nodes. Refinement of the vertical discretization of the sandstone layer into 5 model layers and not one single layer contributed to greater accuracy in representing the actual elevation of the river bottom in the model.

The stage of the river is determined from a rating curve established from field observations of the TVFF Teanaway River gauge located in the river near the southeast corner of the site (47.23628 °N, 120.83000 °W) and discharge information from the Teanaway River at Forks near Cle Elum gage upstream of the site (Station ID 12480000; 47.25 °N, 120.86 °W). The rating curve is applied to discharge data for the period of the model, March 2017 through March 2022, and interpolated upstream from the point of observation as a constant height above the bed

Date	Gage Height h (cm)	Discharge Q ($m^3 \cdot s^{-1}$)
3/18/21	40	13.6
5/4/21	100	32.3
8/6/21	15	0.5
9/23/21	10	0.5
10/27/21	25	4.6
2/19/22	40	14.3
4/8/22	50	21

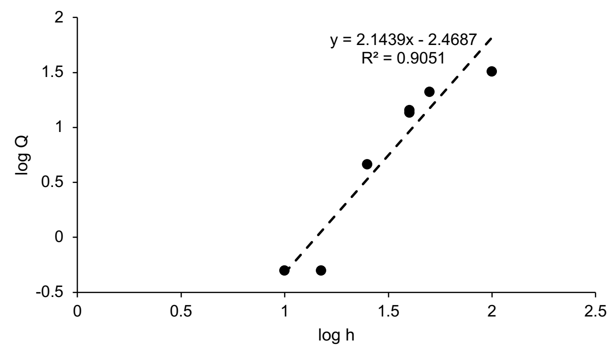


Figure 14. Rating Curve for the Streamflow Gauge at TVFF. The rating curve defines the relationship between stage observations at the gauge installed in the Teanaway River at the southeast corner of the TVFF site and discharge information from the Teanaway River at Forks near Cle Elum gage (Station ID 12480000), approximately 2 river kilometers upstream of the observation point. From the linear relationship in the log-log plot, the regression equation is: $\log Q = 2.14 \cdot \log h - 2.47$. Converting to exponential form, we obtain discharge in $m^3 \cdot s^{-1}$, $Q = (3.40 \times 10^{-3}) \cdot h^{2.14}$. This equation can be solved for the height, h, in cm, for a given discharge Q. The river stage along the perimeter of TVFF is then approximated as the bed elevation from the DEM plus the height, h.

of the river. The median monthly stage height is input at each of the 30 nodes of the RIV boundary condition (Appendix B).

The RIV boundary condition is also used for the Upgradient Pond. The bed elevation is constant at 639.63 meters above sea level (masl), and the width is computed from the polygonal geometry designated as the pond area. The stage varies seasonally depending on whether irrigation is occurring in the adjacent field or not. During months when no irrigation is being applied (January through April and October through December), the stage is "full" at a constant elevation of 641.3 masl. At times when irrigation occurs (May through September), the stage is lowered to 639.7 masl. The lower stage is computed by subtracting the approximate volume of water from the pond that is applied as irrigation water to the nearby field and accounting for the efficiency of the irrigation system. Like the Teanaway River, the clogging layer for the

Upgradient Pond is assumed to be the Cobbles model layer, and the same thickness and hydraulic conductivity of 0.1 m and 3×10^{-4} m·d^{-1}, respectively, are used.

Recharge Boundary Condition

The recharge boundary condition (RCH) is used to apply precipitation and irrigation fluxes to the uppermost active layer of the model domain. Precipitation amounts are obtained from the PRISM Climate Group of Oregon State University (PRISM 2022). Irrigation amounts are informed by the amount of water typically applied to Timothy hay in a semi-arid climate (Efetha et al., 2009) and the USGS Precipitation-Runoff Modeling System (PRMS) and the Deep Percolation Model (DPM) models of Vaccaro and Olsen (2007). Vaccaro and Olsen (2007) estimated 381 mm of annual irrigation recharge in the region containing the TVFF site. In the model here, 400 mm of annual recharge, or 80 mm per month for the months of May through September, is used. The depth of 80 mm (per month), when considered over the area of the irrigated field and accounting for the efficiency of the irrigation system, is volumetrically equivalent to the amount of water by which the stage of the Upgradient Pond is lowered during each month of irrigation.

Two catchments in the uplands adjacent to TVFF contribute recharge via runoff to the model domain: the Freds Creek catchment and an unnamed creek catchment (Figure 15). The RCH boundary condition is utilized to simulate recharge from seasonal overland flow from the unnamed creek catchment, and the streamflow-routing package (SFR2) is used to simulate the contribution from the Freds Creek catchment.

In the area west of the unnamed creek, overland flow proceeds to the Teanaway River upstream of the model domain, thus recharge from this catchment area is considered with the river. Similarly, overland flow in the catchment east of the Freds Creek catchment is considered

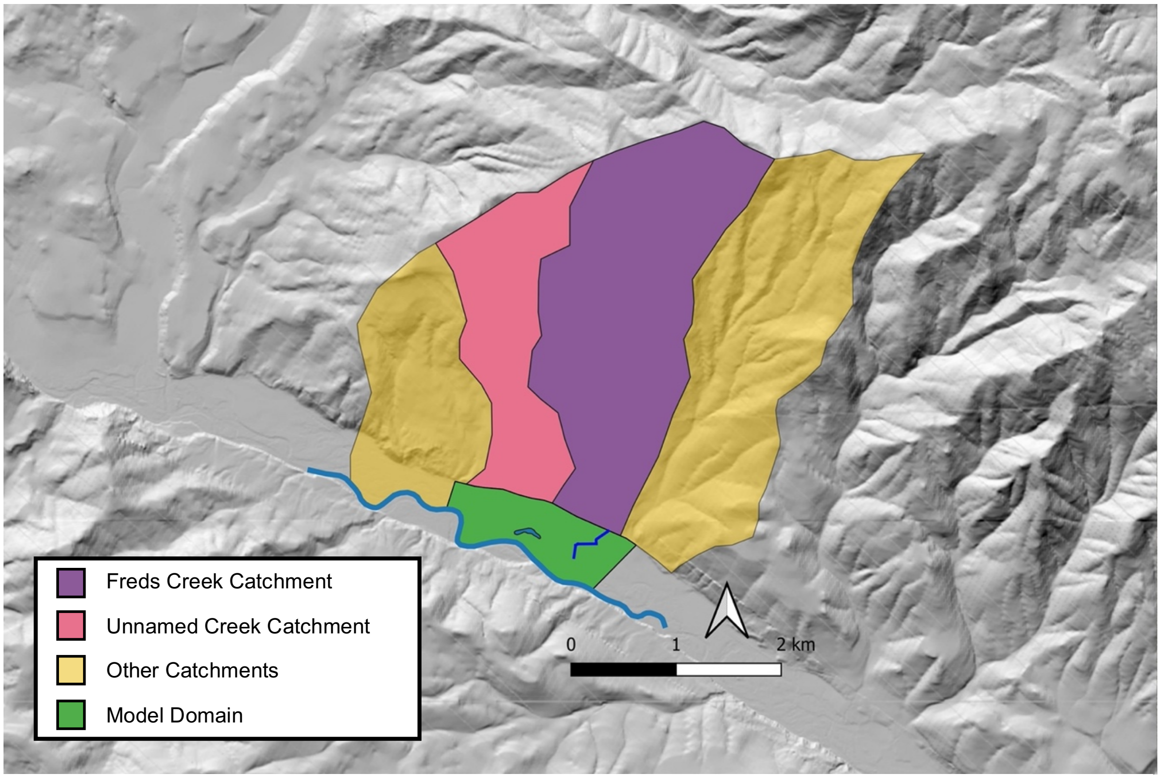


Figure 15. Catchments Contributing Runoff to the Model Domain. Runoff to the model domain originates in the Freds Creek catchment and the unnamed creek catchment, shown here. Runoff from the upstream (west) catchment is delivered to the Teanaway River upstream of the model domain. Runoff from the downstream (east) catchment flows into Johns Creek, which delineates the eastern boundary of the model domain. Flow in Freds Creek, the unnamed creek, and Johns Creek passes under Teanaway Road via culverts, otherwise it continues downstream in the ditch on the north side of the road.

elsewhere. This flow is captured by Johns Creek, the eastern boundary of the model domain. Johns Creek mainly influences groundwater downstream of the model domain; its influence on the model domain itself is captured by the general head boundary condition (detailed below) imposed on the east side of the model.

The recharge contribution from upland catchment areas to the model domain has 2 key components: the volumetric amount of recharge and the timing at which it is delivered. The volume of recharge is net precipitation times the catchment area, where net precipitation is the amount of precipitation that falls in the form of rain or snow less evapotranspiration losses. From the months of October through March, net precipitation is positive, but from April through September, net precipitation, on average, is negative, i.e., evaporative losses exceed amounts of precipitation (PRISM, 2022 and Running et al., 2021). Precipitation generally falls as snow from November to January and is stored as snowpack. In January, snowmelt begins and rain-on-snow events in late January and early February contribute to increases in snowmelt.

Upland recharge is delivered to the model domain via ephemeral creeks that have been observed to flow from January through April. The recharge delivered in January and into February, March, and April includes net precipitation that fell as snow in prior months. To account for this offset in timing, the total volume of net precipitation in the catchment was summed over the months of November through March, and then 20% of this sum was assumed to be delivered to the model domain in each of the months of January through March, and 40% of this sum was assumed to be delivered in April. The percentages are derived from the proportion of the volume of flow in the Teanaway River from January through April (Table 9), since tributaries in the basin are controlling the runoff in the river during this time as well as recharge to groundwater. Note that the volume of net precipitation from October is excluded from the total upland recharge calculation. This is because even though net precipitation is positive for the month of October, no runoff is observed in the on-site creeks at this time. It is assumed that October net precipitation restores soil moisture through infiltration.

After applying the monthly timing percentages to the total volume of upland recharge, an additional volume adjustment based on channel geometry is performed so that the applied amount of recharge is realistic for the size of the channel conveying it. At capacity in April, Freds Creek can convey 2.25% of the 40% of the total volume of net precipitation from its catchment area. The ditch on the northwest border of the site was assumed to be similar, holding 2.25% of

Table 9.
Average Volumetric Discharge at the Teanaway R bl Forks nr Cle Elum Gage (Station ID 12480000) for Years 2017 through 2021 During January through April

Month	Average Volumetric Discharge, 2017 – 2021 (dam^3)	Average Monthly Percentage of Runoff for January through April	Modeled Monthly Percentage of Upland Recharge
January	33051	16.4%	20%
February	45479	22.6%	20%
March	40984	20.4%	20%
April	81773	40.6%	40%
Total from January through April	201288	100%	100%

the 40% of the total volume of net of precipitation from the unnamed creek catchment. For simplicity, these capacity percentages were assumed to be applicable in January, February, and March also. The computed amount for the unnamed creek catchment is applied to the model as a recharge flux ($mm \cdot yr^{-1}$) in the RCH boundary condition, and the computed amount for the Freds Creek catchment is applied as depth of flow (m) in the SFR2 boundary condition, detailed next.

Streamflow-Routing Boundary Condition

Freds Creek is an ephemeral stream that originates in the uplands to the north of the model domain. It reaches the model domain via a culvert under Teanaway Road, and its path across the floodplain is anthropogenically modified into a series of straight segments along property lines to convey water between irrigated (and formerly irrigated) fields. The creek does not have a definitive outlet into the Teanaway River. It terminates with shallow ponding near the river in the cobbly alluvium that has never been plowed for farming.

Because of its nature as an ephemeral stream and because different model scenarios required changing this feature, Freds Creek is modeled with the SFR2 boundary condition. Other boundary conditions were considered, including the RIV and RCH conditions. The RIV boundary condition in MODFLOW requires that the elevation of the river stage cannot be less than or equal to the elevation of the riverbed. The result is a perpetual source of water with a head equivalent to at least the elevation of the riverbed, and so the RIV package is not appropriate for simulating a stream that goes dry. The RCH boundary condition was also attempted, with the volumetric amount of recharge contributed by Freds Creek applied to the model domain in a small polygonal area where the creek flows. This technique produced good results in initial runs of the model, however, it did not provide flexibility to change creek location and infiltration scenarios in future model simulations.

For the SFR2 boundary condition, a stream network is discretized in the model domain with the geometry and flow characteristics of the stream channel. The package allows for variable stream depth to be computed from stream flow, or a specified constant depth may be used. The latter was chosen for Freds Creek, as site observations indicated semi-full flow in the channel in January, February, and March, and full flow in the channel in April. Freds Creek was discretized using 4 segments to allow for variable width along its course (Figure 16). For the initial model run, the upper segment was designated as being 2 m wide and the 3 downstream segments were designated with 1.5 m widths. Depths in the initial run are 0.24 m in January, February, and March, and 0.49 m in April. The months when the creek is dry are designated with a depth of 0.01 m, as a depth of 0 is not allowed. The SFR2 package requires that the stream network be connected to the model in the uppermost layer of the domain, which was the soil layer in this case. Under this constraint, the bed elevation for the creek is calculated from the DEM surface of the bottom of the Soil layer as the bottom elevation plus 0.3 m for bed thickness. Details regarding the geometry of Freds Creek are tabulated in Appendix B.

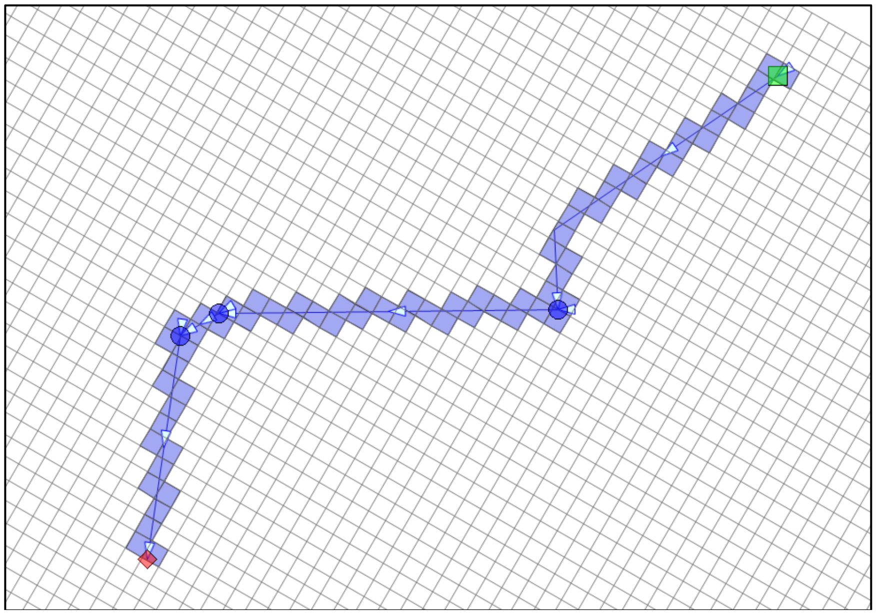


Figure 16. Discretization of Freds Creek for the SFR2 Boundary Condition. The 4 segments must be input into the model from upstream to downstream. The green diamond denotes the beginning node, the red diamond denotes the end node, and blue circles denote intermediate nodes. Each segment has its own geometry and hydraulic properties, detailed in Appendix B.

In preliminary model runs, the hydraulic conductivity of the bed materials used the vertical hydraulic conductivity of the soil in the upstream 3 segments, 5×10^{-5} m·s^{-1}, and in the most downstream segment, the vertical hydraulic conductivity of the Cobbles layer, 1×10^{-4} m·s^{-1}. These values of hydraulic conductivity reflect updated values from prior model runs. They were then updated again with subsequent model calibration.

It should be noted that the Teanaway River is not modeled as part of the streamflow network. This was for 2 reasons: Freds Creek does not directly connect to the river at the surface, and the bed of the Teanaway River is the Roslyn sandstone, which is not the uppermost model layer as required by the SFR2 package. Surface flow in Freds Creek terminates with ponding before it reaches the river, which can be represented with the SFR2 boundary condition. Instead, the Teanaway River was modeled using the RIV boundary condition, which is more ideal for modeling groundwater flux through the bedrock channel.

Evapotranspiration Boundary Condition

Boundary conditions that removed water from the model domain are evapotranspiration (EVT) and general head (GHB) boundary conditions. The EVT boundary condition was applied as a flux from the uppermost active layer of the model over the entire domain. Evapotranspiration amounts for each monthly stress period from 2017 to 2021 are remotely sensed data from the MODIS/Terra Net Evapotranspiration Gap-Filled 8-Day L4 Global 500 m SIN Grid (MOD16A2GF v061) data set, available publicly from the USGS (Running et al., 2021). Data was not available for 2022, so the average of the years 2017 to 2021 was substituted for 2022. The EVT boundary condition is a head dependent flux boundary condition: the rate of water leaving a cell assigned this boundary condition is a maximum when the head is at a high level in the cell but drops to zero via linear interpolation when the head in the boundary cell falls below a specified level, known as the extinction depth. Extinction depth is a function of soil type and land cover. The land cover over the model domain is 82% bare soil and 18% grass in the

Table 10.
Extinction Depth (cm) for a Given Soil and Land Cover Type

	Land Cover Type (cm)		
Soil Type	Bare Soil	Grass	Forest
Sand	50	145	250
Loamy sand	70	170	270
Sandy loam	130	230	330
Sandy clay loam	200	300	400
Sandy clay	210	310	410
Loam	265	370	470
Silty clay	335	430	530
Clay loam	405	505	610
Silt loam	420	515	615
Silt	430	530	630
Silty clay loam	450	550	655
Clay	620	715	820

Note: Depths are rounded up to the nearest 5 cm. Maximum rooting depth for grass and forest was assumed to be 100 and 200 cm, respectively. Reproduced from Shah et al. (2007).

growing season. A uniform extinction depth of 4 meters is used across the entire model domain, informed by computer simulations by Shah et al. (2007) shown in Table 10.

General Head Boundary Condition

The model domain is contained within a larger catchment area and does not have natural hydrologic boundaries on either its east or west edges. To account for the exchange of groundwater between the model domain and the areas adjacent to these two ends of the model, general head (GHB) boundary conditions are used at either end. Flow into or out of a GHB cell is calculated in proportion to the head difference between the model domain water table and the specified head in the boundary cell, allowing for water to flow into the model domain if the water table falls below the specified head and out of the model domain if the water table rises above the specified head. The constant of proportionality used in the head calculation is a conductance computed from the average hydraulic conductivity of the material between the edge of the model and the GHB cell and the individual cell geometry. The initial hydraulic conductivity used is that of the cobbles layer, 3×10^{-4} m·s^{-1}. First approximations for the head in the GHB boundary conditions are the linear edges of the best fit plane computed through the average monthly head elevations in the 9 floodplain observation wells. The GHB head elevations and hydraulic conductivity were adjusted during model calibration to improve results.

Unsaturated Zone Flow

Approximation of unsaturated zone flow in the model uses the UZF package from the USGS. This package simulates vertical flow through the vadose zone, distributing recharge (and evapotranspiration) to the groundwater table from the “top down” rather adding the volume of infiltration to the water table as direct recharge, which would be analogous to addition from the “bottom up.” The rate of recharge is approximated using a kinematic wave equation and requires specification of 3 additional parameters: the initial water content of the vadose zone, the residual water saturation, and the Brooks-Corey exponent, which is used in the relationship between the saturated hydraulic conductivity and the water content. In this groundwater flow model, a value of 3.0 was used for the Brooks-Corey exponent, the initial saturation of the vadose zone was taken to be 0.9 (since the model's starting time is March 1, 2017, and the observed water levels in the monitoring wells at that time are near the ground surface), and the residual saturation was assumed to be 0.2.

Model Calibration

The non-linearity of the equation representing groundwater flow in the unconfined zone impeded model convergence. Model convergence was aided by increasing the number of time steps during the initial stress period and during stress periods when cells were "rewetting," increasing the number of internal iterations of the MODFLOW-NWT solver, and specifying that the bottom 4 sandstone layers were confined and remained fully saturated. Even with these improvements, automated calibration using parameter estimation (PEST) was not performed because the model failed to converge for certain iterations of parameters. Consequently, the model was calibrated manually.

The model was calibrated so that the computed hydraulic heads and the measured hydraulic heads had a Root Mean Square (RMS) error less than 10%, and the yearly analytical mass balance and average yearly model mass balance agreed within 10%. To accomplish the calibration manually, the hydraulic conductivity and specific yield were varied systematically within realistic ranges for alluvium and sandstone, and boundary conditions in the model were adjusted to achieve the appropriate volumetric mass balance output.

Table 11.
Flow and Storage Parameters in the Calibrated Model

Model Zone	Well Numbers	Initial Model $K_x = K_z$ ($\mathrm{m{\cdot}s^{-1}}$)	Calibrated Model K_x ($\mathrm{m{\cdot}s^{-1}}$) $K_z = 0.1K_x$	Initial Model Specific Yield	Calibrated Model Specific Yield
1 – Topsoil		1×10^{-5}	5×10^{-4}	0.20	0.19
2 – Cobbles	4 – 10	3×10^{-4}	1×10^{-3}	0.20	0.23
3 – Clay	2, 3	7×10^{-5}	3×10^{-5}	0.10	0.07
4 – Sandstone		6×10^{-6}	8×10^{-5}	0.10	0.10

Comparison of the water balance and the groundwater flow model mass balance is shown in Figure 17. The water balance uses average monthly values of precipitation, evapotranspiration, and river exchange for inputs and is for annual steady-state conditions, that is, there is no net change in storage annually, and the MODFLOW model mass balance shows the average annual values from transient conditions over the 5-year model run. Another key difference to note is that the RIV boundary used in the MODFLOW model to represent the Upgradient Pond is absent from the water balance. This situation is discussed further later.

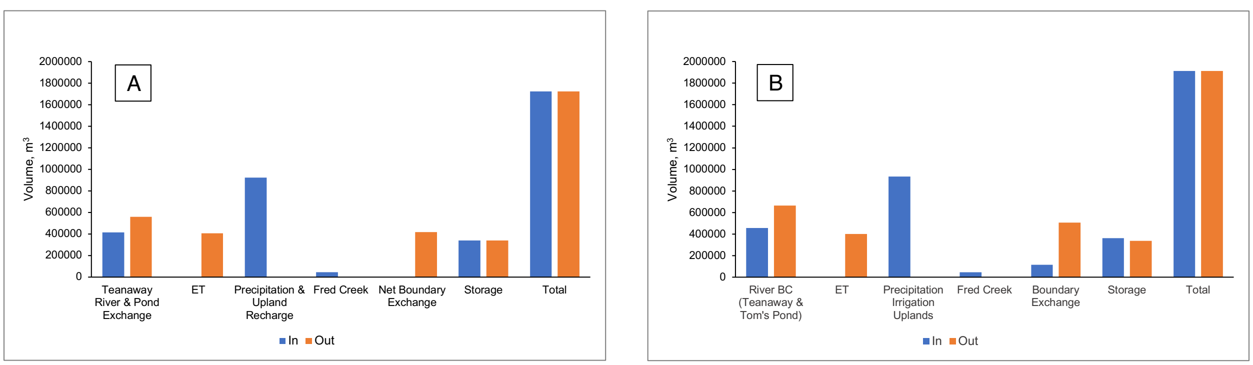


Figure 17. Mass Balance Comparison between the Analytical Water Balance and the Groundwater Flow Model. (A) The mass balance obtained using the best-fit plane for water table elevations (the steady-state analytical model), and (B) the mass balance for the transient, 5-year groundwater flow model (the MODFLOW model).

All boundary conditions were adjusted in some manner to obtain water balance and model mass balances within 10% of one another. Recharge and evapotranspiration fluxes were increased in the model by factors of 1.35 and 2.5, respectively, to achieve the appropriate volumetric outputs. Head elevations for the south GHB boundary condition were revised for the spring months to more accurately reflect the volume of net boundary exchange and improve calculated head results for Wells 2, 3, and 6. For the Teanaway River RIV boundary condition, stage and conductance parameters affected calculated heads in the wells closest to the river: Wells 7, 8, 9, and 10. The conductance, which is a measure of how much the river is connected to the aquifer, is calculated by the model according to $C = (K_{riv} \times L \times W) \div d_{riv}$ given the inputs of K_{riv} ($L \cdot T^{-1}$), the vertical hydraulic conductivity of the river bed sediments (the clogging layer), d_{riv} (L), the thickness of the clogging layer, W (L), the channel width, and L (L), the reach length. Anderson et al. (2015) advise adjusting conductance for surface water bodies to prevent anomalously large fluxes of water into a model. For the Teanaway River boundary condition, conductance controlled baseflow out of the aquifer and river stage controlled the water levels in the wells closest to the river. To meet the mass balance criterion, the conductance was decreased by a factor of 10^3 and the river stage was lowered 0.15 m. The river stage could be lowered a maximum of 0.33 m before the river would theoretically “go dry” according to the water levels computed by the rating curve. Lowering the stage 0.15 m left 0.18 m of water in the river at its lowest discharge, which is reasonable based on late summer observations. The conductance for the Upgradient Pond, also an RIV boundary condition, was likewise decreased by 3 orders of magnitude. Stage elevations of the pond were not changed during calibration since these levels dictated the volume of water withdrawn for irrigation. Finally, the hydraulic conductivity in the SFR2 boundary condition was increased to $0.23\ m \cdot s^{-1}$ from its previous value equal to the vertical hydraulic conductivity of the Soil layer. The low vertical hydraulic conductivity of the Soil layer allowed only 38 m^3 of water into the aquifer, which was unrealistically low. Hydraulic conductivity in the SFR2 boundary condition controlled the volume of recharge that reached the water table. A higher conductivity increased the volume of water from the Freds Creek drainage to the amount estimated by the analytical water balance. It also improved calculated heads for Wells 4 and 5.

Using the RIV boundary condition for both the Teanaway River and the Upgradient Pond presented a challenge in calibrating the model. Output from the model is categorized according to boundary condition, and consequently the volumes of water exchanged with the aquifer are not separated by their individual water bodies. This made it difficult to isolate the amount of exchange between the Upgradient Pond and the aquifer. To inspect the pond's influence on aquifer exchange, a model run was completed omitting the Upgradient Pond. Mass balance results from this run are in Figure 18, and differences between model mass balances with the Upgradient Pond and without the Upgradient Pond are tabulated in Table 12. Notably the pond accounts for about 17% of the aquifer exchange in the RIV boundary condition. Mass balance results without the Upgradient Pond are nearly identical to the volumes computed in the water balance; however, the calculated heads in Wells 9 and 10 are not as close to their observed values as when the Upgradient Pond is present in the model. For Well 9, the RMS error when the Upgradient Pond was omitted increased by 2.71%, and it increased 3.69% for Well 10. The Upgradient Pond was kept in the model for future modeling scenarios to preserve the more accurate computation of heads in Wells 9 and 10, but the limitation of the using the RIV boundary condition to represent the Upgradient Pond for mass balance purposes is acknowledged.

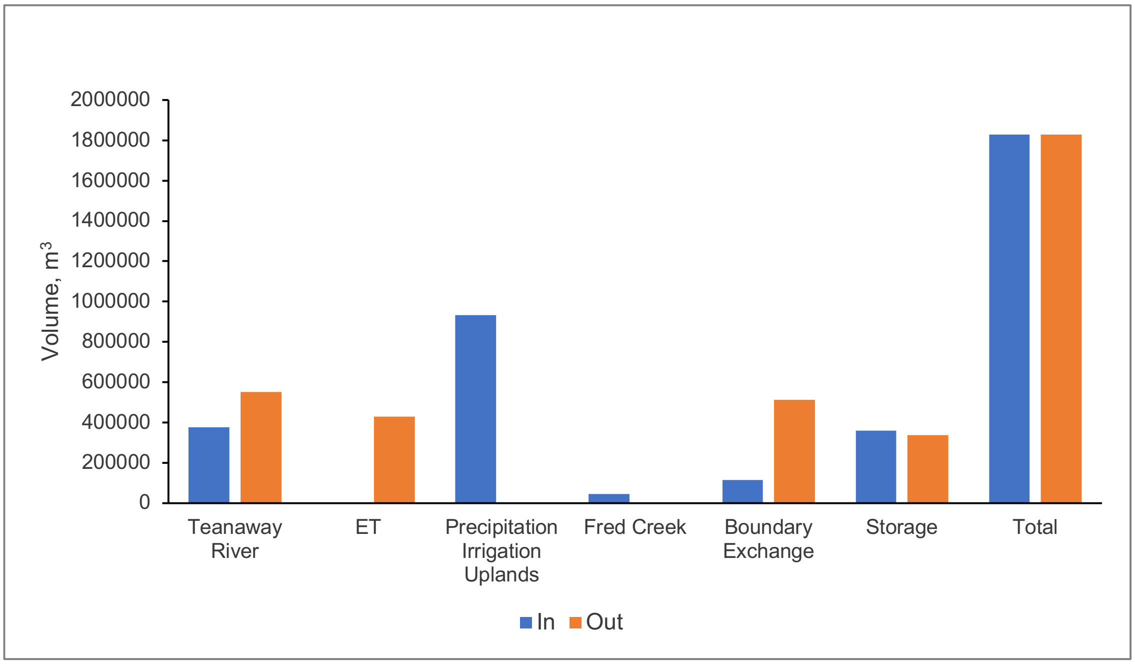


Figure 18. Mass Balance for the MODFLOW Model without the Upgradient Pond RIV Boundary Condition. The RIV boundary condition for the Upgradient Pond was deleted, and the transient, 5-year groundwater flow model re-run. Results are similar to the water balance results, Fig. 17A.

Table 12.

Comparison of the Transient Groundwater Flow Model With and Without the Upgradient Pond as a RIV Boundary Condition, 1000 m^3

	Storage IN	Storage OUT	River IN	River OUT	ET	Bounds IN	Bounds OUT	Recharge IN	Stream IN	Total IN	Total OUT
With	363	338	457	665	402	115	508	933	45.9	1910	1910
Without	360	337	377	552	428	114	513	933	45.4	1830	1830
Residual	-2.86	-0.561	-79.7	-113	25.8	-425	47.2	0	-0.490	-83.4	-83.4
	-0.79%	-0.17%	-17.4%	-17.1%	6.41%	-0.37%	0.93%	0%	-1.07%	-4.36%	-4.36%

Head values calculated by the model were compared to 217 observed values for goodness of fit. The model inputs in Appendix B and the parameters in Table 11 achieved an overall RMS error of 0.45 m, or 8.45%. Calibration results are presented in Figures 19 and 20.

Sensitivity Analysis

As with calibration, automated sensitivity analysis was not possible given the numerical instability associated with non-linear unconfined flow. Manual, informal sensitivity checks were

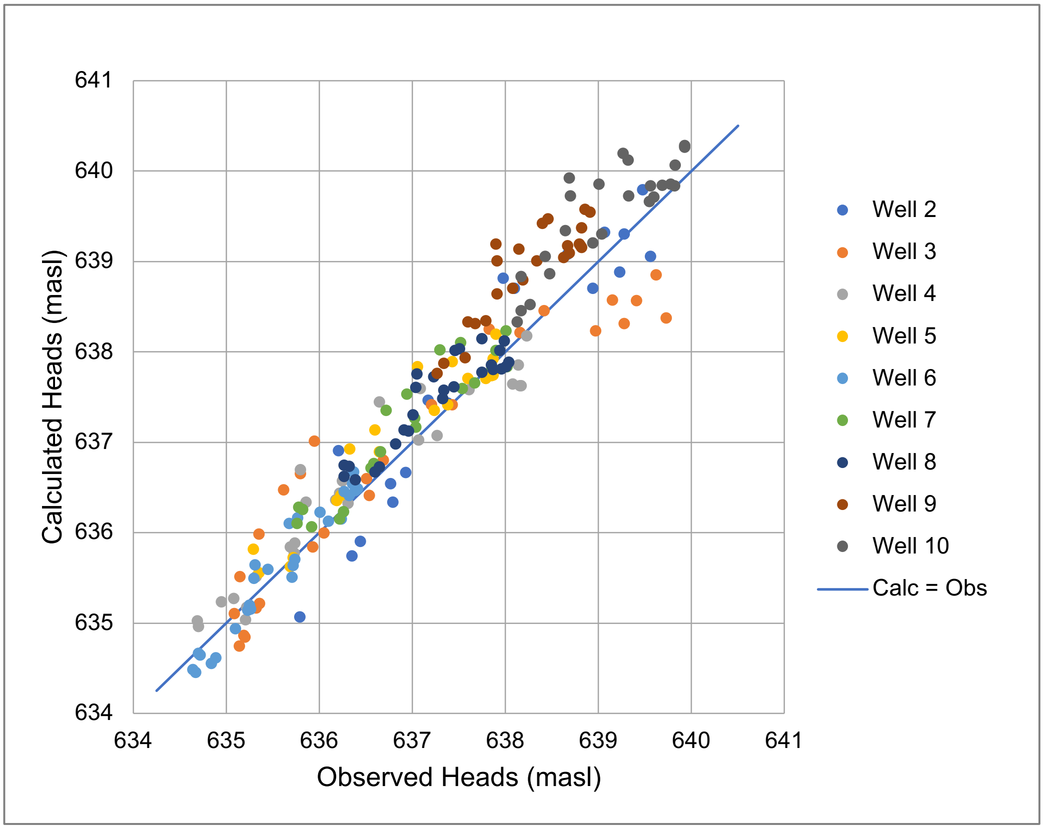


Figure 19. Calculated Heads versus Observed Heads Goodness of Fit. Head elevations computed by the groundwater flow model are plotted against all observed values for times t = 1067 days to t = 1857 days. The line demonstrates where the calculated head elevation is equivalent to the computed head elevation.

performed, and parameters were considered sensitive if the percent RMS error changed significantly when the parameter was varied slightly. The model was sensitive to hydraulic conductivity and specific yield, river stage, river conductance, extinction depth, and the number of model layers. Of particular note, calibration at Wells 2 and 3 improved when the specific yield of the Clay unit was lowered to 0.07. The model did not converge for lower values of specific yield in the Clay. The calibration at Well 6 improved when the vertical grid discretization was refined from 4 to 10 model layers. Adjusting river conductance had the greatest impact on the model mass balance value of River OUT, or baseflow, and river stage affected River IN, or leakage into the system from the Teanaway River. Lowering conductance lowered the amount of

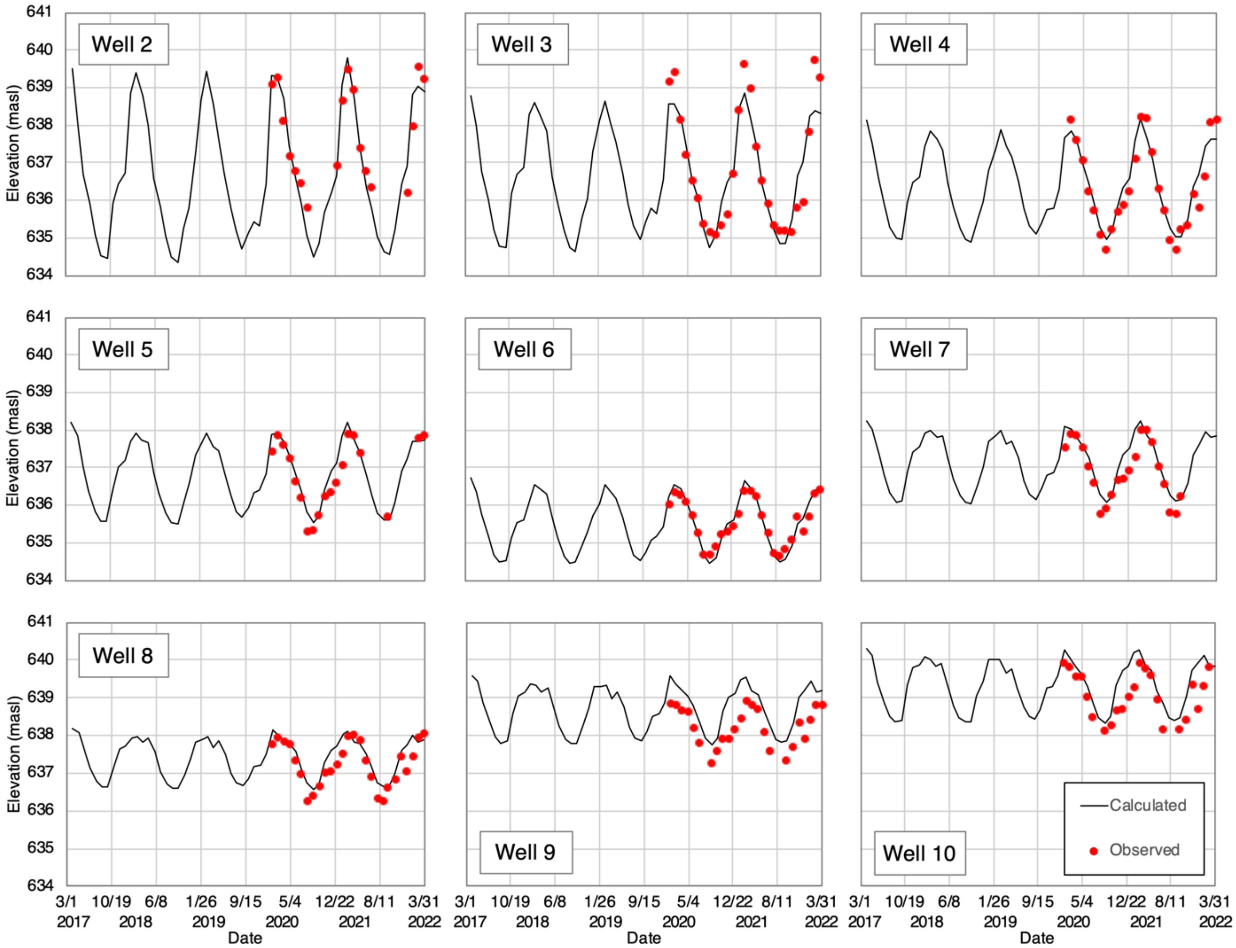


Figure 20. Calculated Heads versus Observed Heads Temporal Comparison. Head elevations calculated by the groundwater flow model are shown continuously over the model time frame, March 1, 2017, through March 31, 2022, for each of the Wells 2 through 10. Observed values at the end of each month beginning January 31, 2020, through March 31, 2022 are plotted. Data gaps exist for Wells 5 and 7 due to transducer failures, and there are no observations for Well 2 in the months of July through September because the well goes dry.

baseflow, and lowering the river stage lowered the amount of inflow from the river. Both parameters impacted the calibration of Wells 9 and 10 the most. The model did not appear to be sensitive to specific storage or porosity, limited changes in recharge and evaporative flux rates (although large changes were required for the water balance and mass balance volumes to agree), and the unconfined zone flow parameters. Informal sensitivity observations are noted in Table 13.

Table 13.
Informal Sensitivity Observations of Parameters Adjusted During Model Calibration

Parameter	Variation	Change in %RMS	Comments
Hydraulic Conductivity	Initial approximation to final calibration	Decreased 8.99%	A 1% decrease in %RMS error was noted when K_z was lowered to $0.1K_x$.
Specific Yield	Initial approximation to final calibration	Decreased 8.99%	Decreasing S_y in the clay layer decreased %RMS error in Wells 2 and 3; increasing S_y in the cobbles layer decreased %RMS error in Wells 4-10; overall numerical stability was sensitive to S_y
Specific Storage	Change from default value of 1×10^{-4} to values from literature	No change	Lowering S_s decreased model stability; the model did not converge when S_s for the sandstone layer was lowered to 1×10^{-6}
Porosity	±5%	No change	
River Stage	Decreased 0.15 m	Decreased 0.3% for every 3 cm decrease in stage	%RMS error for Well 6 improved to the best of all Wells at 7.41%; Wells 9 and 10 improved approximately 5%
Extinction Depth	Varied between 2 and 4.5 meters	Undocumented	Overall %RMS decreased as extinction depth increased to 4 m; beyond 4 m there was no improvement
Recharge	±20%	%RMS varied ±0.04%	Increasing flux by 35% was ultimately required for mass balance calibration
Number of Model Layers	Increased from 4 to 10	Decreased 1.45%	Individual %RMS error for Wells 4 and 5 decreased an average of 4.18%; %RMS error for Well 6 decreased 13.65%
Conductance	Decreased by 3 orders of magnitude	Increased 0.1%, but mass balance results improved	For C ÷ 100, %RMS did not change, but mass balance results (baseflow) did not improve; for C ÷ 1000, %RMS increased slightly and mass balance results improved; for C ÷ 10000, %RMS was worse by 2.27% and mass balance results did not agree
Upgradient Pond	Removing pond from the model	Increased 0.67% overall	The overall %RMS did not improve; Wells 9 and 10 were worse by approximately 3%
Freds Creek SFR2 Bed Hydraulic Conductivity	Increased from $K = 1 \times 10^{-3}$ m·s^{-1} (Cobbles unit) to 0.23 m·s^{-1}	Undocumented	Improvements to %RMS for Wells 4, 5, and 7; improved mass balance from unreasonably low seepage of 38 m^3 to agreement with water balance

Model Scenarios

Once the groundwater flow model was calibrated, the SFR2 boundary condition representing Freds Creek was modified to simulate the capture of flow in a shallow pond. The change in heads and mass balances between the calibrated model and the modified model could then be compared to determine any amount of recharge realized from an infiltration pond that holds back a portion of the total runoff in the creek.

In the calibrated model, the existing creek was discretized as 4 segments that followed the anthropogenically channelized course. For the modified creek, the first segment was left unchanged. That portion of the creek follows property lines between parcels leading to the TVFF property, and those parcels are privately owned. The remaining segments were modified to follow the theoretical stream course that would have existed had the creek not been channelized. This was the natural low in the surface topography as determined by the Strahler stream-ordering algorithm from the surface DEM in a GIS (van der Kwast and Menke, 2021). No further changes were made to geometry or flow conditions in the third and fourth segments of the creek. The hydraulic conductivity for all segments was held fixed at 0.23 $m \cdot s^{-1}$.

The second segment of the creek was modified to simulate an infiltration pond. This segment, which is 110 m in length, was widened in successive trials to 8, 10, 20, 30, and 35 meters, respectively. Numerical instability prevented modeling a pond wider than 35 m. The specified depth condition was used for the channel in the same way that it was used in the calibrated model. In the model scenarios, the depth of the second segment was deepened from 0.24 m in January, February, and March to 0.44 m, and from 0.49 m in April to 0.63 m. The depth of 0.63 m was the maximum depth allowed under the constraints of the SFR2 boundary condition. This depth required reducing the thickness of the soil beneath the channel bottom to 0.1 m to maintain the channel in the topmost layer of the model. At the maximum depth in the month of April, the trial ponds ranged in size from 554 m^3 to 2430 m^3 (approximately 0.449 to 1.97 acre-feet). The original and modified Freds Creek are shown in Figure 21, and inputs for the model scenarios are tabulated in Appendix B.

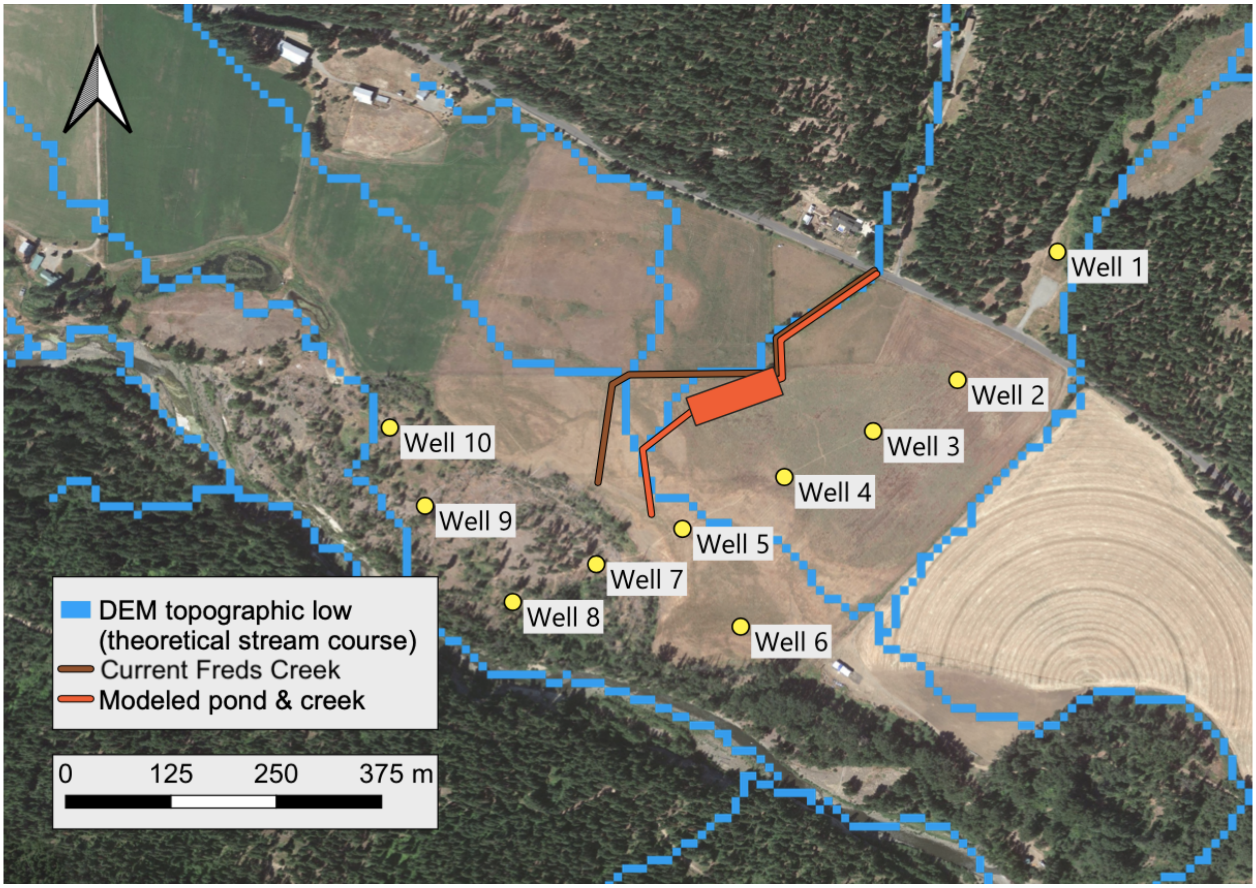


Figure 21. Location of the Modeled Ephemeral Infiltration Pond. The anthropogenically channelized Freds Creek, shown here as brown, was modeled as part of the calibrated groundwater flow model. Modeled scenarios modified Freds Creek and created ponds 0.63 m deep of different widths that had volumes ranging from 554 m^3 to 2430 m^3 (approximately 0.449 to 1.97 acre-feet), shown as orange. The pond depicted in the figure is the largest modeled, 110 m long and 35 m wide. Blue lines delineate the theoretical stream course calculated from the DEM topography by the Strahler stream-ordering algorithm in a GIS.

CHAPTER VII

MODEL SCENARIO RESULTS

Mass Balance Comparison with the Calibrated Model

Mass balance results for the calibrated model and the 5 different model scenarios are presented in Figure 22. The mass balances are annual averages over the 5-year simulation period. The volumes of water going into the system (IN) and exiting the system (OUT) are shown separately.

Storage is reported by MODFLOW for transient simulations. Storage IN indicates water exits storage and is added to the simulation, and storage OUT accounts for water removed from the system and apportioned into storage (Anderson et al., 2015). In Figure 22, storage IN increases more with increasing pond size than storage OUT. The net change in storage, storage IN – OUT, is positive, indicating that overall the model releases water from storage to satisfy the mass balance.

Inflows and outflows from the RIV boundary condition are presented in the second row of Figure 22 (note that the scales are shifted for the graphical representation of flow into the system, which was much less than flow out of the system). Flow from a RIV boundary condition cell goes into an aquifer cell when the head in the aquifer cell is less than the river stage. If the head in the aquifer cell is greater than the river stage, flow is OUT to the river. Consequently, the calibrated model, having lower head elevations and no infiltration pond, had more water entering into the system from the river than any of the pond simulations. The pond simulations demonstrated less flow in from the river as pond size increased, and more flow out to the river. Conductance, which conceptually is a factor of resistance between the river bed materials and the aquifer, was the same for both the calibrated model and the pond simulations.

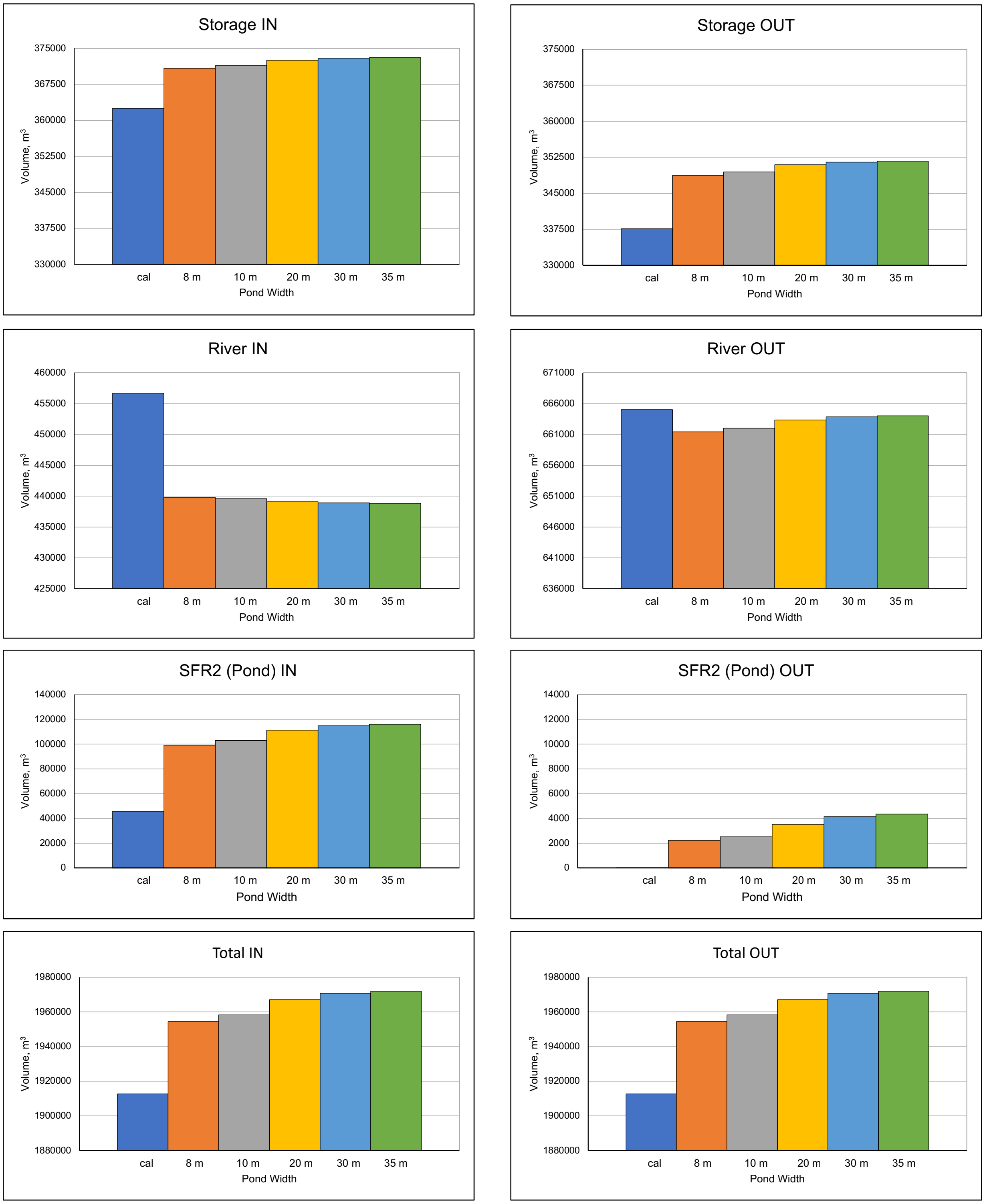


Figure 22. Average Annual Mass Balance Results for the Different Model Scenarios. The calibrated model is denoted "cal," and model scenarios by their different pond widths (8 m, 10 m, 20 m, 30 m, and 35 m). "IN" indicates water going into the system; "OUT" indicates water removed from the system. Note the shifted scales for the River IN and River OUT mass balances, and that the scale for Pond OUT is an order of magnitude less than Pond IN.

SFR2 (Pond) IN and SFR2 (Pond) OUT in Figure 22 represent the exchange of water between the SFR2 stream boundary condition, which was used to simulate Freds Creek and the pond scenarios, and the system. The volume of water entering the aquifer is an order of magnitude greater than the amount exiting to the stream network. SFR2 (Pond) IN and SFR2 (Pond) OUT in Figure 22 quantify the leakage from all 4 segments of the stream, but the contribution of segment 2, the segment modified to create a pond, is evident given the increase in inflows to the aquifer over the calibrated model. Water going out to the SFR2 network occurred mostly during the pond simulations and in the months of February to May (Table 14), with the highest amounts in February when the natural water table is at its maximum elevation and lowest

Table 14.
Average Monthly Leakage from the Aquifer into the Streamflow Routing Network

	Calibrated Model (m^3)	Pond Width in Different Model Scenarios				
		8 m (m^3)	10 m (m^3)	20 m (m^3)	30 m (m^3)	35 m (m^3)
January	0	242	282	413	539	566
February	23.2	1057	1187	1600	1833	1918
March	23.3	639	721	1011	1198	1267
April	0	80.6	94.7	149	186	201
May	0.580	117	141	227	278	296
June	0	0	0	0	0	0
July	0	0	0	0	0	0
August	0	0	0	0	0	0
September	0	0	0	0	0	0
October	0	0	0	0	0	0
November	0	0	0	0	0	0
December	0	0	0	0	0	0

amounts in April when the pond was simulated as having a greater depth. This suggests that the model used groundwater exfiltration to supplement the constant depths specified in the streamflow network channels, particularly the wider segment 2, and thus the channels were not entirely filled by theoretical surface runoff from the Freds Creek catchment.

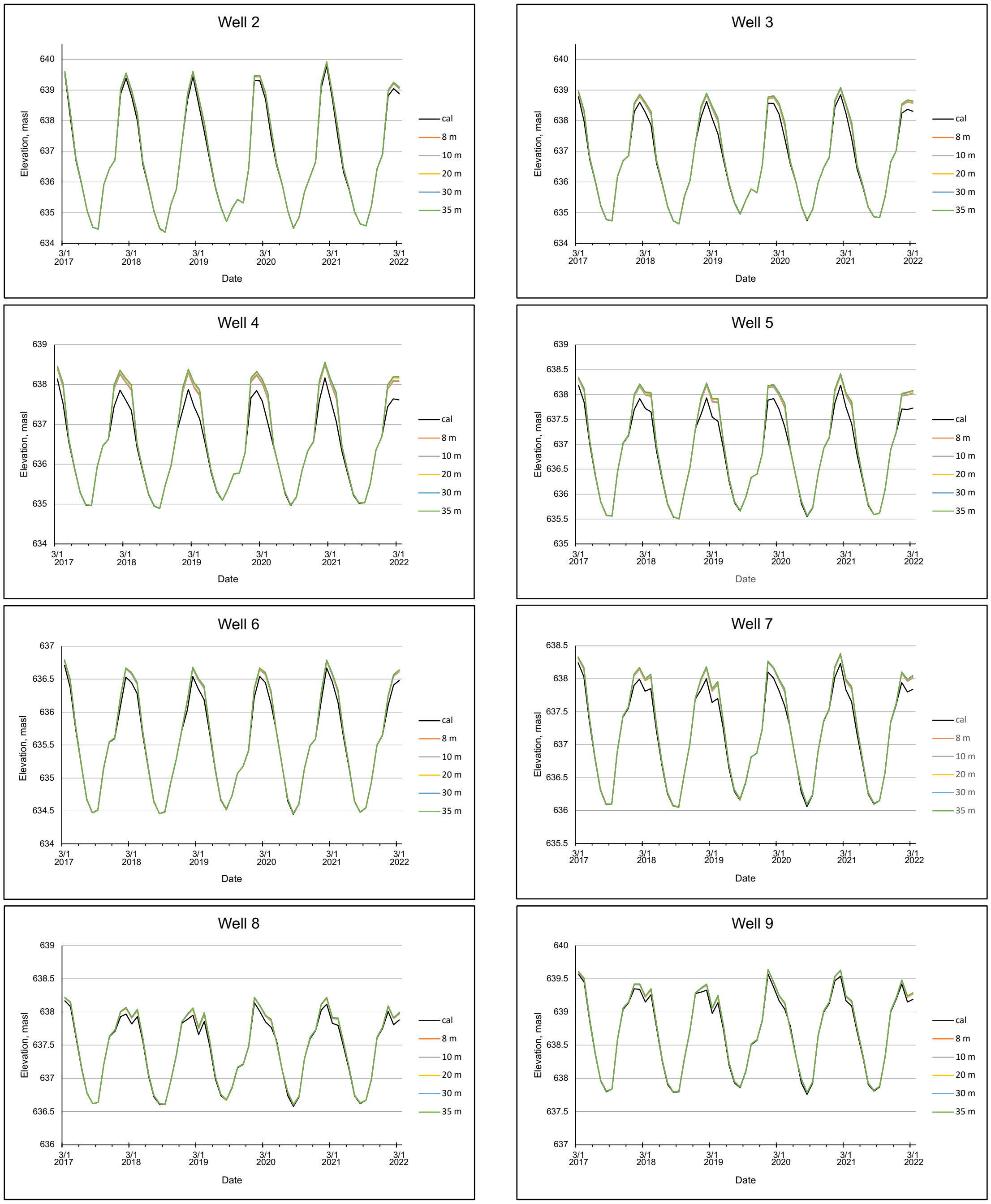
Solution of the groundwater flow equation by MODFLOW is based on conservation of mass, and so the total inflows should necessarily equal the total outflows. This holds true for the calibrated model and all the pond scenarios, as shown in Total IN and Total OUT in Figure 22.

Head Elevations for Different Pond Scenarios

Groundwater head elevations at the 9 observation wells from the calibrated model are compared with head elevations in each of the modeled pond scenarios in Figure 23. Water levels in each pond scenario increase above the calibrated heads in the months of January through April but return to baseline levels in the fall months. Water levels peak in March, but the greatest differences in head levels (residuals) between the calibrated model and the pond scenarios occur in April when the simulated pond has the greatest depth. The average increases are summarized in Table 15. Well 4, immediately downstream of the pond location, has the largest increase of all the wells at 0.76 m, which occurs during the simulation with the largest (35-meter wide) pond. This simulated maximum water elevation of 638.56 masl is 0.45 m below the true ground surface elevation. The maximum water elevation at Well 5 comes within 0.03 m of the true ground surface, which is the closest of any well. Well 10 experiences the least amount of increase in

Table 15.
Average Increase in Water Elevation in April

	Pond Width in Different Model Scenarios					Maximum in the 5-yr Simulation (m)
	8 m (m)	10 m (m)	20 m (m)	30 m (m)	35 m (m)	
Well 2	0.20	0.21	0.25	0.27	0.27	0.31
Well 3	0.36	0.38	0.45	0.47	0.48	0.54
Well 4	0.54	0.57	0.64	0.67	0.68	0.76
Well 5	0.33	0.35	0.39	0.40	0.41	0.47
Well 6	0.14	0.15	0.17	0.18	0.18	0.21
Well 7	0.18	0.19	0.21	0.22	0.22	0.26
Well 8	0.09	0.09	0.10	0.11	0.11	0.13
Well 9	0.07	0.07	0.08	0.09	0.09	0.11
Well 10	0.06	0.06	0.07	0.08	0.08	0.09



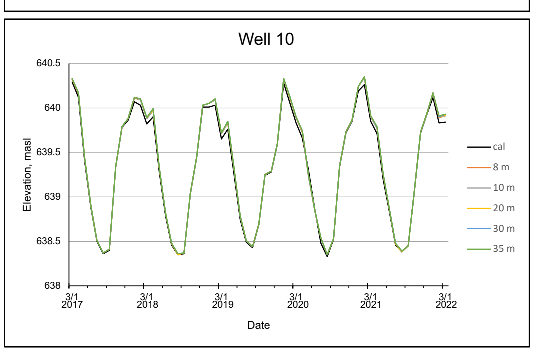


Figure 23. Calibrated Heads versus Pond Scenario Heads at the Observation Well Locations. Head elevations in each well over the 5-year simulation period for the calibrated model (cal) and the pond scenarios, labeled by their widths, are shown.

head from the pond simulations, and Well 9 has the least variance. Both Wells 9 and 10 are upgradient of the infiltration pond location.

Figure 24 shows mass balance information for the General Head Boundary condition, which is termed “Head Dependent Boundary condition” in Visual MODFLOW Flex 7.0 output, and so that is how it is reported here. The difference in volume withdrawn from the system between the pond scenarios and the calibrated model is also shown. In the figure, HDB IN is analogous to the western, upgradient boundary of the model, and HDB OUT coincides with the eastern, downgradient boundary of the model. The calibrated model requires the most input from the upgradient boundary (i.e., it has no additional input from a pond). The pond scenarios

Figure 24. Comparison of the Head Dependent Boundary Condition between the Calibrated Model and the Modeled Scenarios. Figures (A) and (B): Average annual mass balance results for the Head Dependent Boundary (HDB) condition along the east edge of the model domain for the calibrated model (cal) and the model scenarios with different pond widths (8 m, 10 m, 20 m, 30 m, and 35 m). (C) is the temporal change in volume over the simulation period for the calibrated model and different pond scenarios.

indicate more water is removed from the model at the downgradient boundary with increasing pond size. Figure 24C shows the temporal fluctuation in the volume of water removed from the system at the downgradient boundary of the model domain. Similar to the well heads, the greatest difference in the volume of water is present between a pond scenario and the calibrated model occurs in April (Table 16). The maximum amount removed is 9780 m^3, or 7.93 acre-feet. The increase in water surface elevation at the boundary is difficult to correlate with the volume removed; for the maximum, given the length of the boundary and the timeframe, it amounts to 0.562 m^3 per meter per day. For comparison, nearby Well 6 experiences a maximum increase of 0.21 m. It's possible that the removal of water by the HDB condition prevents the head elevation in Well 6 from increasing realistically as this boundary condition is designed to remove water from the system to improve calibration of the model.

Table 16.
Average Increase in Volume of Water Removed at the East Boundary in April

	Pond Width in Different Model Scenarios					Maximum in The 5-yr Simulation (m^3)
	8 m (m^3)	10 m (m^3)	20 m (m^3)	30 m (m^3)	35 m (m^3)	
HDB Out	6478	6920	7949	8371	8505	9780

Net Storage and Total Mass Results

The addition of an infiltration pond on the TVFF property increases heads in the observation wells and increases the volume of water at the downstream boundary, and it also increases the output of the system to the river, as seen in Figures 25 and 26, and the total volume of the system in Figure 27. Figure 25 demonstrates that as ponds with larger volume are simulated, additional water added by an infiltration pond triggers less additional water input to the system from storage and more water to leave the system via outflow into the river. The

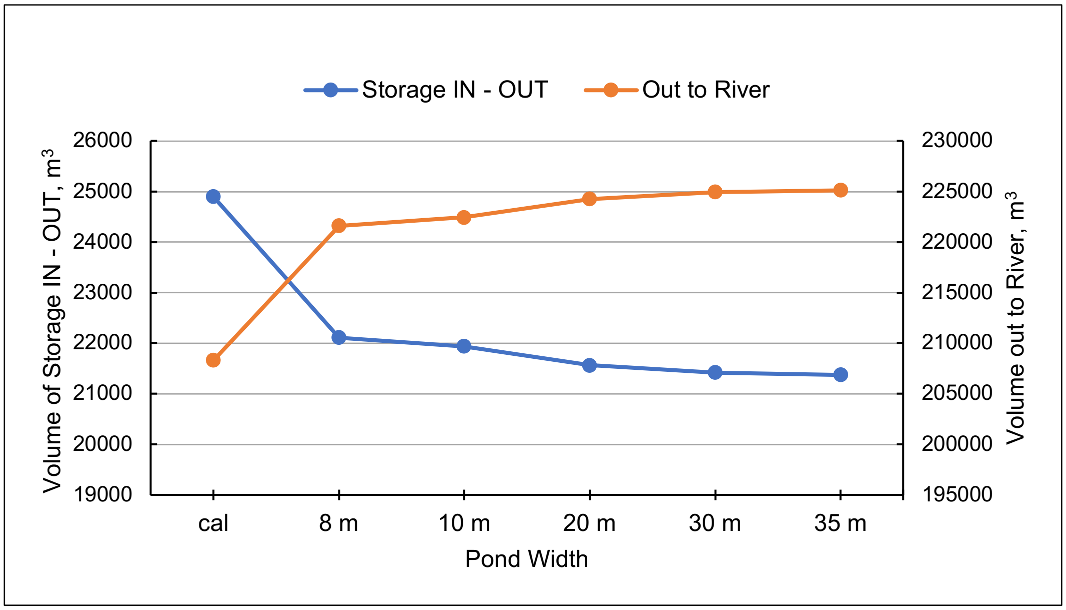


Figure 25. Net Storage and River Exchange for the Model Scenarios. The volume of water added to the system from storage and the volume of water exiting to the river for the calibrated model (cal) and each model scenario.

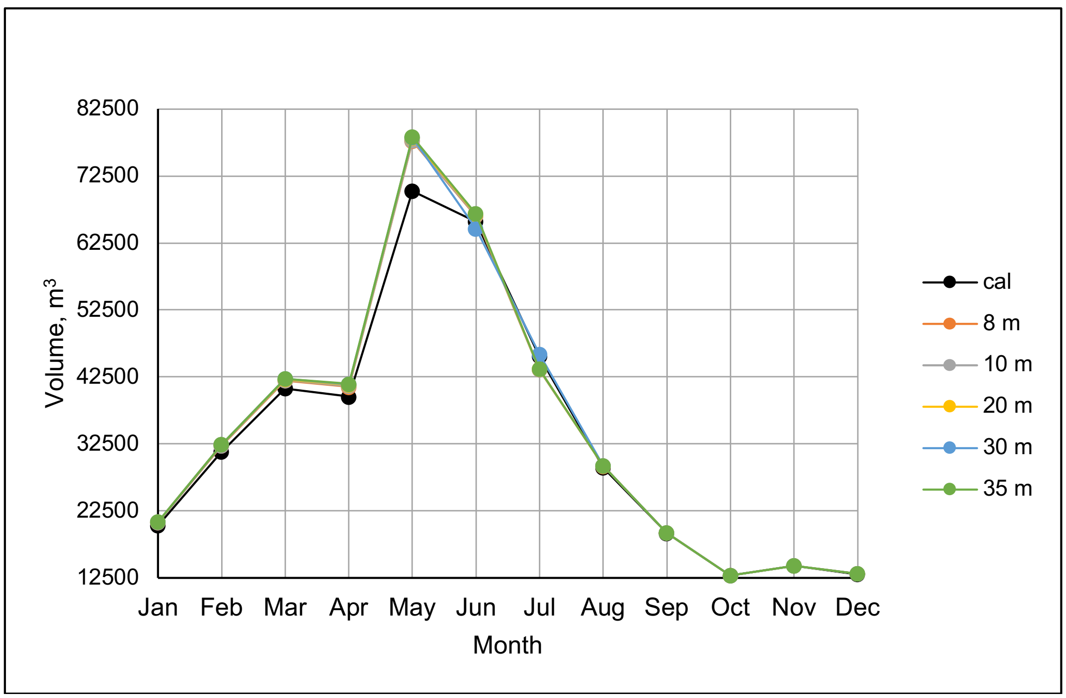


Figure 26. Modeled Average Monthly Discharge to the River for the Different Scenarios. The average monthly volume of discharge to the Teanaway River, in m^3, is shown for the calibrated model (cal) and the modeled pond scenarios, indicated by pond width.

greater magnitude of water exiting to the river demonstrates that the volume of water added by a pond does not stay in the system. The timing and volume of discharge into the river is shown in Figure 26, and similar to the behavior of the groundwater heads: discharge is high in the spring when the simulated pond is present and tapers down to baseline levels in the fall. However, Figure 27 shows that an overall increase in the total volume of the system occurs, and the amount of increase can be attributed to the increased volume from the pond. Evapotranspiration appears to remove the difference in volume between the total increase in the system and the increased input by an infiltration pond.

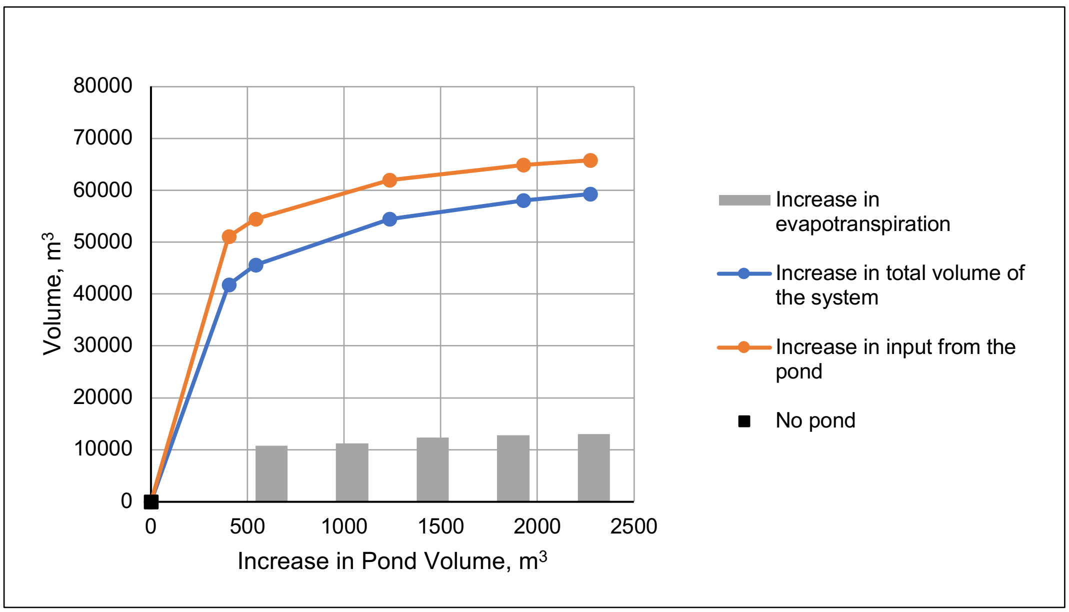


Figure 27. Increase in Total Volume of the System, Pond Input, and Evapotranspiration for the Different Model Scenarios. The change in volume over the calibrated model is shown for each scenario. Increased evapotranspiration is also shown.

Evapotranspiration

Evapotranspiration is handled in MODFLOW by the EVT boundary condition, which requires an evaporative flux (L^3/T) and a depth below the ground surface where evaporation ceases, known as the extinction depth (Table 10), to be specified. For the calibrated model, the extinction depth was 4 m and the evaporative flux was adjusted from initial values based on MODIS actual evapotranspiration (AET) data (Running et al., 2021) to values which enabled the total evaporative volume to be met. In Figure 27, the total evaporated volume increases by 10^4 m^3 above the calibrated model value for each pond scenario, but it does not increase appreciably as ponds increase in size.

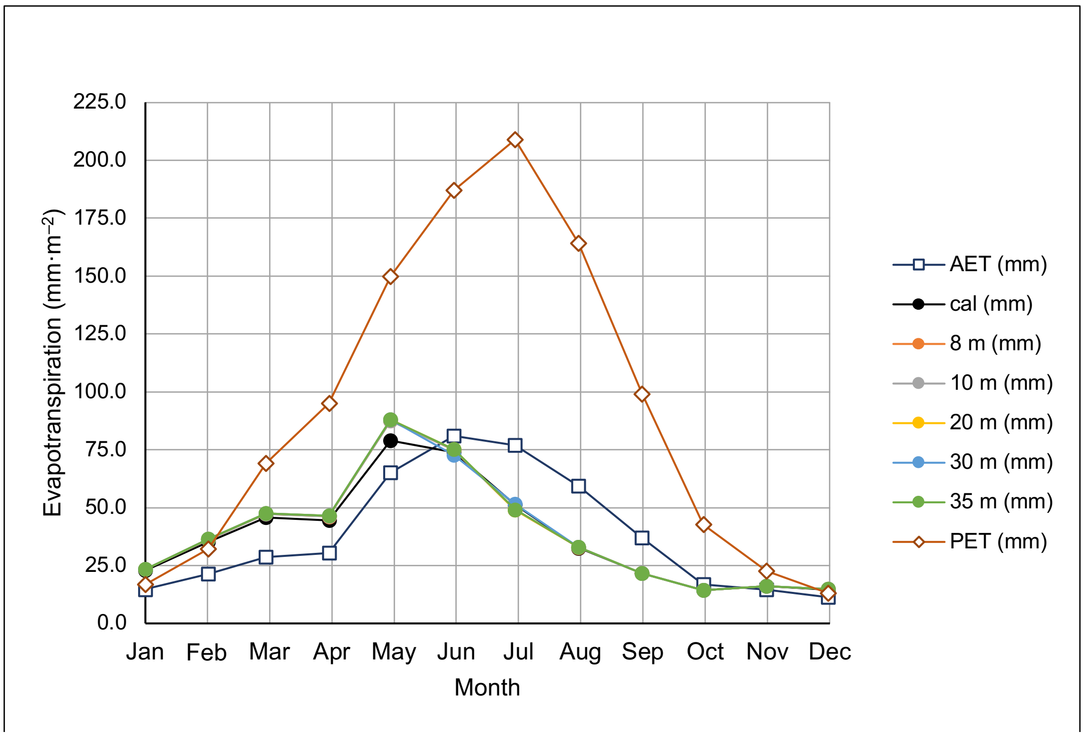


Figure 28. Average Monthly Actual Evapotranspiration (AET), Potential Evapotranspiration (PET) and Evapotranspiration (ET) for the Different Model Scenarios. AET and PET are from MODIS data (Running et al., 2021) at gap-filled 500-m resolution over the model domain. ET is calculated by the MODFLOW EVT boundary condition from a monthly specified flux.

Figure 28 presents the monthly amounts of AET and potential evapotranspiration (PET) from MODIS data (Running et al., 2021), and the evapotranspiration (ET) computed by the model over the area of the model domain, in mm. Model computed values of ET are greater than AET in the months of January through May and November to December, and below AET for

June through October. This is not only true of the pond scenarios, but also the calibrated model, and suggests that model calibration should have also considered the temporal nature of the evaporative flux in additional to calibrating for the total annual volume of water removed by evapotranspiration. The slight increase in May of approximately 9 mm for the pond scenarios above the calibrated model denotes the ET contribution from the water surface of the modeled pond.

PET is the upper limit of water loss to evapotranspiration if there were no deficiency in soil moisture for vegetative use. The vertical gap between the AET and PET curves gives insight into the amount of soil-moisture storage, which at the TVFF site is low in the summer months. The modeled pond scenarios do not seem to be improving soil moisture storage, as there is no long-term decrease in the vertical distance between the pond scenario ET curves and the PET curve.

Duration of Elevated Water Levels

The modeled pond scenarios input water to the system in January through April, theoretically capturing additional runoff from the Freds Creek catchment area that would otherwise discharge into the Teanaway River. The infiltrated water from the ponds increases the heads at observation well locations, increases the volume of water output at the downgradient model domain boundary and out to the river, and reduces the input to the system from storage. Overall, the total volume of the system increases. The question remains whether the increased volume is sustained into the late summer and early fall, thereby contributing additional baseflow to the river.

Figure 29 shows the water level contours in the months of April and September for the calibrated model, the 8-meter-wide pond scenario, and the 35-meter-wide pond scenario. The pond scenarios in April exhibit higher water levels around Freds Creek as expected. The pond scenarios in September show that water levels return to levels similar to the calibrated model and any lasting effects of water level increases have diminished. Table 17 supports the contour observations numerically, showing the months of September and October having no residual increase in heads for most wells. However, wells closer to the river, that is, Wells 8, 9, and 10,

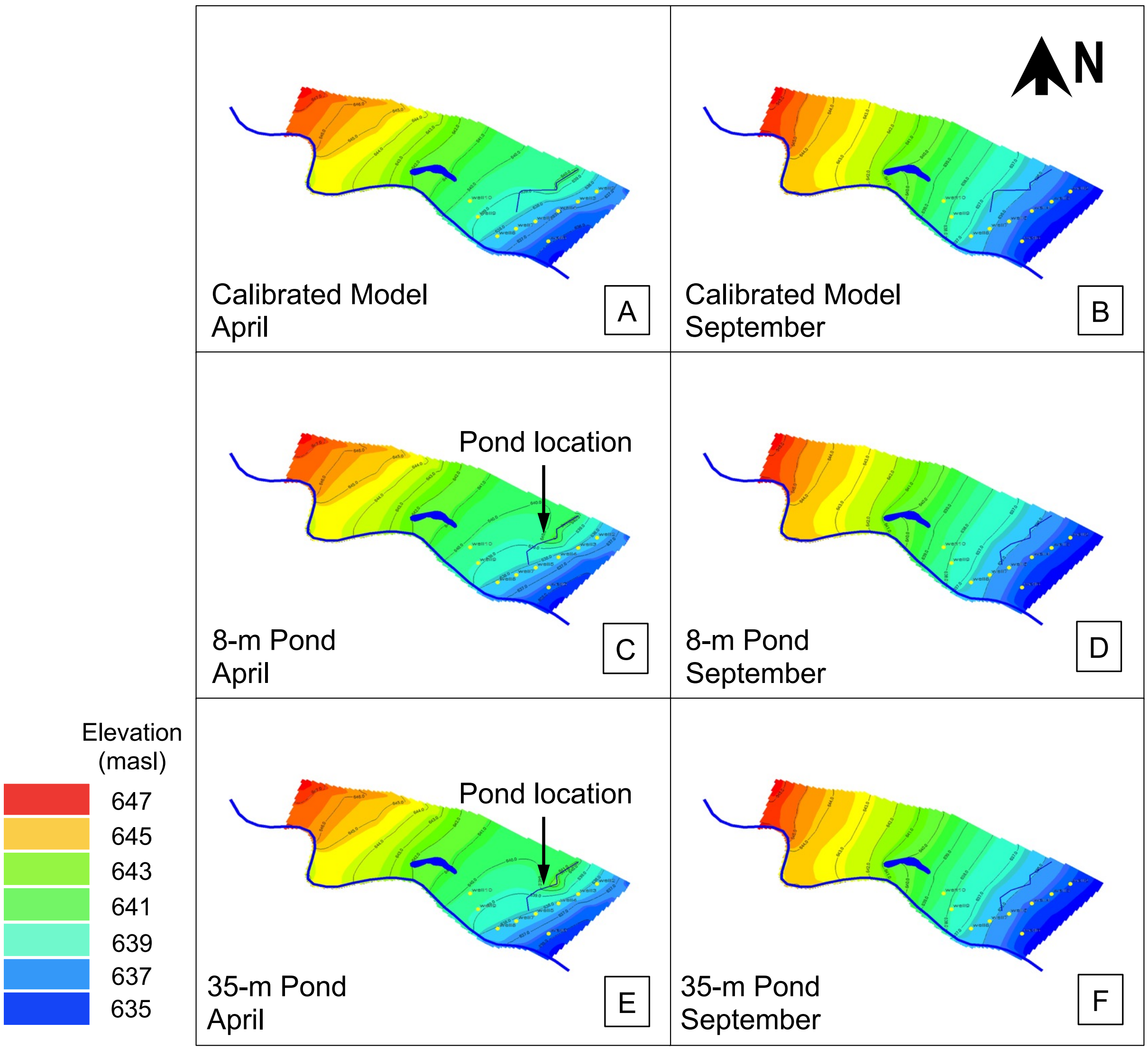


Figure 29. Water Elevation Contours for Different Model Scenarios in April and September of Simulation Year 4. (A) and (B): the calibrated model in April and September, respectively, (C) and (D): the model with an 8-meter-wide pond in April and September, respectively, and (E) and (F): the model with a 35-meter-wide pond, again in April and September, respectively.

Table 17.

Average Monthly Residual Heads (m) at each Well Location for the Different Pond Scenarios

Well 2 Average Residual Heads

Month	8 m	10 m	20 m	30 m	35 m
January	0.13	0.14	0.16	0.17	0.18
February	0.13	0.14	0.16	0.17	0.17
March	0.15	0.16	0.18	0.19	0.2
April	0.2	0.21	0.25	0.27	0.27
May	0.08	0.08	0.09	0.1	0.1
June	0.03	0.03	0.04	0.04	0.04
July	0.01	0.01	0.02	0.02	0.02
August	0.01	0.01	0.01	0.01	0.01
September	0	0	0	0	0
October	0	0	0	0	0
November	0	0	0	0	0
December	0	0	0	0	0

Well 3 Average Residual Heads

Month	8 m	10 m	20 m	30 m	35 m
January	0.21	0.22	0.26	0.27	0.27
February	0.2	0.21	0.25	0.26	0.27
March	0.25	0.26	0.3	0.31	0.32
April	0.36	0.38	0.45	0.47	0.48
May	0.08	0.09	0.11	0.11	0.11
June	0.03	0.03	0.04	0.04	0.05
July	0.02	0.02	0.02	0.02	0.02
August	0.01	0.01	0.01	0.01	0.01
September	0	0	0	0	0
October	0	0	0	0	0
November	0	0	0	0	0
December	0	0	0	0	0

Well 4 Average Residual Heads

Month	8 m	10 m	20 m	30 m	35 m
January	0.43	0.45	0.51	0.53	0.53
February	0.39	0.41	0.46	0.48	0.49
March	0.41	0.43	0.49	0.51	0.52
April	0.54	0.57	0.64	0.67	0.68
May	0.08	0.09	0.1	0.11	0.11
June	0.03	0.03	0.04	0.04	0.04
July	0.02	0.02	0.02	0.02	0.02
August	0.01	0.01	0.01	0.01	0.01
September	0	0	0	0	0
October	0	0	0	0	0
November	0	0	0	0	0
December	0.01	0.01	0.01	0.01	0.01

Well 5 Average Residual Heads

Month	8 m	10 m	20 m	30 m	35 m
January	0.25	0.27	0.29	0.3	0.3
February	0.24	0.25	0.28	0.28	0.29
March	0.25	0.26	0.29	0.3	0.3
April	0.33	0.35	0.39	0.4	0.41
May	0.08	0.08	0.09	0.1	0.1
June	0.03	0.03	0.04	0.04	0.04
July	0.02	0.02	0.03	0.03	0.03
August	0.01	0.01	0.01	0.01	0.01
September	0	0	0	0	0
October	0	0	0	0	0
November	0	0	0	0	0
December	0.01	0.01	0.01	0.01	0.01

Well 6 Average Residual Heads

Month	8 m	10 m	20 m	30 m	35 m
January	0.12	0.13	0.14	0.14	0.15
February	0.11	0.12	0.13	0.14	0.14
March	0.11	0.12	0.13	0.14	0.14
April	0.14	0.15	0.17	0.18	0.18
May	0.04	0.04	0.05	0.05	0.05
June	0.01	0.01	0.02	0.02	0.02
July	0.01	0.01	0.01	0.02	0.02
August	0	0	0	0	0
September	0	0	0	0	0
October	0	0	0	0	0
November	0	0	0	0	0
December	0.01	0.01	0.01	0.01	0.01

Well 7 Average Residual Heads

Month	8 m	10 m	20 m	30 m	35 m
January	0.14	0.15	0.16	0.16	0.17
February	0.15	0.15	0.17	0.17	0.17
March	0.14	0.15	0.17	0.17	0.17
April	0.18	0.19	0.21	0.22	0.22
May	0.06	0.06	0.08	0.08	0.08
June	0.03	0.03	0.03	0.04	0.04
July	0.03	0.03	0.03	0.03	0.03
August	0.01	0.01	0.01	0.02	0.02
September	0	0	0	0	0
October	0	0	0	0	0
November	0.01	0.01	0.01	0.01	0.01
December	0.01	0.01	0.01	0.01	0.01

Well 8 Average Residual Heads

Month	8 m	10 m	20 m	30 m	35 m
January	0.07	0.08	0.08	0.08	0.08
February	0.08	0.09	0.1	0.1	0.1
March	0.08	0.08	0.09	0.09	0.09
April	0.09	0.09	0.1	0.11	0.11
May	0.03	0.03	0.04	0.04	0.04
June	0.02	0.02	0.02	0.02	0.02
July	0.02	0.02	0.02	0.03	0.03
August	0.01	0.01	0.01	0.01	0.01
September	0	0	0	0	0
October	0	0.01	0.01	0.01	0.01
November	0.01	0.01	0.01	0.01	0.01
December	0.02	0.02	0.02	0.02	0.02

Well 9 Average Residual Heads

Month	8 m	10 m	20 m	30 m	35 m
January	0.06	0.06	0.07	0.07	0.07
February	0.07	0.08	0.08	0.09	0.09
March	0.06	0.06	0.07	0.08	0.08
April	0.07	0.07	0.08	0.09	0.09
May	0.02	0.02	0.03	0.03	0.03
June	0.01	0.02	0.02	0.02	0.02
July	0.03	0.03	0.03	0.03	0.03
August	0.01	0.01	0.01	0.01	0.01
September	0.01	0.01	0.01	0.01	0.01
October	0.01	0.01	0.01	0.01	0.01
November	0.02	0.02	0.02	0.02	0.02
December	0.01	0.01	0.01	0.01	0.02

Well 10 Average Residual Heads

Month	8 m	10 m	20 m	30 m	35 m
January	0.04	0.05	0.05	0.05	0.05
February	0.06	0.07	0.07	0.07	0.08
March	0.05	0.05	0.06	0.07	0.07
April	0.06	0.06	0.07	0.08	0.08
May	0.02	0.02	0.03	0.03	0.03
June	0.02	0.02	0.02	0.02	0.02
July	0.02	0.02	0.02	0.03	0.03
August	0.01	0.01	0.01	0.01	0.01
September	0.01	0.01	0.01	0.01	0.01
October	0.01	0.01	0.01	0.01	0.01
November	0.01	0.01	0.01	0.01	0.01
December	0.01	0.01	0.01	0.01	0.01

Note: Pond scenarios are labeled according to pond width. Coloring indicates the extent to which residual head is elevated (red = 0, orange ≤ 0.04, yellow 0.05 – 0.06, variegated green > 0.06).

and to some degree Wells 6 and 7, exhibit residuals greater than zero into the fall months. The increase in input from any infiltration pond scenario does not appear to have a sustained effect on the overall system.

Limitations of the Model

The calibrated model is useful but has several limitations. The model has an RMS error of 8.45% and the simulated heads are generally higher than observed values (Figure 20), especially for Wells 9 and 10. Hydraulic conductivity parameters were based on observed values but were increased during calibration to achieve an RMS error less than 10% for the simulated heads. Furthermore, the calibration was based on comparison of annual mass balances between the analytical best-fit plane water balance and the MODFLOW mass balance, yet temporal discrepancies exist on a month-by-month basis as in the case of evapotranspiration (Figure 28).

Modeling techniques were limited for the pond scenarios. The MODFLOW lake package (LAK) was not used because it renders cells below the lakebed inactive, which was not suitable in this situation. The SFR2 boundary condition was chosen for its ability to model ephemeral streams, but in order to use this package, ponds had to be confined to Layer 1 of the model and limited in depth. The SFR2 package also has inherent limitations as detailed by Niswonger and Prudic (2005), including numerical stability issues.

One final limitation of the model is the model domain. The domain excluded Johns Creek, which flows just east of the downgradient model boundary, on the assumption that this creek influences groundwater further downstream. Considering Johns Creek within the model domain may have provided additional insight into the behavior of the system at the downgradient boundary.

CHAPTER VIII

CONCLUSIONS

The analytical water balance computed using a best-fit plane through the head elevations at the observation wells demonstrated that the volume of storage was not only dependent on the volume of aquifer physically available to store water, but also on an accurate value of specific yield for the aquifer medium. This type of idealized model was appropriate at the research site because the model domain was comprised of a gently-sloping, nearly planar floodplain. The analytical water balance informed the MODFLOW model regarding total masses for measurable quantities at the site, e.g., precipitation, evaporation, and river stage, and the MODFLOW model informed the analytical model regarding specific yield by providing the physical volume of the aquifer (inherent in the volume of the discretized cells) and calibrated values of specific yield necessary for the simulated heads to match the observed heads at the wells. The coupling of the analytical water balance model and MODFLOW groundwater flow model provides the baseline mass balances necessary to enable comparison of the pond model scenario mass balances to the calibrated model.

The results of the model scenarios with infiltration ponds of different sizes indicate that increased infiltration from a pond increases the overall volume of the system in the short term, but the lasting effects of additional water diminish to zero by the September stress period following the drying up of the pond at the end of the April stress period. The total volume increase can be directly attributed to infiltration, as less water is input to the system from storage when the infiltration pond is present. Additional water into the system discharges to the river or is removed at the eastern head dependent boundary in the spring months and does not remain in the system into the summer and fall when increased baseflow is desired.

The amount of evapotranspiration from the model domain increases with the addition of an infiltration pond. Over the calibrated (no pond) model, average annual ET increases 2.67% for the simulated 8-m wide pond up to 3.22% for the 35-m wide pond. More evapotranspiration occurs as pond size increases, but not appreciably. The increased evapotranspiration does not exceed measured PET over the model domain. The simulated ponds were designed to go dry at the end of April when recharge from the uplands north of the site ceases. At this time PET is below its maximum value. If the simulation extended the timeframe in which the ponds had water, losses to evaporation would likely be higher and more noticeable for ponds of larger size.

The benefit of an infiltration pond is not entirely lost if groundwater storage is not enhanced long term. A possible solution to slow infiltration, and thus delay discharge into the river, could be accomplished by adding a pond liner. Even without slowed infiltration, a pond at TVFF would capture excess runoff, which may serve to prevent downstream flooding. The type of infiltration pond simulated here was shallow and essentially spread water over the floodplain; it could be created simply with a small structure similar to a beaver dam analog. This would add habitat complexity to the floodplain and over time may serve to reconnect upper areas the floodplain with the Teanaway River.

Future work that addresses the limitations of the groundwater flow model may provide more conclusive answers regarding the quantity and timing of infiltration and discharge. In particular, considering the influence of Johns Creek and assessing the risk of downgradient flooding would be instructive. Additional model scenarios could investigate using a lowered hydraulic conductivity in the pond to determine if delayed infiltration would affect the timing of discharge into the river or if evaporative losses would negate any gains in groundwater volume. Lastly, continuing to refine the groundwater flow model's calibration against observed heads may be able to provide further insight into the in-situ physical properties of the aquifer materials at the site, including hydraulic conductivity, porosity, and specific yield. The iterative nature of calibrating the groundwater flow model and updating the weighted average of specific yield for the shallow alluvial aquifer in the analytical mass balance model helps to provide valuable information on the amount of groundwater storage physically available at TVFF and can be extended along the extent of the Teanaway River.

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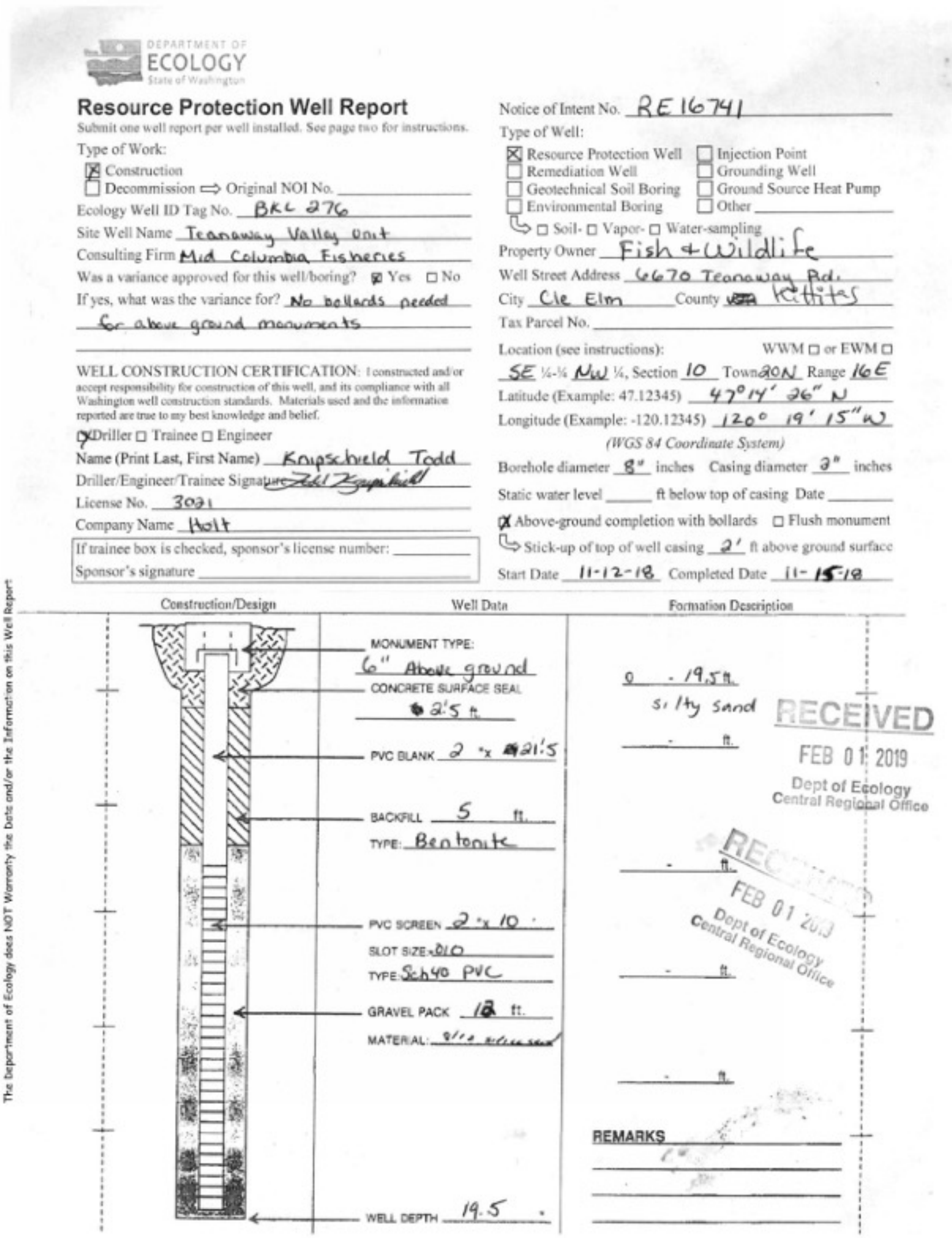
APPENDICES

APPENDIX A

FIELD DATA AND ANALYSES

Well Logs

Well 1



DEPARTMENT OF ECOLOGY State of Washington

Resource Protection Well Report

Submit one well report per well installed. See page two for instructions.

Type of Work:
[X] Construction
[ ] Decommission ⇒ Original NOI No. ____

Ecology Well ID Tag No. BKL 276

Site Well Name Teanaway Valley Unit

Consulting Firm Mid Columbia Fisheries

Was a variance approved for this well/boring? [X] Yes [ ] No

If yes, what was the variance for? No bollards needed for above ground monuments

WELL CONSTRUCTION CERTIFICATION: I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported are true to my best knowledge and belief.

[X] Driller [ ] Trainee [ ] Engineer

Name (Print Last, First Name) Knipschield Todd

Driller/Engineer/Trainee Signature Todd Knipschield

License No. 3021

Company Name Holt

If trainee box is checked, sponsor's license number: ____

Sponsor's signature ____

Notice of Intent No. RE16741

Type of Well:
[X] Resource Protection Well [ ] Injection Point
[ ] Remediation Well [ ] Grounding Well
[ ] Geotechnical Soil Boring [ ] Ground Source Heat Pump
[ ] Environmental Boring [ ] Other ____
[ ] Soil- [ ] Vapor- [ ] Water-sampling

Property Owner Fish + Wildlife

Well Street Address 6670 Teanaway Rd.

City Cle Elm County Kittitas

Tax Parcel No. ____

Location (see instructions): WWM [ ] or EWM [ ]

SE ¼-¼ NW ¼, Section 10 Town 20N Range 16E

Latitude (Example: 47.12345) 47° 14' 26" N

Longitude (Example: -120.12345) 120° 19' 15" W

(WGS 84 Coordinate System)

Borehole diameter 8" inches Casing diameter 2" inches

Static water level ____ ft below top of casing Date ____

[X] Above-ground completion with bollards [ ] Flush monument

Stick-up of top of well casing 2' ft above ground surface

Start Date 11-12-18 Completed Date 11-15-18

Construction/Design	Well Data	Formation Description
	MONUMENT TYPE: 6" Above ground	0 - 19.5 ft. silty sand
	CONCRETE SURFACE SEAL 2.5 ft	- ft.
	PVC BLANK 2 "x 21.5	- ft.
	BACKFILL 5 ft. TYPE: Bentonite	- ft.
	PVC SCREEN 2 "x 10 ' SLOT SIZE .010 TYPE: Sch40 PVC	- ft.
	GRAVEL PACK 12 ft. MATERIAL: silica sand	REMARKS
	WELL DEPTH 19.5 '	

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Well 2

DEPARTMENT OF ECOLOGY
State of Washington

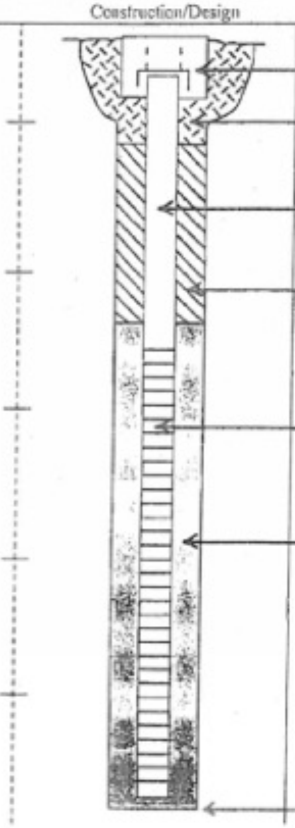
Resource Protection Well Report

Submit one well report per well installed. See page two for instructions.

Type of Work:
[X] Construction
[ ] Decommission ⇨ Original NOI No. ______
Ecology Well ID Tag No. BKL 277
Site Well Name Teanaway Valley Unit
Consulting Firm Mid Columbia Fisheries
Was a variance approved for this well/boring? [X] Yes [ ] No
If yes, what was the variance for? No bollards needed for above ground monuments

WELL CONSTRUCTION CERTIFICATION: I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported are true to my best knowledge and belief.
[X] Driller [ ] Trainee [ ] Engineer
Name (Print Last, First Name) Knipschield Todd
Driller/Engineer/Trainee Signature Todd Knipschield
License No. 3021
Company Name Holt
If trainee box is checked, sponsor's license number: ______
Sponsor's signature ______

Notice of Intent No. RE16741
Type of Well:
[X] Resource Protection Well [ ] Injection Point
[ ] Remediation Well [ ] Grounding Well
[ ] Geotechnical Soil Boring [ ] Ground Source Heat Pump
[ ] Environmental Boring [ ] Other ______
↳ [ ] Soil- [ ] Vapor- [ ] Water-sampling
Property Owner Fish + Wildlife
Well Street Address 6670 Teanaway Rd.
City Cle Elm County Kittitas
Tax Parcel No. ______
Location (see instructions): WWM [ ] or EWM [ ]
SE ¼-¼ NW ¼, Section 10 Town 20N Range 16E
Latitude (Example: 47.12345) ______
Longitude (Example: -120.12345) ______
(WGS 84 Coordinate System)
Borehole diameter 8" inches Casing diameter 2" inches
Static water level ______ ft below top of casing Date ______
[X] Above-ground completion with bollards [ ] Flush monument
↳ Stick-up of top of well casing 2' ft above ground surface
Start Date 11-12-18 Completed Date 11-15-18

Construction/Design	Well Data	Formation Description
	MONUMENT TYPE: 6" Above ground CONCRETE SURFACE SEAL 2.5 ft. PVC BLANK 2"x 23.5 BACKFILL 7 ft. TYPE: Bentonite PVC SCREEN 2"x 10' SLOT SIZE: 0.010 TYPE: PVC Sc40 GRAVEL PACK 12' ft. MATERIAL: 8/12 silica sand WELL DEPTH 22.5	0 - 18 ft. silt 18 - 22.5 ft. Silty sand + gravel - ft. - ft. - ft. REMARKS

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The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report

Well 3

DEPARTMENT OF ECOLOGY
State of Washington

Resource Protection Well Report

Submit one well report per well installed. See page two for instructions.

Type of Work:
☒ Construction
☐ Decommission ⇒ Original NOI No. ________

Ecology Well ID Tag No. BKL 275

Site Well Name Teanaway Valley Unit

Consulting Firm Mid Columbia Fisheries

Was a variance approved for this well/boring? ☒ Yes ☐ No

If yes, what was the variance for? No bollards needed for above ground monuments

WELL CONSTRUCTION CERTIFICATION: I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported are true to my best knowledge and belief.

☒ Driller ☐ Trainee ☐ Engineer

Name (Print Last, First Name) Knipschield Todd

Driller/Engineer/Trainee Signature [signature]

License No. 3021

Company Name Holt

If trainee box is checked, sponsor's license number: ________

Sponsor's signature ________

Notice of Intent No. RE16741

Type of Well:
☒ Resource Protection Well ☐ Injection Point
☐ Remediation Well ☐ Grounding Well
☐ Geotechnical Soil Boring ☐ Ground Source Heat Pump
☐ Environmental Boring ☐ Other ________
☐ Soil- ☐ Vapor- ☐ Water-sampling

Property Owner Fish + Wildlife

Well Street Address 6670 Teanaway Rd.

City Cle Elm County Kittitas

Tax Parcel No. ________

Location (see instructions): WWM ☐ or EWM ☐

SE ¼-¼ NW ¼, Section 10 Town 20N Range 16E

Latitude (Example: 47.12345) 47° 14' 18'N

Longitude (Example: -120.12345) 120° 49' 27"W

(WGS 84 Coordinate System)

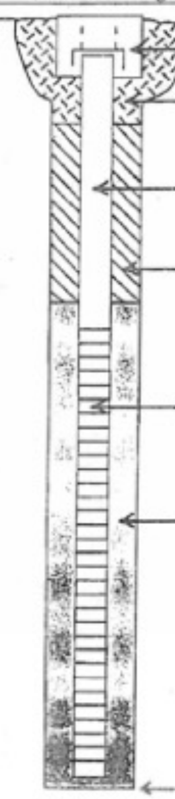
Borehole diameter 8" inches Casing diameter 2" inches

Static water level ______ ft below top of casing Date ________

☒ Above-ground completion with bollards ☐ Flush monument

Stick-up of top of well casing 2' ft above ground surface

Start Date 11-12-18 Completed Date 11-15-18

Construction/Design	Well Data	Formation Description
	MONUMENT TYPE: 6" Above ground CONCRETE SURFACE SEAL 2.5' ft. PVC BLANK 2 "x 22' BACKFILL 5.5 ft. TYPE: Bentonite PVC SCREEN 2 "x 10' SLOT SIZE: 0.010 TYPE: Sch40 PVC GRAVEL PACK 12' ft. MATERIAL: 8/12 silica WELL DEPTH 20'	0 - 15 ft. silt 15 - 20 ft. silty sand & gravel - ft. - ft. - ft. REMARKS

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Dept of Ecology
Central Regional Office

The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report

Well 4

DEPARTMENT OF ECOLOGY State of Washington

Resource Protection Well Report

Submit one well report per well installed. See page two for instructions.

Type of Work:
☒ Construction
☐ Decommission ⇨ Original NOI No. ____________

Ecology Well ID Tag No. BKL 274
Site Well Name Teanaway Valley Unit
Consulting Firm Mid Columbia Fisheries
Was a variance approved for this well/boring? ☒ Yes ☐ No
If yes, what was the variance for? No bollards needed for above ground monuments

WELL CONSTRUCTION CERTIFICATION: I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported are true to my best knowledge and belief.

☒ Driller ☐ Trainee ☐ Engineer
Name (Print Last, First Name) Knipschield Todd
Driller/Engineer/Trainee Signature [signature]
License No. 3021
Company Name Holt

If trainee box is checked, sponsor's license number: ____________
Sponsor's signature ____________

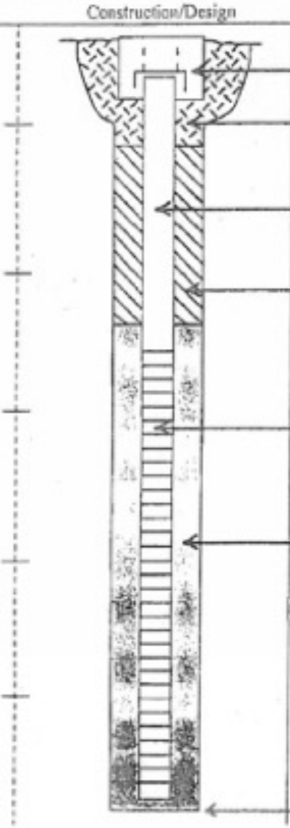
Notice of Intent No. RE16741

Type of Well:
☒ Resource Protection Well ☐ Injection Point
☐ Remediation Well ☐ Grounding Well
☐ Geotechnical Soil Boring ☐ Ground Source Heat Pump
☐ Environmental Boring ☐ Other ____________
↳ ☐ Soil- ☐ Vapor- ☐ Water-sampling

Property Owner Fish & Wildlife
Well Street Address 6670 Teanaway Rd.
City Cle Elm County Kittitas
Tax Parcel No. ____________

Location (see instructions): WWM ☐ or EWM ☐
SE ¼-¼ NW ¼, Section 10 Town 20N Range 16E
Latitude (Example: 47.12345) 47° 14' 17 N
Longitude (Example: -120.12345) 120° 49 32W
(WGS 84 Coordinate System)

Borehole diameter 8" inches Casing diameter 2" inches
Static water level ______ ft below top of casing Date ______
☒ Above-ground completion with bollards ☐ Flush monument
↳ Stick-up of top of well casing 2' ft above ground surface
Start Date 11-12-18 Completed Date 11-15-18

Construction/Design	Well Data	Formation Description
	MONUMENT TYPE: 6" Above ground	0 - 10 ft. Silt
	CONCRETE SURFACE SEAL 2.5 ft.	10 - 14.5 ft. Silty sand & gravel
	PVC BLANK 2"x 19.5"	- ft.
	BACKFILL 5 ft. TYPE: Bentonite	- ft.
	PVC SCREEN 2" x 5'. SLOT SIZE: 0.010 TYPE: sch 40 PVC	- ft.
	GRAVEL PACK 7 ft. MATERIAL: [illegible] silica	
	WELL DEPTH 14.5	REMARKS

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The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report

Well 5

DEPARTMENT OF ECOLOGY State of Washington

Resource Protection Well Report

Submit one well report per well installed. See page two for instructions.

Type of Work:

- [X] Construction
- [ ] Decommission ⇒ Original NOI No. ____

Ecology Well ID Tag No. BKL 270

Site Well Name Teanaway Valley Unit

Consulting Firm Mid Columbia Fisheries

Was a variance approved for this well/boring? [X] Yes [ ] No

If yes, what was the variance for? No bollards needed for above ground monuments

Notice of Intent No. RE16741

Type of Well:

- [X] Resource Protection Well
- [ ] Remediation Well
- [ ] Geotechnical Soil Boring
- [ ] Environmental Boring
- [ ] Injection Point
- [ ] Grounding Well
- [ ] Ground Source Heat Pump
- [ ] Other ____

↳ □ Soil- □ Vapor- □ Water-sampling

Property Owner Fish + Wildlife

Well Street Address 6670 Teanaway Rd.

City Cle Elm County Kittitas

Tax Parcel No. ____

Location (see instructions): WWM □ or EWM □

SE ¼-¼ NW ¼, Section 10 Town 20N Range 16E

Latitude (Example: 47.12345) 47° 14' 15" N

Longitude (Example: -120.12345) 120° 49' 37" W

(WGS 84 Coordinate System)

WELL CONSTRUCTION CERTIFICATION: I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported are true to my best knowledge and belief.

[X] Driller □ Trainee □ Engineer

Name (Print Last, First Name) Knipschield Todd

Driller/Engineer/Trainee Signature [signature]

License No. 3021

Company Name Holt

If trainee box is checked, sponsor's license number: ____

Sponsor's signature ____

Borehole diameter 8" inches Casing diameter 2" inches

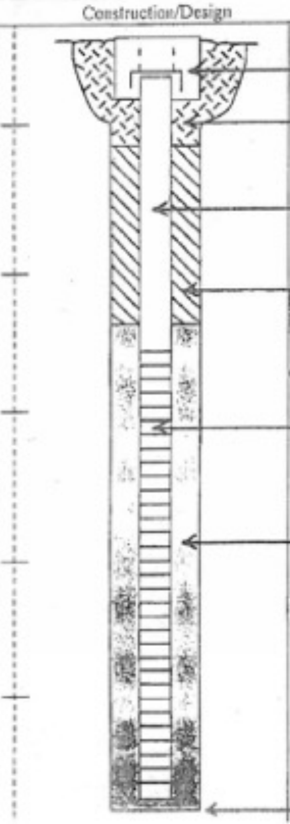
Static water level ____ ft below top of casing Date ____

[X] Above-ground completion with bollards □ Flush monument

↳ Stick-up of top of well casing 2' ft above ground surface

Start Date 11-12-18 Completed Date 11-15-18

The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report

Construction/Design	Well Data	Formation Description
	MONUMENT TYPE: 6" Above ground	0 - 5 ft. Silt sand + gravel
	CONCRETE SURFACE SEAL 2.5' ft.	5 - 12.5 ft. sand + gravel
	PVC BLANK 2" x 9.5'	- ft.
	BACKFILL 3 ft.	- ft.
	TYPE: bentonite	- ft.
	PVC SCREEN 2" x 5'.	
	SLOT SIZE: 0.010	
	TYPE: Sch40	
	GRAVEL PACK 7' ft.	
	MATERIAL: 8/12 silica	
	WELL DEPTH 12.5	REMARKS

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Well 6

DEPARTMENT OF ECOLOGY State of Washington

Resource Protection Well Report

Submit one well report per well installed. See page two for instructions.

Type of Work:
☒ Construction
☐ Decommission ⇨ Original NOI No. ________

Ecology Well ID Tag No. 273

Site Well Name Teanaway Valley Unit

Consulting Firm Mid Columbia Fisheries

Was a variance approved for this well/boring? ☒ Yes ☐ No

If yes, what was the variance for? No bollards needed for above ground monuments

WELL CONSTRUCTION CERTIFICATION: I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported are true to my best knowledge and belief.

☒ Driller ☐ Trainee ☐ Engineer

Name (Print Last, First Name) Knipschield Todd

Driller/Engineer/Trainee Signature [signature]

License No. 3021

Company Name Holt

If trainee box is checked, sponsor's license number: ________

Sponsor's signature ________

Notice of Intent No. RE16741

Type of Well:
☒ Resource Protection Well ☐ Injection Point
☐ Remediation Well ☐ Grounding Well
☐ Geotechnical Soil Boring ☐ Ground Source Heat Pump
☐ Environmental Boring ☐ Other ________
☐ Soil- ☐ Vapor- ☐ Water-sampling

Property Owner Fish + Wildlife

Well Street Address 6670 Teanaway Rd.

City Cle Elm County Kittitas

Tax Parcel No. ________

Location (see instructions): WWM ☐ or EWM ☐

SE ¼-¼ NW ¼, Section 10 Town 20N Range 16E

Latitude (Example: 47.12345) 47° 14' 12" N

Longitude (Example: -120.12345) 120° 49' 32" W

(WGS 84 Coordinate System)

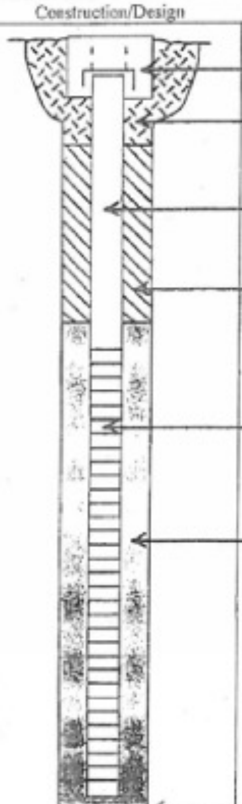
Borehole diameter 8" inches Casing diameter 2" inches

Static water level ______ ft below top of casing Date ______

☒ Above-ground completion with bollards ☐ Flush monument

Stick-up of top of well casing 2' ft above ground surface

Start Date 11-12-18 Completed Date 11-15-18

Construction/Design	Well Data	Formation Description
	MONUMENT TYPE: 6" Above ground CONCRETE SURFACE SEAL 2.5" ft. PVC BLANK 2" x 10.5' BACKFILL 4 ft. TYPE: Bentonite PVC SCREEN 2" x 5' SLOT SIZE: .010 TYPE: PVC Sch 40 GRAVEL PACK 7 ft. MATERIAL: 8/12 Silica WELL DEPTH 13.5'	0 - 8 ft. Silty sand 8 - 13.5 ft. Sand + gravel - ft. - ft. - ft. REMARKS

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The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report

Well 7

DEPARTMENT OF ECOLOGY State of Washington

Resource Protection Well Report

Submit one well report per well installed. See page two for instructions.

Type of Work:
[X] Construction
[ ] Decommission ⇒ Original NOI No. ______

Ecology Well ID Tag No. BKL 272

Site Well Name Teanaway Valley Unit

Consulting Firm Mid Columbia Fisheries

Was a variance approved for this well/boring? [X] Yes [ ] No

If yes, what was the variance for? No bollards needed for above ground monuments

WELL CONSTRUCTION CERTIFICATION: I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported are true to my best knowledge and belief.

[X] Driller [ ] Trainee [ ] Engineer

Name (Print Last, First Name) Knipschield Todd

Driller/Engineer/Trainee Signature [signature]

License No. 3021

Company Name Holt

If trainee box is checked, sponsor's license number: ______

Sponsor's signature ______

Notice of Intent No. RE 16741

Type of Well:
[X] Resource Protection Well [ ] Injection Point
[ ] Remediation Well [ ] Grounding Well
[ ] Geotechnical Soil Boring [ ] Ground Source Heat Pump
[ ] Environmental Boring [ ] Other ______
[ ] Soil- [ ] Vapor- [ ] Water-sampling

Property Owner Fish + Wildlife

Well Street Address 6670 Teanaway Rd.

City Cle Elm County WA Kittitas

Tax Parcel No. ______

Location (see instructions): WWM [ ] or EWM [ ]

SE ¼-¼ NW ¼, Section 10 Town 20N Range 16E

Latitude (Example: 47.12345) 47° 14' 19" N

Longitude (Example: -120.12345) 120° 49' 53" W

(WGS 84 Coordinate System)

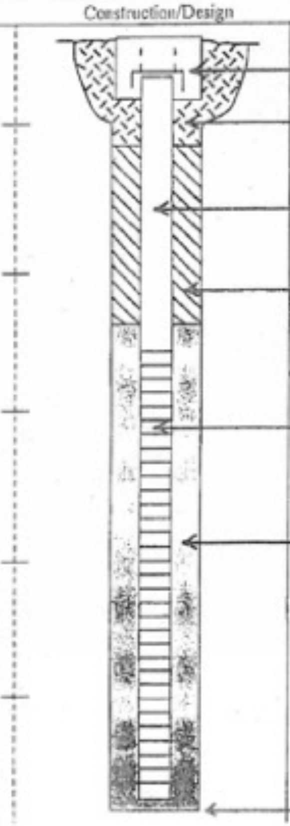
Borehole diameter 8" inches Casing diameter 2" inches

Static water level ______ ft below top of casing Date ______

[X] Above-ground completion with bollards [ ] Flush monument

Stick-up of top of well casing 2' ft above ground surface

Start Date 11-12-18 Completed Date 11-15-18

Construction/Design	Well Data	Formation Description
	MONUMENT TYPE: 6" Above ground CONCRETE SURFACE SEAL 2.5' ft. PVC BLANK 2"x 10' BACKFILL 3.5 ft. TYPE: Bentonite PVC SCREEN 2"x 5' SLOT SIZE .010 TYPE: Sch40 PVC GRAVEL PACK 7 ft. MATERIAL: 8/12 silica WELL DEPTH 13'	0 - 13' ft. Sand gravel cobbles - ft. - ft. - ft. - ft. REMARKS

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The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report

Well 8

DEPARTMENT OF ECOLOGY State of Washington

Resource Protection Well Report

Submit one well report per well installed. See page two for instructions.

Type of Work:
- [x] Construction
- [ ] Decommission ⇨ Original NOI No. ______

Ecology Well ID Tag No. BKL 269

Site Well Name Teanaway Valley Unit

Consulting Firm Mid Columbia Fisheries

Was a variance approved for this well/boring? ☒ Yes ☐ No

If yes, what was the variance for? No bollards needed for above ground monuments

WELL CONSTRUCTION CERTIFICATION: I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported are true to my best knowledge and belief.

☒ Driller ☐ Trainee ☐ Engineer

Name (Print Last, First Name) Knipschield Todd

Driller/Engineer/Trainee Signature Todd Knipschield

License No. 3021

Company Name Holt

If trainee box is checked, sponsor's license number: ______

Sponsor's signature ______

Notice of Intent No. RE 16741

Type of Well:
- [x] Resource Protection Well
- [ ] Remediation Well
- [ ] Geotechnical Soil Boring
- [ ] Environmental Boring
  - ☐ Soil- ☐ Vapor- ☐ Water-sampling
- [ ] Injection Point
- [ ] Grounding Well
- [ ] Ground Source Heat Pump
- [ ] Other ______

Property Owner Fish + Wildlife

Well Street Address 6670 Teanaway Rd.

City Cle Elm County WA Kittitas

Tax Parcel No. ______

Location (see instructions): WWM ☐ or EWM ☐

SE ¼-¼ NW ¼, Section 10 Town 20N Range 16E

Latitude (Example: 47.12345) 47° 14' 13" N

Longitude (Example: -120.12345) 120° 49' 44" W

(WGS 84 Coordinate System)

Borehole diameter 8" inches Casing diameter 2" inches

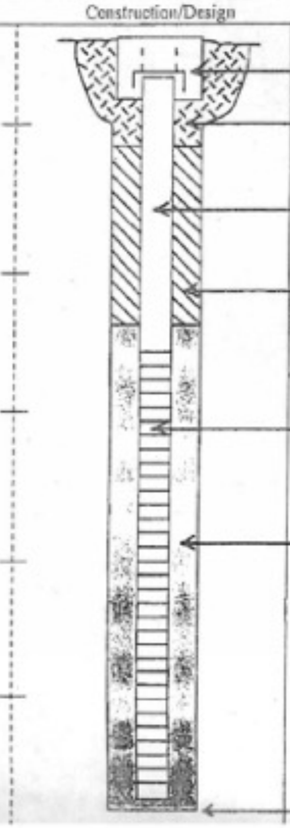
Static water level ______ ft below top of casing Date ______

☒ Above-ground completion with bollards ☐ Flush monument

Stick-up of top of well casing 2' ft above ground surface

Start Date 11-12-18 Completed Date 11-15-18

The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report

Construction/Design	Well Data	Formation Description
	MONUMENT TYPE: 6" Above ground CONCRETE SURFACE SEAL 2.5' ft. PVC BLANK 2" x 9' BACKFILL 2.5 ft. TYPE: Bentonite PVC SCREEN 2" x 5' SLOT SIZE: 0.010 TYPE: Sch40 PVC GRAVEL PACK 7' ft. MATERIAL: 8/12 silica WELL DEPTH 12'	0 - 12 ft. Cobbles sand + gravel - ft. - ft. - ft. - ft. REMARKS

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Well 9

DEPARTMENT OF ECOLOGY State of Washington

Resource Protection Well Report

Submit one well report per well installed. See page two for instructions.

Type of Work:
[X] Construction
[ ] Decommission ⇨ Original NOI No. ______

Ecology Well ID Tag No. BKL 271

Site Well Name Teanaway Valley Unit

Consulting Firm Mid Columbia Fisheries

Was a variance approved for this well/boring? [X] Yes [ ] No

If yes, what was the variance for? No bollards needed for above ground monuments

WELL CONSTRUCTION CERTIFICATION: I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported are true to my best knowledge and belief.

[X] Driller [ ] Trainee [ ] Engineer

Name (Print Last, First Name) Knipschield Todd

Driller/Engineer/Trainee Signature Todd Knipschield

License No. 3021

Company Name Holt

If trainee box is checked, sponsor's license number: ______

Sponsor's signature ______

Notice of Intent No. RE 16741

Type of Well:
[X] Resource Protection Well [ ] Injection Point
[ ] Remediation Well [ ] Grounding Well
[ ] Geotechnical Soil Boring [ ] Ground Source Heat Pump
[ ] Environmental Boring [ ] Other ______
↳ [ ] Soil- [ ] Vapor- [ ] Water-sampling

Property Owner Fish + Wildlife

Well Street Address 6670 Teanaway Rd.

City Cle Elm County ~~WA~~ Kittitas

Tax Parcel No. ______

Location (see instructions): WWM [ ] or EWM [ ]

SE ¼-¼ NW ¼, Section 10 Town 20N Range 16E

Latitude (Example: 47.12345) 47° 14' 16"N

Longitude (Example: -120.12345) 12° 49' 50"W

(WGS 84 Coordinate System)

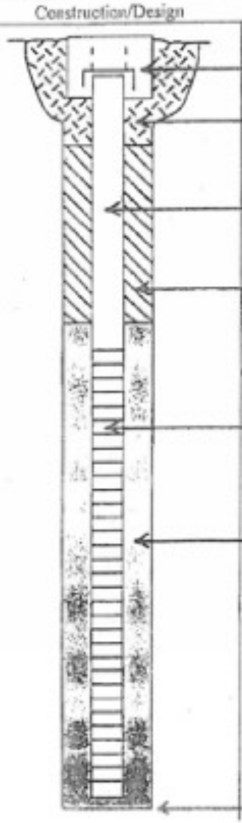
Borehole diameter 8" inches Casing diameter 2" inches

Static water level ______ ft below top of casing Date ______

[X] Above-ground completion with bollards [ ] Flush monument

↳ Stick-up of top of well casing 2' ft above ground surface

Start Date 11-12-18 Completed Date 11-15-18

Construction/Design	Well Data	Formation Description
	MONUMENT TYPE: 6" Above ground CONCRETE SURFACE SEAL 2.5' ft. PVC BLANK 2"x7.5' BACKFILL 2 ft. TYPE: Bentonite PVC SCREEN 2"x 5' SLOT SIZE: 0.010 TYPE: Sch40 PVC GRAVEL PACK 6 ft. MATERIAL: ~~PEA~~ 8/12 silica WELL DEPTH 10.5	0 - 10.5 ft. Cobbles sand & gravel - ft. - ft. - ft. - ft. REMARKS

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FEB 01 2019
Dept of Ecology
Central Regional Office

The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report

Well 10

DEPARTMENT OF ECOLOGY State of Washington

Resource Protection Well Report

Submit one well report per well installed. See page two for instructions.

Type of Work:
- [x] Construction
- [ ] Decommission ⇨ Original NOI No. ______

Ecology Well ID Tag No. BKL 268

Site Well Name Teanaway Valley Unit

Consulting Firm Mid Columbia Fisheries

Was a variance approved for this well/boring? ☒ Yes ☐ No

If yes, what was the variance for? No bollards needed for above ground monuments

WELL CONSTRUCTION CERTIFICATION: I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported are true to my best knowledge and belief.

☒ Driller ☐ Trainee ☐ Engineer

Name (Print Last, First Name) Knipschield Todd

Driller/Engineer/Trainee Signature [signature]

License No. 3021

Company Name Holt

If trainee box is checked, sponsor's license number: ______

Sponsor's signature ______

Notice of Intent No. RE 16741

Type of Well:
- [x] Resource Protection Well
- [ ] Injection Point
- [ ] Remediation Well
- [ ] Grounding Well
- [ ] Geotechnical Soil Boring
- [ ] Ground Source Heat Pump
- [ ] Environmental Boring
- [ ] Other ______

☐ Soil- ☐ Vapor- ☐ Water-sampling

Property Owner Fish + Wildlife

Well Street Address 6670 Teanaway Rd.

City Cle Elm County Kittitas

Tax Parcel No. ______

Location (see instructions): WWM ☐ or EWM ☐

SE ¼-¼ NW ¼, Section 10 Town 20N Range 16E

Latitude (Example: 47.12345) 47° 14' 13" N

Longitude (Example: -120.12345) 120° 49' 41" W

(WGS 84 Coordinate System)

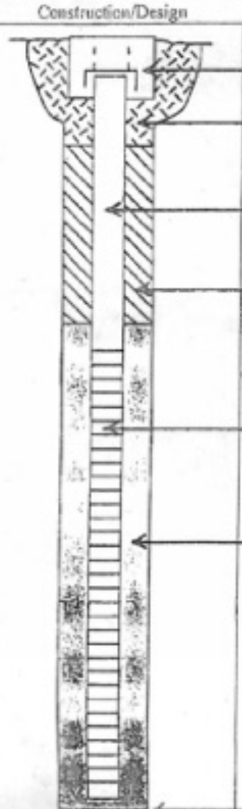
Borehole diameter 8" inches Casing diameter 2" inches

Static water level ______ ft below top of casing Date ______

☒ Above-ground completion with bollards ☐ Flush monument

Stick-up of top of well casing 2' ft above ground surface

Start Date 11-12-18 Completed Date 11-15-18

Construction/Design	Well Data	Formation Description
	MONUMENT TYPE: 6" Above ground CONCRETE SURFACE SEAL 2½' ft. PVC BLANK 2" x 9.5" BACKFILL 3.5 ft. TYPE: Bentonite PVC SCREEN 2" x 5' SLOT SIZE: .010 TYPE: PVC Sch 40 GRAVEL PACK 7' ft. MATERIAL: 8/12 WELL DEPTH 12.5'	0 - 12½ ft. Sand + gravel riverrock ~~12 - 12½~~ ft. - ft. - ft. - ft. REMARKS:

RECEIVED FEB 04 2019 Dept of Ecology Central Regional Office

The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report

Slug Test Data and Analysis

Slug tests were performed in 7 of the site observation wells. Tests used the Hvorslev method as described in Fetter (2001). The Hvorslev method calculates hydraulic conductivity according to:

$$K = \frac{r^2 \ln(L_e/R)}{2L_e t_{37}} \tag{11}$$

where

K = hydraulic conductivity (cm/s)

r = radius of the well casing (cm)

R = radius of the well screen (cm)

L_e = length of the well screen (cm)

t_{37} = time for the water level to rise (or fall) to 37% of the initial change.

t_{37} is determined from a semi-logarithmic plot of the ratio h/h_0 versus time, t. In the head ratio, h_0 is the height to which the water level rises above the static water level immediately upon lowering the slug and h is the height of water above the static water level at time t.

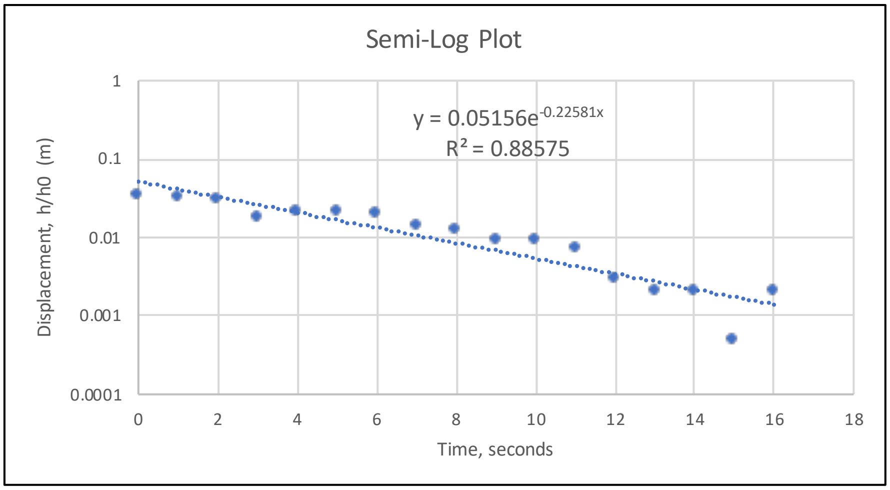
Worksheets on the following pages for each slug test performed at TVFF calculate hydraulic conductivity by (11). Pressure transducer data loggers in the wells recorded water level data at 1-second intervals for each test.

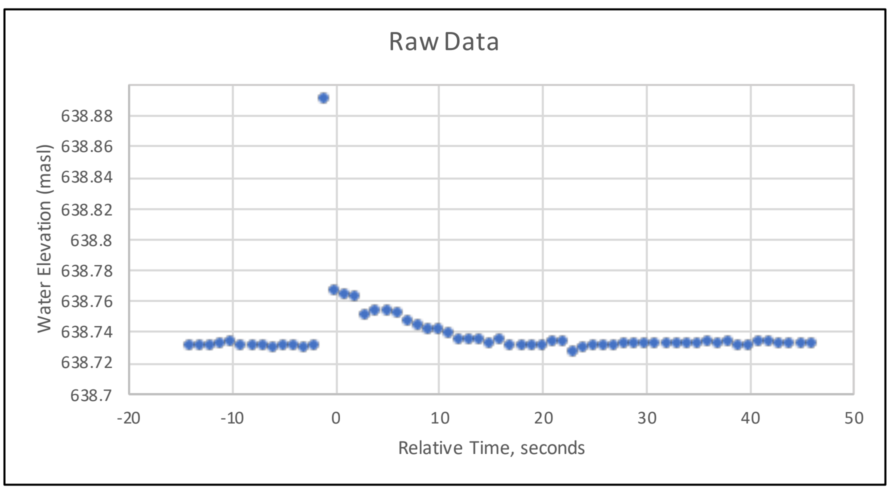
Slug tests at Wells 4 – 6 and 8 were used to characterize the Cobbles unit, and tests at Well 2 characterized the Clay unit. The hydraulic conductivities determined by the slug tests for Well 3 and Well 10 were not used. Table 2 lists the measured hydraulic conductivities.

Slug Test Data Sheet

Well ID: Well 2 — Note: the test is when the slug was dropped into the water
Date: 4/8/22
Technician: Lindsay Henning

Well Geometry			static					
r =	2.54	cm	water level =	638.732		K =	6.94E-03	cm/s
R =	5.08	cm	h_0 =	0.034			2.28E-04	ft/s
L_e =	304.8	cm	37% of h_0 =	0.013			1.97E+01	ft/d
			t_{37} =	6.25				

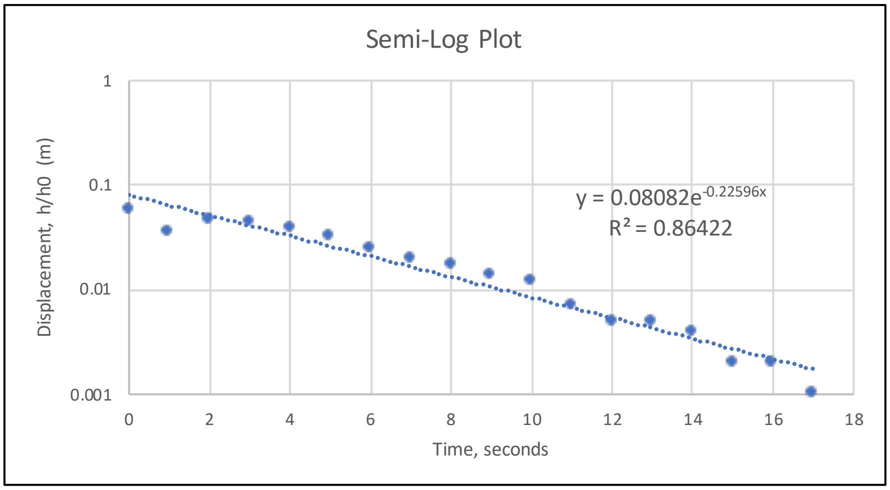


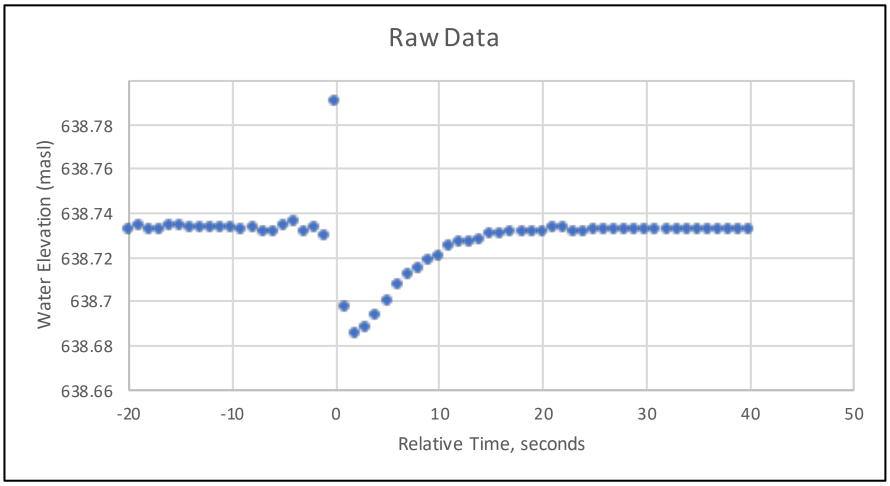


Slug Test Data Sheet

Well ID: Well 2 Note: the test is when the slug was removed from the water
Date: 4/8/22
Technician: Lindsay Henning

Well Geometry			static				
r =	2.54	cm	water level =	638.732	K =	7.38E-03	cm/s
R =	5.08	cm	h_0 =	0.058		2.42E-04	ft/s
L_e =	304.8	cm	37% of h_0 =	0.021		2.09E+01	ft/d
			t_{37} =	5.87			

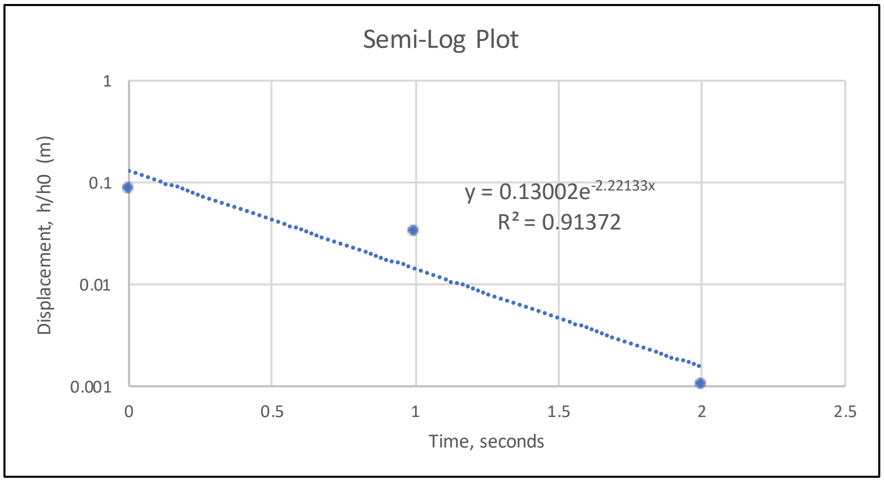


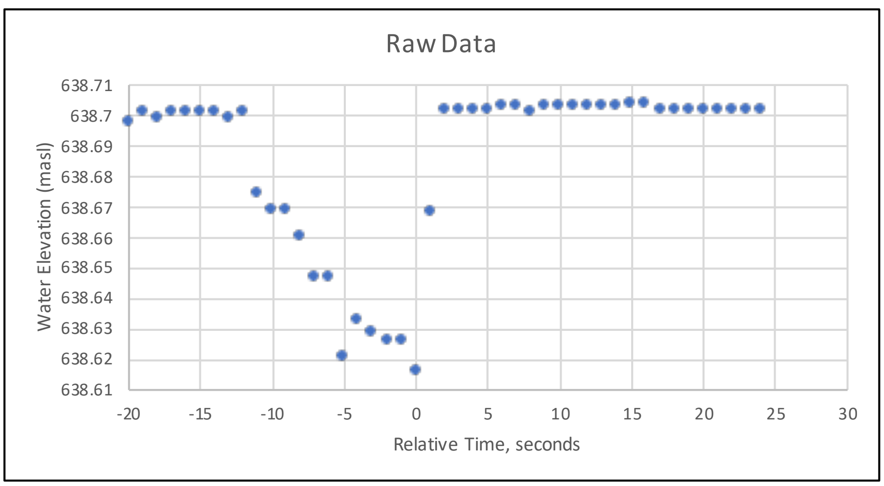


Slug Test Data Sheet

Well ID:	Well 3	Note: the test is when the slug was removed from the water	
Date:	4/8/22		
Technician:	Lindsay Henning		

Well Geometry			static				
r =	2.54	cm	water level =	638.701	K =	6.78E-02	cm/s
R =	5.08	cm	h_0 =	0.085		2.23E-03	ft/s
L_e =	304.8	cm	37% of h_0 =	0.031		1.92E+02	ft/d
			t_{37} =	0.64			

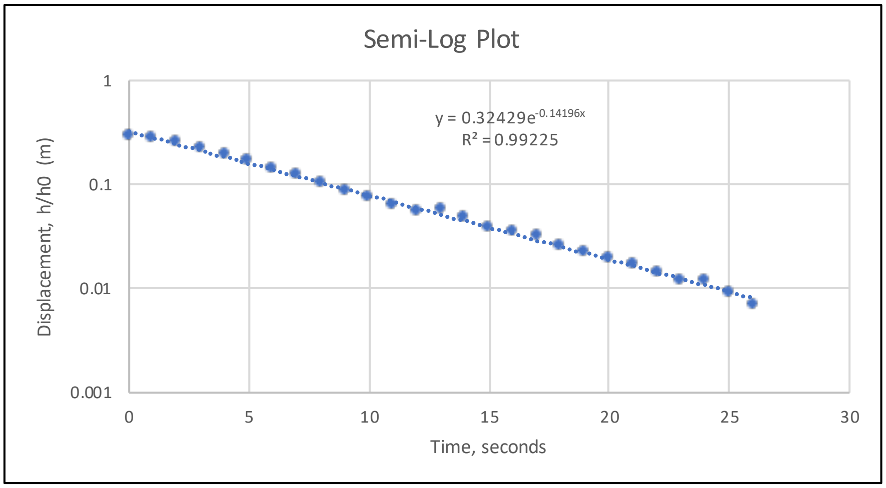


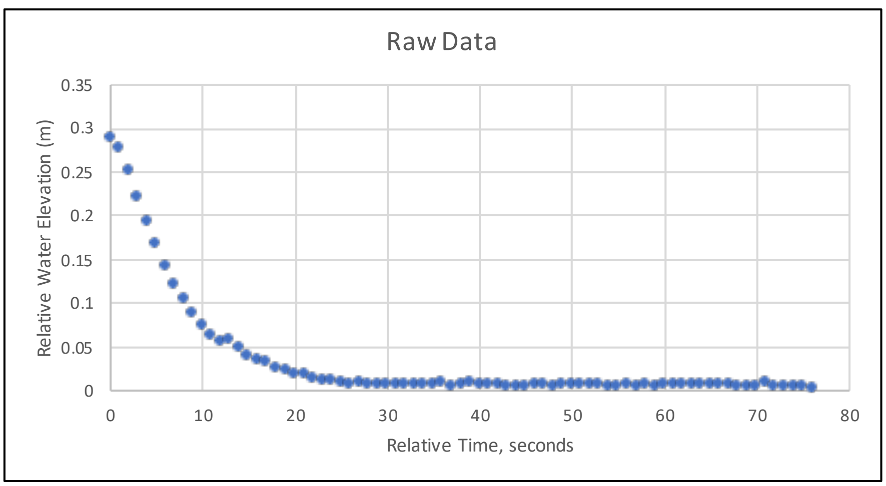


Slug Test Data Sheet

Well ID: Well 4
Date: 2/2/21
Technician: Hydrogeology class, Winter 2021

Well Geometry			static				
$r =$	2.54	cm	water level =	0	$K =$	9.18E-03	cm/s
$R =$	5.08	cm	$h_0 =$	0.288		3.01E-04	ft/s
$L_e =$	152.4	cm	37% of $h_0 =$	0.107		2.60E+01	ft/d
			$t_{37} =$	7.84			

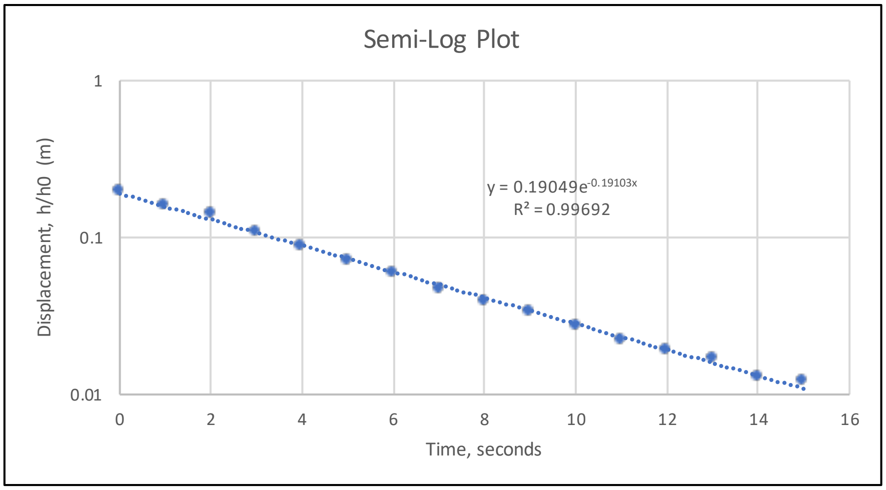


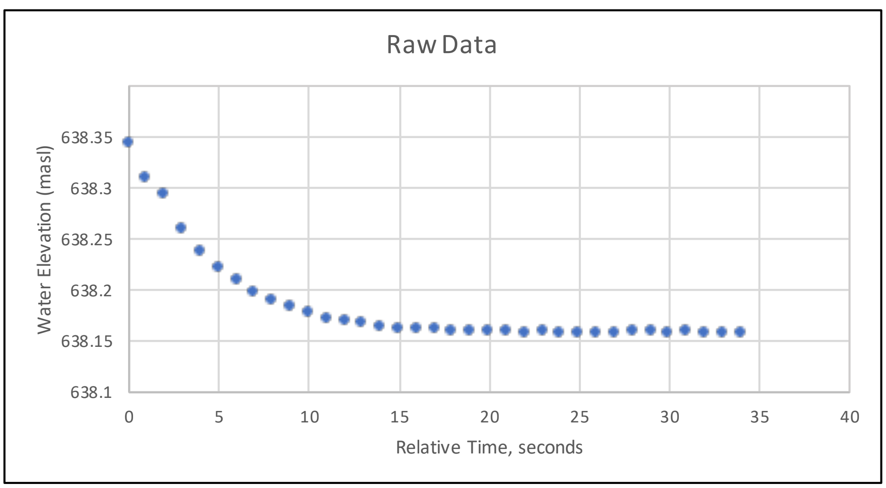


Slug Test Data Sheet

Well ID: Well 4
Date: 2/22/22
Technician: Hydrogeology class, Winter 2022

Well Geometry			static				
r =	2.54	cm	water level =	638.15	K =	1.41E-02	cm/s
R =	5.08	cm	h_0 =	0.194		4.62E-04	ft/s
L_e =	152.4	cm	37% of h_0 =	0.072		3.99E+01	ft/d
			t_{37} =	5.11			

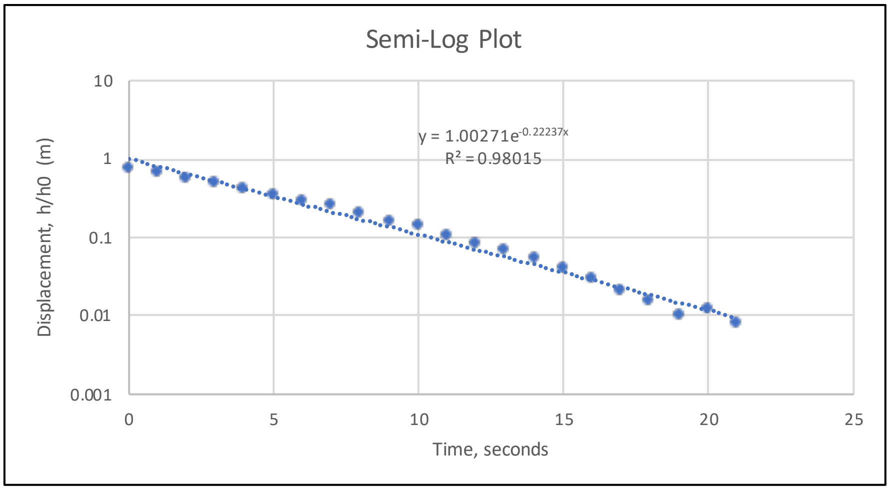


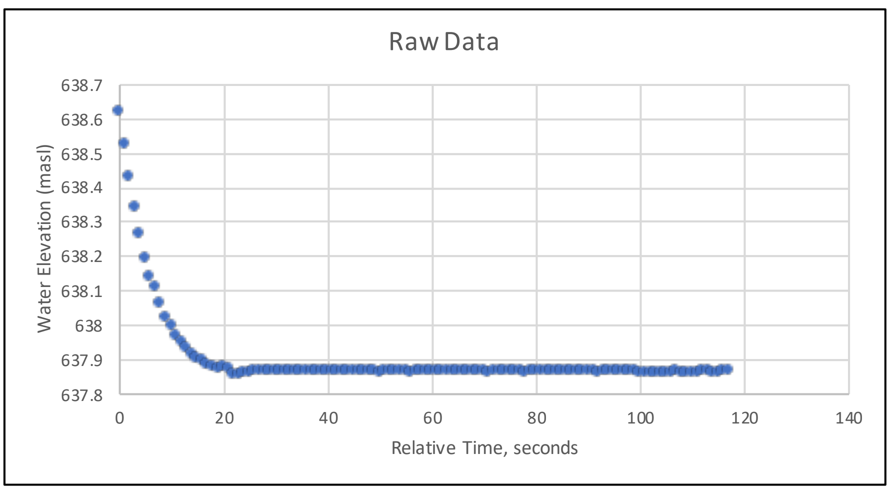


Slug Test Data Sheet

Well ID: Well 5
Date: 2/27/20
Technician: Hydrogeology Class, Winter 2020

Well Geometry			static				
r =	2.54	cm	water level =	637.864	K =	1.25E-02	cm/s
R =	5.08	cm	h_0 =	0.755		4.11E-04	ft/s
L_e =	152.4	cm	37% of h_0 =	0.279		3.55E+01	ft/d
			t_{37} =	5.75			





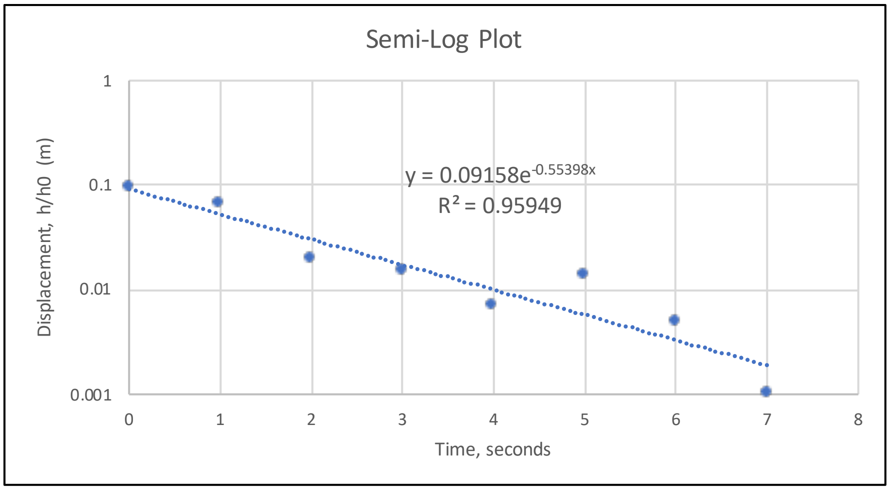
Slug Test Data Sheet

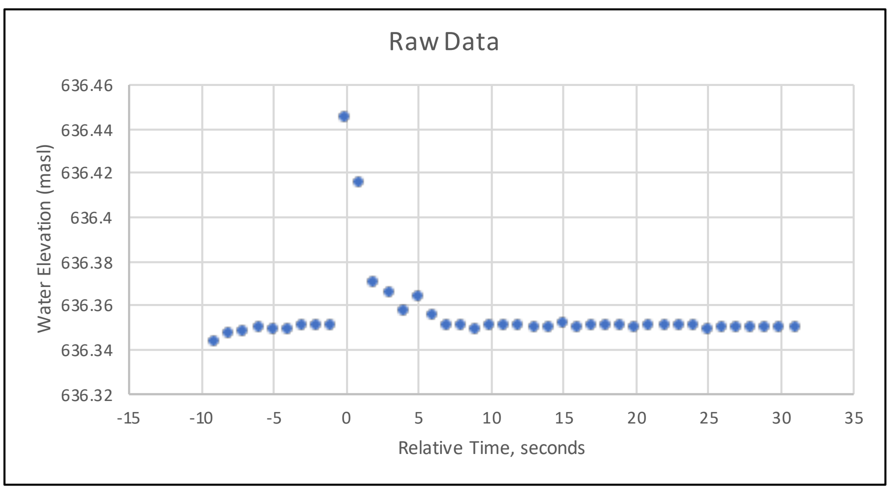
Well ID: Well 6 Note: the test is when the slug was dropped into the water

Date: 4/8/22

Technician: Lindsay Henning

Well Geometry			static		K =	4.16E-02	cm/s
r =	2.54	cm	water level =	636.350		1.37E-03	ft/s
R =	5.08	cm	h_0 =	0.095		1.18E+02	ft/d
L_e =	152.4	cm	37% of h_0 =	0.035			
			t_{37} =	1.73			

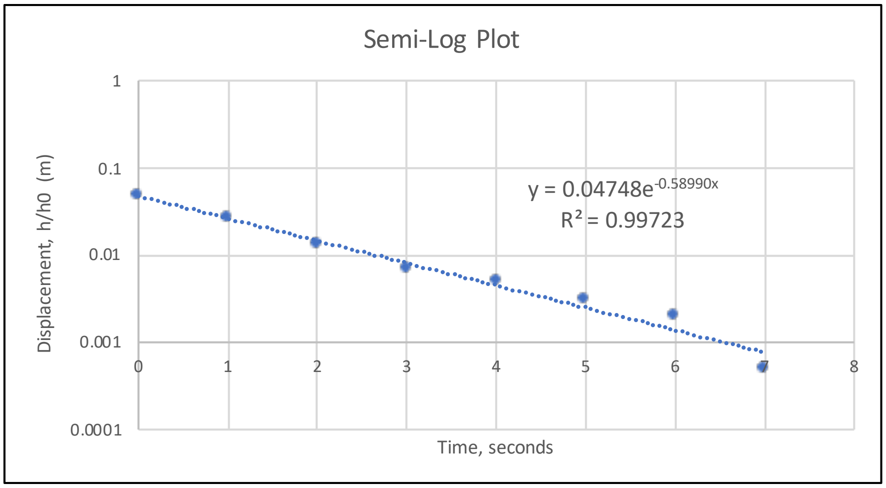


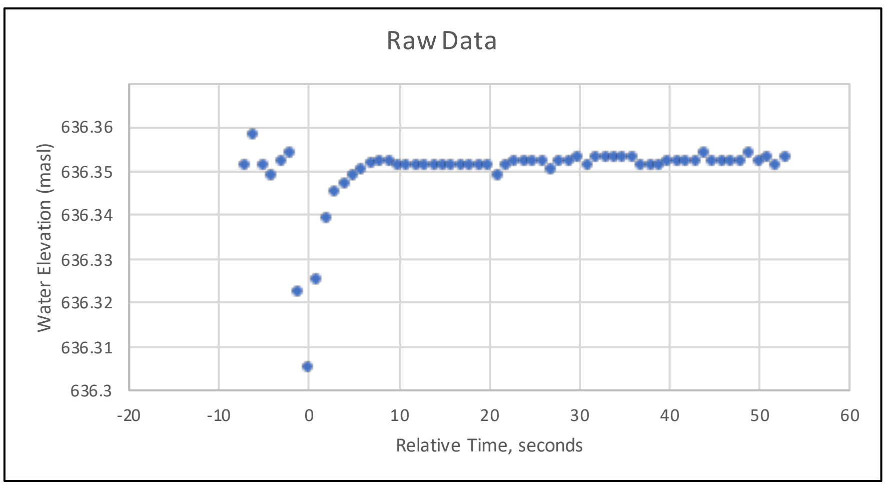


Slug Test Data Sheet

Well ID: Well 6 Note: the test is when the slug was removed from the water
Date: 4/8/22
Technician: Lindsay Henning

Well Geometry			static				
r =	2.54	cm	water level =	636.352	K =	4.23E-02	cm/s
R =	5.08	cm	h_0 =	0.047		1.39E-03	ft/s
L_e =	152.4	cm	37% of h_0 =	0.017		1.20E+02	ft/d
			t_{37} =	1.70			





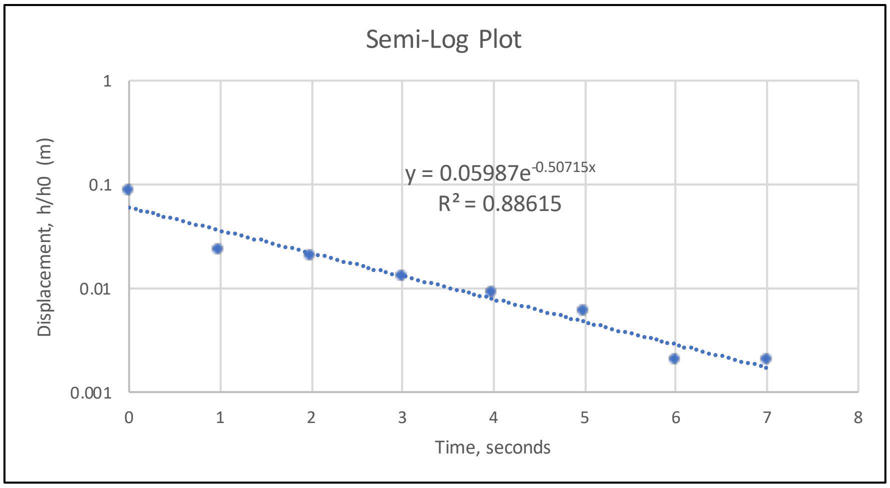
Slug Test Data Sheet

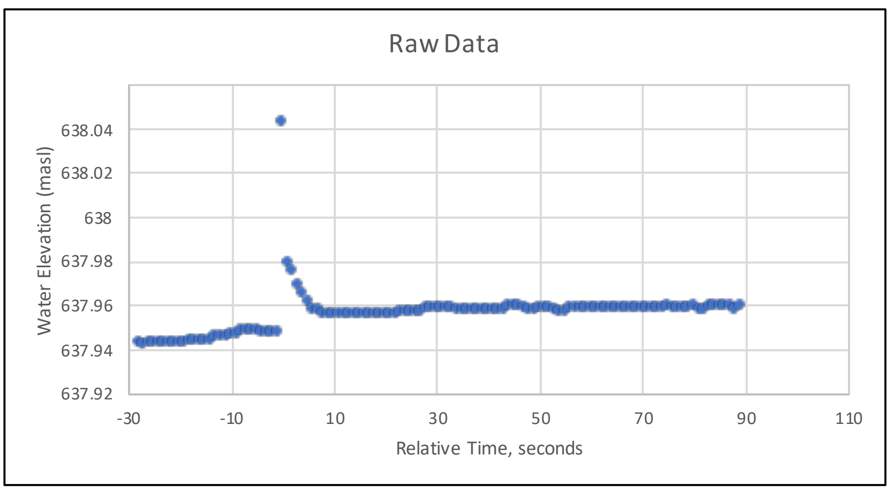
Well ID: Well 8 Note: the test is when the slug was dropped into the water

Date: 4/8/22

Technician: Lindsay Henning

Well Geometry			static		K =	5.88E-02	cm/s
r =	2.54	cm	water level =	637.956		1.93E-03	ft/s
R =	5.08	cm	h_0 =	0.087		1.67E+02	ft/d
L_e =	152.4	cm	37% of h_0 =	0.032			
			t_{37} =	1.22			

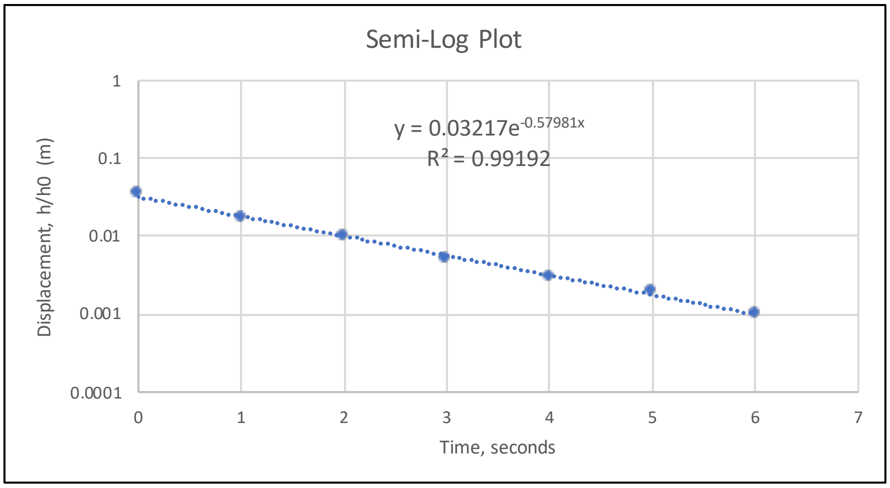


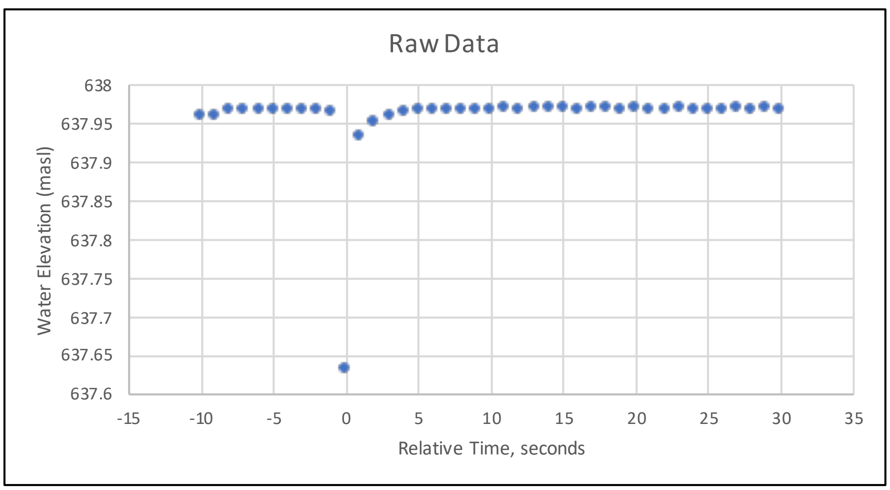


Slug Test Data Sheet

Well ID: Well 8 — Note: the test is when the slug was removed from the water
Date: 4/8/22 — water levels appear to be rising at the time of the test
Technician: Lindsay Henning

Well Geometry			static			
$r =$	2.54	cm	water level =	637.969	$K =$	4.59E-02 cm/s
$R =$	5.08	cm	$h_0 =$	0.035		1.51E-03 ft/s
$L_e =$	152.4	cm	37% of $h_0 =$	0.013		1.30E+02 ft/d
			$t_{37} =$	1.57		





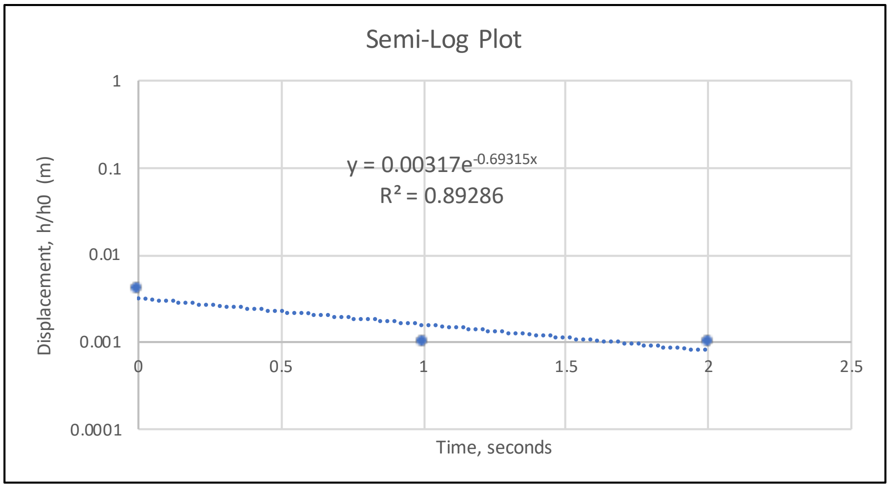
Slug Test Data Sheet

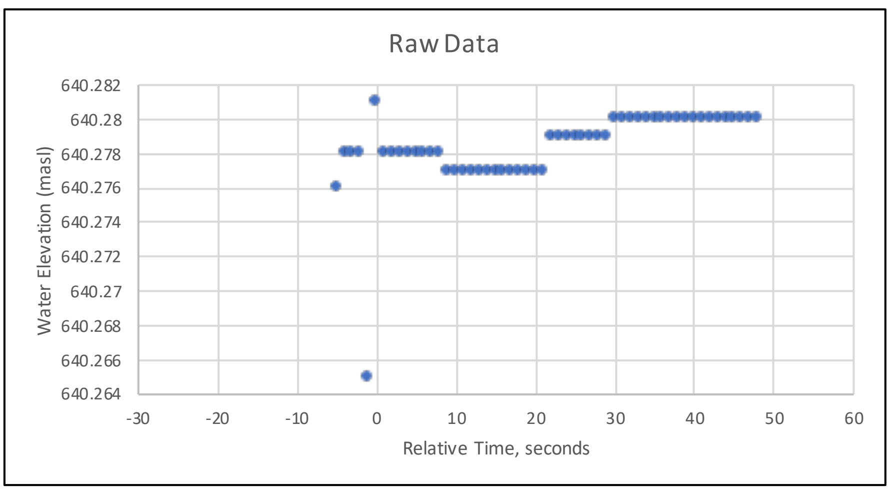
Well ID: Well 10 Note: the test is when the slug was dropped into the water

Date: 4/8/22 water levels appear to be rising at the time of the test

Technician: Lindsay Henning

Well Geometry			static			Not enough data points to be reliable	
r =	2.54	cm	water level =	640.277		K = 6.55E-02	cm/s
R =	5.08	cm	h_0 =	0.004		2.15E-03	ft/s
L_e =	152.4	cm	37% of h_0 =	0.001		1.86E+02	ft/d
			t_{37} =	1.10			





Porosity Tests

Porosity of the alluvial material was approximated in laboratory experiments from soil samples obtained at the site. Laboratory testing was performed by the Winter 2021 GEOL 545 Hydrogeology class. Volumetric and gravimetric methods were used. Results are given in Table A1.

Table A1.
Porosity Measurements by the CWU Winter 2021 GEOL 545 Hydrogeology Class

	Control	**Control**	**A**	**A**	**B**	**B**	**C**	**C**
Members	**grav (%)**	**vol (%)**	**grav (%)**	**vol (%)**	**grav (%)**	**vol (%)**	**grav (%)**	**vol (%)**
Group 1	42%	35%	41%	41%			46%	41%
Group 2	50%	51%	51%	46%	46%	29%		
Group 3 (author's group)	40%	39%	44%	43%	46%	44%	51%	45%
Group 4	42%	33%	37%	39%	45%	46%		
Mean:	44%	40%	43%	42%	46%	40%	49%	43%
Std. Dev.	4%	8%	6%	3%	1%	9%	4%	3%
Description	Cobbles		Silt, sand and gravel		Gravel Pack		Clay (with possible Soil)	
Grain Size	1mm-2cm, sand to pebbles, subrounded		~0.5cm on average with some fines, angular		< 1mm sand; very fine		<1 mm fine, powdery organics present	
Sorting	Poorly sorted		Moderate to well sorted		Well sorted		Well sorted	
Color	Brown/gray and tan		Varying grays		White		Brown	

Water Level Daily Averages

On-site wells were instrumented with Onset pressure transducers (U20-001-04 HOBO Freshwater Water Level Data Logger). A barometer was located in the top casing of Well 1. Pressure transducers logged readings at 15-minute intervals beginning in August 2019. Raw pressure transducer data was processed with HOBOware Pro software (Onset, 2019) to determine water level, and the program R was used to compute daily averages from the 15-minute data. Daily averages from February 2021 to April 2022 appear in Table A2. For water level data from November 2019 to February 2021, see Petralia (2022). A data gap for all on-site wells exists from September 15, 2021, to October 27, 2021, when the available memory to store data on each logger was exceeded. Individual data gaps exist for Wells 4, 5, and 7 due to suspension cable repair, battery failure, and data exceeding memory storage capacity, respectively. End-of-month water elevations from Wells 2 to 9 used to calibrate the groundwater flow model are tabulated in Appendix B.

Table A2.
Daily Average Observation Well Water Elevations, in masl

Date	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10
2/1/21	649.553	638.603	638.354	637.047	637.029	635.752	637.282	637.488	638.441	639.235
2/2/21	649.590	638.545	638.304	637.011	637.008	635.747	637.263	637.481	638.427	639.226
2/3/21	649.662	638.512	638.290	636.980	636.997	635.746	637.254	637.484	638.430	639.249
2/4/21	649.735	638.507	638.329		636.983	635.738	637.242	637.478	638.424	639.245
2/5/21	649.847	638.632	638.659		637.046	635.801	637.269	637.496	638.457	639.381
2/6/21	649.990	638.875	638.939		637.264	635.978	637.414	637.607	638.651	639.652
2/7/21	650.014	639.051	639.123		637.505	636.153	637.675	637.795	638.843	639.832
2/8/21	649.979	639.173	639.249		637.662	636.236	637.853	637.898	638.891	639.897
2/9/21	649.909	639.237	639.313		637.707	636.248	637.880	637.918	638.889	639.906
2/10/21	649.849	639.269	639.344		637.687	636.222	637.858	637.902	638.865	639.887
2/11/21	649.798	639.275	639.354		637.658	636.193	637.830	637.884	638.829	639.866
2/12/21	649.761	639.271	639.353		637.626	636.158	637.793	637.856	638.782	639.837
2/13/21	649.740	639.272	639.357		637.593	636.124	637.757	637.830	638.741	639.804
2/14/21	649.707	639.250	639.340		637.555	636.095	637.718	637.806	638.706	639.766
2/15/21	649.704	639.245	639.331		637.522	636.073	637.687	637.784	638.688	639.741
2/16/21	649.657	639.191	639.269		637.479	636.043	637.649	637.759	638.663	639.681
2/17/21	649.618	639.141	639.205		637.439	636.016	637.615	637.736	638.642	639.624
2/18/21	649.617	639.112	639.142		637.401	635.989	637.579	637.712	638.619	639.549
2/19/21	649.616	639.072	639.072		637.359	635.961	637.541	637.684	638.598	639.494

Date	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10
2/20/21	649.588	639.009	638.976		637.314	635.933	637.501	637.656	638.575	639.430
2/21/21	649.571	638.940	638.886		637.266	635.906	637.460	637.626	638.547	639.389
2/22/21	649.661	638.955	639.017		637.322	636.018	637.527	637.675	638.627	639.539
2/23/21	650.003	639.177	639.345		637.748	636.324	637.994	637.967	638.899	639.889
2/24/21	650.137	639.390	639.550	638.157	637.928	636.438	638.092	638.084	639.009	640.035
2/25/21	650.107	639.449	639.588	638.204	637.903	636.389	638.036	638.025	638.957	639.992
2/26/21	650.097	639.489	639.613	638.217	637.903	636.379	638.023	638.010	638.940	639.974
2/27/21	650.050	639.479	639.595	638.211	637.891	636.366	638.011	637.996	638.921	639.947
2/28/21	650.031	639.484	639.619	638.229	637.901	636.366	638.006	637.988	638.909	639.930
3/1/21	650.119	639.526	639.680	638.267	637.921	636.378	638.019	637.994	638.910	639.934
3/2/21	650.209	639.575	639.733	638.294	637.943	636.386	638.028	637.999	638.913	639.942
3/3/21	650.291	639.652	639.804	638.330	637.974	636.397	638.038	638.006	638.923	639.964
3/4/21	650.367	639.736	639.868	638.368	638.016	636.413	638.048	638.014	638.935	639.987
3/5/21	650.408	639.845	639.917	638.398	638.056	636.433	638.065	638.031	638.948	640.015
3/6/21	650.341	639.837	639.882	638.379	638.052	636.445	638.075	638.043	638.956	640.029
3/7/21	650.260	639.780	639.840	638.364	638.032	636.434	638.073	638.044	638.949	640.023
3/8/21	650.189	639.724	639.803	638.352	638.001	636.418	638.060	638.029	638.933	639.994
3/9/21	650.128	639.668	639.761	638.337	637.973	636.406	638.050	638.019	638.918	639.967
3/10/21	650.074	639.610	639.709	638.320	637.948	636.395	638.040	638.008	638.901	639.934
3/11/21	650.011	639.535	639.635	638.299	637.924	636.386	638.031	637.999	638.882	639.901
3/12/21	649.978	639.480	639.581	638.292	637.916	636.382	638.028	637.996	638.869	639.878
3/13/21	649.964	639.438	639.542	638.289	637.914	636.385	638.029	637.997	638.860	639.862
3/14/21	649.972	639.414	639.522	638.295	637.922	636.389	638.036	638.002	638.857	639.852
3/15/21	649.950	639.373	639.478	638.280	637.911	636.386	638.033	637.998	638.850	639.838
3/16/21	649.943	639.342	639.445	638.278	637.909	636.385	638.031	637.996	638.842	639.822
3/17/21	649.946	639.317	639.418	638.277	637.909	636.389	638.034	638.000	638.836	639.811
3/18/21	649.955	639.304	639.408	638.285	637.923	636.404	638.046	638.012	638.836	639.813
3/19/21	649.962	639.303	639.414	638.310	637.954	636.438	638.078	638.046	638.865	639.865
3/20/21	649.970	639.277	639.389	638.292	637.934	636.420	638.063	638.034	638.859	639.880
3/21/21	649.963	639.259	639.363	638.283	637.926	636.411	638.053	638.026	638.850	639.866
3/22/21	649.975	639.248	639.342	638.279	637.923	636.406	638.048	638.019	638.844	639.850
3/23/21	649.944	639.204	639.279	638.253	637.904	636.394	638.037	638.008	638.825	639.810
3/24/21	649.975	639.195	639.267	638.266	637.919	636.403	638.041	638.009	638.817	639.791
3/25/21	649.967	639.161	639.223	638.243	637.904	636.399	638.041	638.012	638.820	639.801
3/26/21	649.933	639.112	639.162	638.222	637.893	636.394	638.036	638.009	638.817	639.800
3/27/21	649.922	639.075	639.123	638.214	637.895	636.398	638.039	638.017	638.820	639.809
3/28/21	649.957	639.083	639.136	638.247	637.933	636.432	638.068	638.048	638.844	639.842
3/29/21	649.973	639.073	639.121	638.260	637.956	636.463	638.101	638.084	638.882	639.879
3/30/21	649.913	638.980	639.017	638.184	637.883	636.396	638.035	638.016	638.822	639.807
3/31/21	649.907	638.939	638.968	638.166	637.873	636.390	638.025	638.005	638.808	639.782
4/1/21	649.922	638.900	638.927	638.148	637.865	636.388	638.022	638.003	638.800	639.772
4/2/21	649.898	638.843	638.865	638.119	637.854	636.387	638.021	638.009	638.798	639.774
4/3/21	649.879	638.791	638.815	638.099	637.849	636.387	638.022	638.014	638.797	639.776
4/4/21	649.875	638.750	638.780	638.087	637.849	636.393	638.028	638.026	638.799	639.780
4/5/21	649.870	638.711	638.743	638.071	637.842	636.391	638.025	638.026	638.797	639.773
4/6/21	649.867	638.671	638.701	638.049	637.831	636.385	638.015	638.017	638.792	639.764
4/7/21	649.862	638.627	638.649	638.019	637.817	636.381	638.005	638.014	638.787	639.756
4/8/21	649.843	638.572	638.588	637.990	637.808	636.377	637.998	638.007	638.785	639.746
4/9/21	649.837	638.509	638.524	637.944	637.776	636.357	637.970	637.982	638.764	639.716
4/10/21	649.830	638.450	638.460	637.908	637.758	636.352	637.960	637.972	638.758	639.700
4/11/21	649.802	638.368	638.376	637.849	637.712	636.329	637.923	637.946	638.734	639.659

Date	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10
4/12/21	649.794	638.292	638.302	637.799	637.675	636.313	637.887	637.923	638.713	639.623
4/13/21	649.787	638.216	638.227	637.747	637.641	636.298	637.850	637.901	638.696	639.580
4/14/21	649.787	638.138	638.155	637.699	637.608	636.285	637.818	637.883	638.686	639.576
4/15/21	649.775	638.059	638.083	637.656	637.583	636.284	637.803	637.886	638.695	639.608
4/16/21	649.759	637.984	638.017	637.618	637.570	636.292	637.813	637.908	638.710	639.638
4/17/21	649.754	637.923	637.967	637.601	637.574	636.302	637.844	637.939	638.725	639.662
4/18/21	649.755	637.873	637.931	637.596	637.586	636.313	637.875	637.970	638.738	639.682
4/19/21	649.736	637.823	637.893	637.588	637.592	636.321	637.895	637.997	638.752	639.699
4/20/21	649.737	637.784	637.863	637.581	637.586	636.315	637.881	637.984	638.750	639.689
4/21/21	649.742	637.749	637.827	637.558	637.565	636.304	637.850	637.960	638.738	639.673
4/22/21	649.739	637.710	637.785	637.528	637.545	636.300	637.829	637.955	638.735	639.670
4/23/21	649.723	637.665	637.737	637.494	637.525	636.295	637.812	637.949	638.732	639.665
4/24/21	649.724	637.627	637.698	637.469	637.510	636.288	637.798	637.936	638.728	639.655
4/25/21	649.714	637.585	637.653	637.439	637.492	636.273	637.775	637.913	638.716	639.634
4/26/21	649.692	637.539	637.603	637.402	637.466	636.256	637.744	637.888	638.702	639.612
4/27/21	649.671	637.492	637.550	637.364	637.438	636.241	637.713	637.870	638.695	639.601
4/28/21	649.661	637.449	637.502	637.330	637.415	636.230	637.689	637.856	638.686	639.586
4/29/21	649.663	637.413	637.461	637.300	637.394	636.229	637.674	637.853	638.684	639.586
4/30/21	649.665	637.383	637.427	637.275	637.383	636.240	637.674	637.874	638.694	639.602
5/1/21	649.664	637.352	637.392	637.254	637.376	636.244	637.679	637.890	638.702	639.609
5/2/21	649.647	637.320	637.358	637.233	637.362	636.227	637.664	637.864	638.679	639.561
5/3/21	649.640	637.293	637.328	637.210	637.340	636.207	637.630	637.823	638.607	639.396
5/4/21	649.632	637.268	637.299	637.179	637.314	636.180	637.583	637.780	638.565	639.319
5/5/21	649.628	637.246	637.271	637.141		636.158	637.539	637.746	638.529	639.272
5/6/21	649.624	637.225	637.238	637.097		636.139	637.503	637.718	638.501	639.244
5/7/21	649.606	637.195	637.198	637.048		636.128	637.477	637.702	638.485	639.231
5/8/21	649.596	637.169	637.158	637.002		636.091	637.442	637.666	638.461	639.236
5/9/21	649.601	637.148	637.126	636.957		636.047	637.407	637.634	638.444	639.241
5/10/21	649.595	637.125	637.090	636.909		636.008	637.375	637.607	638.418	639.201
5/11/21	649.589	637.102	637.055	636.864		635.985	637.348	637.588	638.393	639.175
5/12/21	649.584	637.082	637.024	636.822		635.975	637.332	637.579	638.382	639.171
5/13/21	649.575	637.063	636.995	636.785		635.972	637.322	637.578	638.381	639.187
5/14/21	649.572	637.046	636.971	636.757		635.979	637.325	637.590	638.397	639.223
5/15/21	649.565	637.028	636.948	636.736		635.983	637.331	637.601	638.414	639.247
5/16/21	649.562	637.014	636.930	636.721		635.991	637.341	637.614	638.424	639.242
5/17/21	649.555	637.001	636.912	636.710		635.998	637.348	637.623	638.433	639.260
5/18/21	649.533	636.983	636.889	636.697		635.986	637.348	637.620	638.445	639.293
5/19/21	649.534	636.970	636.867	636.682		635.947	637.328	637.594	638.426	639.256
5/20/21	649.526	636.953	636.845	636.661		635.907	637.300	637.562	638.383	639.170
5/21/21	649.518	636.939	636.824	636.631		635.873	637.270	637.537	638.390	639.325
5/22/21	649.517	636.930	636.806	636.603		635.845	637.260	637.536	638.395	639.293
5/23/21	649.519	636.919	636.786	636.580		635.826	637.240	637.511	638.311	639.006
5/24/21	649.510	636.907	636.764	636.549		635.818	637.202	637.464	638.213	638.846
5/25/21	649.500	636.893	636.734	636.505		635.810	637.158	637.422	638.172	638.854
5/26/21	649.496	636.878	636.700	636.455		635.795	637.124	637.401	638.192	639.081
5/27/21	649.497	636.864	636.664	636.412		635.786	637.127	637.426	638.246	639.077
5/28/21	649.473	636.843	636.625	636.386		635.770	637.121	637.418	638.222	639.007
5/29/21	649.473	636.828	636.597	636.366		635.748	637.103	637.395	638.183	638.928
5/30/21	649.468	636.811	636.569	636.339		635.729	637.076	637.364	638.117	638.761
5/31/21	649.459	636.794	636.540	636.306		635.715	637.041	637.328	638.084	638.941
6/1/21	649.459	636.780	636.513	636.274		635.733	637.048	637.357	638.155	638.997

Date	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10
6/2/21	649.456	636.765	636.492	636.264		635.758	637.079	637.399	638.205	639.109
6/3/21	649.445	636.750	636.476	636.273		635.774	637.115	637.441	638.275	639.178
6/4/21	649.431	636.734	636.461	636.290		635.768	637.142	637.462	638.312	639.296
6/5/21	649.425	636.720	636.450	636.307		635.746	637.160	637.478	638.358	639.347
6/6/21	649.421	636.704	636.436	636.319		635.721	637.161	637.468	638.310	639.079
6/7/21	649.415	636.689	636.422	636.316		635.693	637.121	637.412	638.187	638.801
6/8/21	649.405	636.675	636.404	636.287		635.657	637.055	637.334	638.054	638.605
6/9/21	649.395	636.660	636.376	636.236		635.618	636.980	637.252	637.938	638.484
6/10/21	649.389	636.643	636.344	636.173		635.576	636.901	637.177	637.849	638.405
6/11/21	649.394	636.630	636.310	636.102		635.536	636.825	637.113	637.792	638.458
6/12/21	649.387	636.612	636.272	636.029		635.493	636.769	637.076	637.831	638.669
6/13/21	649.386	636.600	636.241	635.973		635.465	636.760	637.091	637.877	638.632
6/14/21	649.383	636.589	636.216	635.943		635.480	636.772	637.111	637.851	638.494
6/15/21	649.363	636.568	636.186	635.916		635.466	636.747	637.079	637.799	638.505
6/16/21	649.352	636.556	636.167	635.894	636.330	635.441	636.724	637.066	637.838	638.657
6/17/21	649.365	636.548	636.153	635.874		635.419	636.726	637.083	637.887	638.697
6/18/21	649.378	636.539	636.139	635.865		635.409	636.743	637.103	637.912	638.699
6/19/21	649.376	636.530	636.126	635.866		635.406	636.757	637.116	637.918	638.684
6/20/21	649.364	636.518	636.114	635.867		635.408	636.765	637.121	637.913	638.667
6/21/21	649.363	636.509	636.103	635.867		635.404	636.763	637.117	637.905	638.655
6/22/21	649.359	636.500	636.092	635.863		635.398	636.755	637.109	637.894	638.644
6/23/21	649.341	636.486	636.077	635.855		635.390	636.746	637.101	637.885	638.631
6/24/21	649.322	636.469	636.059	635.844		635.375	636.730	637.086	637.871	638.604
6/25/21	649.311	636.452	636.041	635.830		635.359	636.714	637.070	637.851	638.576
6/26/21	649.300	636.435	636.021	635.814		635.344	636.697	637.053	637.835	638.556
6/27/21	649.296	636.416	636.000	635.797		635.326	636.677	637.036	637.818	638.520
6/28/21	649.293	636.396	635.978	635.778		635.307	636.655	637.013	637.773	638.368
6/29/21	649.284	636.375	635.954	635.757		635.286	636.616	636.968	637.682	638.218
6/30/21	649.268	636.352	635.928	635.727		635.260	636.559	636.906	637.602	638.168
7/1/21	649.247	636.327	635.899	635.687		635.229	636.497	636.850	637.538	638.101
7/2/21	649.232	636.301	635.865	635.641		635.196	636.437	636.799	637.466	638.027
7/3/21	649.223	636.275	635.831	635.592		635.160	636.377	636.746	637.389	637.973
7/4/21	649.211	636.250	635.798	635.543		635.124	636.318	636.694	637.313	637.927
7/5/21	649.195	636.224	635.767	635.498		635.089	636.258	636.645	637.283	637.887
7/6/21	649.185	636.198	635.734	635.452		635.053	636.199	636.597	637.283	637.855
7/7/21	649.175	636.175	635.704	635.409		635.021	636.144	636.557	637.284	637.848
7/8/21	649.159	636.147	635.672	635.363		634.990	636.094	636.520	637.282	637.847
7/9/21	649.139	636.122	635.644	635.327		634.961	636.053	636.492	637.282	637.847
7/10/21	649.127	636.097	635.615	635.295		634.934	636.020	636.469	637.283	637.847
7/11/21	649.114	636.071	635.585	635.266		634.908	635.997	636.452	637.282	637.847
7/12/21	649.101	636.047	635.554	635.243		634.888	635.979	636.440	637.283	637.847
7/13/21	649.084	636.023	635.531	635.221		634.870	635.962	636.426	637.283	637.847
7/14/21	649.071	636.001	635.520	635.205		634.854	635.944	636.413	637.283	637.848
7/15/21	649.062	635.979	635.514	635.193		634.840	635.927	636.399	637.284	637.849
7/16/21	649.128	635.955	635.506	635.178		634.828	635.913	636.388	637.284	637.848
7/17/21	649.130	635.930	635.499	635.163		634.815	635.899	636.378	637.283	637.848
7/18/21	649.125	635.908	635.493	635.148		634.803	635.889	636.369	637.283	637.847
7/19/21	649.097	635.888	635.485	635.134		634.792	635.884	636.366	637.283	637.848
7/20/21	649.083	635.869	635.474	635.122		634.783	635.883	636.366	637.284	637.849
7/21/21	649.058	635.849	635.460	635.109		634.777	635.883	636.366	637.284	637.848
7/22/21	649.034	635.830	635.443	635.095		634.772	635.878	636.362	637.284	637.849

Date	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10
7/23/21	649.031	635.812	635.427	635.081		634.765	635.869	636.356	637.283	637.848
7/24/21	649.087	635.793	635.414	635.065		634.757	635.861	636.349	637.282	637.848
7/25/21	649.018	635.777	635.400	635.049		634.750	635.858	636.347	637.283	637.847
7/26/21	648.974	635.760	635.387	635.034		634.743	635.858	636.347	637.283	637.847
7/27/21	648.962	635.745	635.375	635.015		634.739	635.857	636.346	637.284	637.848
7/28/21	648.915	635.742	635.362	634.995		634.735	635.851	636.341	637.283	637.848
7/29/21	648.873	635.743	635.350	634.977		634.729	635.843	636.333	637.284	637.849
7/30/21	648.838	635.742	635.334	634.963		634.723	635.834	636.325	637.284	637.849
7/31/21	648.807	635.742	635.317	634.954		634.717	635.824	636.317	637.284	637.850
8/1/21	648.778	635.741	635.303	634.943		634.716	635.816	636.314	637.283	637.848
8/2/21	648.759	635.742	635.290	634.932		634.715	635.811	636.312	637.284	637.849
8/3/21	648.743	635.742	635.281	634.918		634.708	635.803	636.304	637.284	637.848
8/4/21	648.725	635.741	635.272	634.903		634.706	635.798	636.302	637.283	637.847
8/5/21	648.711	635.741	635.267	634.876		634.700	635.794	636.299	637.283	637.847
8/6/21	648.697	635.741	635.264	634.840	635.260	634.692	635.799	636.303	637.282	637.847
8/7/21	648.657	635.742	635.262	634.811		634.688	635.816	636.315	637.281	637.850
8/8/21	648.644	635.743	635.260	634.801		634.690	635.841	636.335	637.281	637.890
8/9/21	648.629	635.741	635.254	634.793		634.695	635.869	636.358	637.281	637.938
8/10/21	648.616	635.741	635.251	634.792		634.701	635.900	636.380	637.281	637.963
8/11/21	648.603	635.742	635.247	634.799		634.708	635.927	636.398	637.282	637.946
8/12/21	648.589	635.743	635.242	634.814		634.716	635.942	636.407	637.282	637.922
8/13/21	648.574	635.742	635.235	634.845		634.721	635.946	636.408	637.282	637.899
8/14/21	648.559	635.742	635.230	634.882		634.723	635.943	636.404	637.282	637.911
8/15/21	648.545	635.742	635.225	634.912		634.724	635.945	636.405	637.282	637.954
8/16/21	648.534	635.743	635.222	634.935		634.723	635.955	636.412	637.282	637.964
8/17/21	648.522	635.743	635.219	634.950		634.728	635.964	636.421	637.282	637.918
8/18/21	648.505	635.743	635.215	634.960		634.733	635.960	636.417	637.282	637.859
8/19/21	648.491	635.743	635.213	634.970		634.731	635.942	636.400	637.283	637.846
8/20/21	648.478	635.743	635.214	634.978		634.727	635.915	636.379	637.283	637.848
8/21/21	648.466	635.743	635.215	634.982		634.721	635.888	636.359	637.284	637.847
8/22/21	648.454	635.743	635.213	634.977		634.712	635.860	636.338	637.283	637.847
8/23/21	648.440	635.742	635.209	634.966		634.700	635.833	636.317	637.283	637.847
8/24/21	648.427	635.742	635.207	634.951		634.687	635.807	636.299	637.282	637.847
8/25/21	648.419	635.741	635.204	634.933		634.676	635.786	636.283	637.282	637.848
8/26/21	648.411	635.742	635.202	634.906		634.667	635.769	636.270	637.282	637.848
8/27/21	648.402	635.742	635.199	634.849		634.659	635.756	636.261	637.283	637.848
8/28/21	648.393	635.742	635.196	634.784		634.651	635.749	636.256	637.282	637.847
8/29/21	648.391	635.741	635.196	634.743		634.645	635.747	636.256	637.282	637.848
8/30/21	648.390	635.742	635.194	634.714		634.639	635.751	636.258	637.282	637.848
8/31/21	648.386	635.742	635.192	634.694		634.638	635.760	636.268	637.282	637.848
9/1/21	648.379	635.741	635.189	634.682		634.639	635.772	636.278	637.282	637.846
9/2/21	648.371	635.740	635.187	634.678		634.641	635.783	636.287	637.281	637.851
9/3/21	648.364	635.741	635.187	634.677		634.644	635.805	636.307	637.282	638.007
9/4/21	648.358	635.741	635.185	634.677		634.650	635.851	636.345	637.282	638.080
9/5/21	648.352	635.742	635.184	634.679		634.661	635.905	636.387	637.294	638.182
9/6/21	648.345	635.742	635.182	634.689		634.676	635.962	636.429	637.352	638.145
9/7/21	648.336	635.742	635.180	634.711		634.696	636.008	636.461	637.356	638.086
9/8/21	648.329	635.742	635.178	634.759		634.713	636.031	636.475	637.343	638.061
9/9/21	648.322	635.742	635.177	634.820		634.728	636.042	636.480	637.339	638.069
9/10/21	648.316	635.743	635.176	634.882		634.744	636.053	636.490	637.365	638.171
9/11/21	648.304	635.742	635.171	634.929		634.756	636.073	636.506	637.456	638.282

Date	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10
9/12/21	648.296	635.743	635.171	634.965		634.766	636.112	636.541	637.512	638.257
9/13/21	648.287	635.743	635.170	635.000		634.775	636.145	636.570	637.533	638.267
9/14/21	648.278	635.742	635.168	635.034		634.786	636.169	636.591	637.547	638.253
9/15/21	648.272	635.742	635.167	635.061		634.794	636.185	636.604	637.548	638.238
No Data										
9/23/21	648.230	635.740	635.200	635.210	635.690	634.840	636.219	636.605	637.341	638.175
No Data										
10/27/21	648.067	635.738	635.150	635.272	635.740	634.988	636.304	636.730	637.592	638.310
10/28/21	648.076	635.737	635.149	635.277		635.007		636.743	637.605	638.324
10/29/21	648.088	635.737	635.149	635.288		635.097		636.800	637.628	638.351
10/30/21	648.095	635.737	635.148	635.304		635.112		636.818	637.655	638.389
10/31/21	648.102	635.736	635.148	635.325		635.098		636.818	637.685	638.426
11/1/21	648.107	635.736	635.147	635.342		635.085		636.819	637.707	638.448
11/2/21	648.110	635.736	635.147	635.357		635.075		636.823	637.723	638.463
11/3/21	648.114	635.735	635.146	635.370		635.078		636.831	637.737	638.500
11/4/21	648.125	635.735	635.146	635.382		635.082		636.840	637.753	638.526
11/5/21	648.135	635.736	635.146	635.394		635.126		636.869	637.764	638.527
11/6/21	648.143	635.737	635.146	635.408		635.149		636.890	637.774	638.538
11/7/21	648.146	635.736	635.145	635.423		635.150		636.895	637.784	638.560
11/8/21	648.149	635.736	635.145	635.439		635.147		636.898	637.795	638.578
11/9/21	648.153	635.736	635.145	635.453		635.144		636.901	637.804	638.587
11/10/21	648.153	635.736	635.144	635.462		635.143		636.905	637.810	638.592
11/11/21	648.156	635.735	635.144	635.470		635.147		636.909	637.816	638.603
11/12/21	648.180	635.735	635.399	635.484		635.330		637.046	637.930	638.908
11/13/21	648.236	635.736	635.532	635.551		635.576		637.305	638.217	639.457
11/14/21	648.293	635.734	635.570	635.681		635.622		637.400	638.364	639.591
11/15/21	648.355	635.738	635.675	635.849		635.722		637.527	638.482	639.662
11/16/21	648.391	635.737	635.688	635.995		635.711		637.531	638.498	639.591
11/17/21	648.407	635.736	635.696	636.104		635.677		637.509	638.465	639.464
11/18/21	648.424	635.735	635.728	636.180		635.644		637.482	638.426	639.371
11/19/21	648.435	635.735	635.738	636.207		635.614		637.452	638.386	639.308
11/20/21	648.429	635.736	635.725	636.204		635.582		637.423	638.349	639.256
11/21/21	648.421	635.735	635.716	636.193		635.554		637.397	638.318	639.213
11/22/21	648.421	635.736	635.711	636.179		635.530		637.373	638.287	639.153
11/23/21	648.422	635.735	635.695	636.156		635.507		637.345	638.251	639.104
11/24/21	648.408	635.736	635.660	636.120		635.484		637.316	638.213	639.065
11/25/21	648.398	635.736	635.639	636.091		635.462		637.286	638.177	639.026
11/26/21	648.397	635.736	635.620	636.063		635.489		637.280	638.156	639.014
11/27/21	648.403	635.736	635.603	636.049		635.551		637.308	638.160	639.028
11/28/21	648.427	635.736	635.656	636.064		635.663		637.387	638.209	639.120
11/29/21	648.455	635.737	635.735	636.122		635.729		637.445	638.297	639.297
11/30/21	648.473	635.736	635.798	636.185		635.710		637.451	638.341	639.333
12/1/21	648.485	635.735	635.845	636.227		635.686		637.449	638.348	639.313
12/2/21	648.491	635.738	635.871	636.250		635.667		637.442	638.342	639.285
12/3/21	648.484	635.737	635.873	636.251		635.638		637.423	638.322	639.238
12/4/21	648.478	635.736	635.870	636.242		635.610		637.403	638.299	639.187
12/5/21	648.463	635.736	635.840	636.213		635.580		637.377	638.271	639.141
12/6/21	648.454	635.735	635.828	636.193		635.555		637.355	638.245	639.098
12/7/21	648.446	635.735	635.807	636.165		635.531		637.330	638.217	639.066
12/8/21	648.448	635.735	635.788	636.136		635.510		637.307	638.192	639.029
12/9/21	648.452	635.736	635.764	636.105		635.492		637.285	638.168	638.997

Date	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10
12/10/21	648.455	635.741	635.740	636.075		635.471		637.262	638.143	638.967
12/11/21	648.475	635.748	635.745	636.053		635.458		637.243	638.124	638.948
12/12/21	648.506	635.760	635.758	636.029		635.447		637.230	638.113	638.944
12/13/21	648.540	635.775	635.771	636.012		635.432		637.216	638.102	638.940
12/14/21	648.574	635.794	635.777	635.993		635.418		637.206	638.095	638.938
12/15/21	648.604	635.815	635.786	635.976		635.404		637.195	638.083	638.917
12/16/21	648.633	635.837	635.797	635.960		635.390		637.183	638.068	638.898
12/17/21	648.656	635.860	635.802	635.942		635.378		637.170	638.053	638.878
12/18/21	648.686	635.888	635.822	635.934		635.371		637.158	638.040	638.866
12/19/21	648.716	635.914	635.830	635.921		635.360		637.146	638.028	638.855
12/20/21	648.739	635.939	635.832	635.903		635.347		637.132	638.011	638.830
12/21/21	648.762	635.966	635.840	635.890		635.339		637.119	637.996	638.816
12/22/21	648.793	635.997	635.856	635.881		635.330		637.106	637.983	638.796
12/23/21	648.830	636.027	635.869	635.870		635.322		637.094	637.971	638.780
12/24/21	648.873	636.053	635.876	635.853		635.312		637.082	637.958	638.769
12/25/21	648.896	636.081	635.885	635.839		635.304		637.072	637.948	638.756
12/26/21	648.917	636.114	635.904	635.834		635.301		637.068	637.943	638.747
12/27/21	648.927	636.133	635.907	635.817		635.283		637.052	637.927	638.728
12/28/21	648.938	636.156	635.920	635.808		635.285		637.045	637.915	638.713
12/29/21	648.948	636.177	635.930	635.799		635.309		637.051	637.905	638.697
12/30/21	648.964	636.200	635.945	635.801		635.340		637.059	637.901	638.692
12/31/21	648.973	636.215	635.946	635.798		635.305		637.054	637.902	638.694
1/1/22	648.976	636.229	635.949	635.792		635.306		637.060	637.899	638.686
1/2/22	648.989	636.248	635.962	635.794		635.324		637.076	637.902	638.687
1/3/22	649.011	636.268	635.977	635.799		635.292		637.038	637.907	638.703
1/4/22	649.017	636.275	635.971	635.787		635.289		637.039	637.907	638.708
1/5/22	649.021	636.284	635.973	635.782		635.288		637.039	637.905	638.701
1/6/22	649.038	636.299	635.985	635.785		635.273		637.030	637.911	638.744
1/7/22	649.054	636.312	635.989	635.781		635.244		637.022	637.937	638.795
1/8/22	649.040	636.310	635.975	635.767		635.276		637.057	637.939	638.748
1/9/22	649.031	636.315	635.976	635.773		635.301		637.072	637.925	638.703
1/10/22	649.035	636.322	635.988	635.785		635.315		637.067	637.911	638.686
1/11/22	649.051	636.332	636.000	635.794		635.323		637.059	637.903	638.684
1/12/22	649.071	636.342	636.023	635.800		635.340		637.072	637.908	638.705
1/13/22	649.120	636.373	636.095	635.836		635.522		637.171	637.967	638.778
1/14/22	649.184	636.421	636.157	635.917		635.601		637.225	638.044	638.892
1/15/22	649.189	636.432	636.174	635.962		635.546		637.207	638.057	638.937
1/16/22	649.235	636.492	636.231	636.029		635.539		637.235	638.110	639.006
1/17/22	649.272	636.548	636.301	636.070		635.535		637.254	638.145	639.047
1/18/22	649.286	636.613	636.429	636.104		635.541		637.273	638.167	639.068
1/19/22	649.295	636.683	636.549	636.139		635.563		637.298	638.188	639.083
1/20/22	649.316	636.763	636.678	636.182		635.584		637.320	638.208	639.104
1/21/22	649.377	636.921	636.974	636.279		635.701		637.409	638.279	639.206
1/22/22	649.399	637.064	637.206	636.349		635.711		637.424	638.307	639.270
1/23/22	649.430	637.244	637.406	636.441		635.715		637.445	638.354	639.337
1/24/22	649.436	637.420	637.561	636.510		635.715		637.462	638.389	639.376
1/25/22	649.427	637.580	637.661	636.557		635.718		637.477	638.411	639.394
1/26/22	649.425	637.716	637.743	636.594		635.719		637.487	638.424	639.402
1/27/22	649.406	637.805	637.780	636.619		635.715		637.489	638.429	639.396
1/28/22	649.417	637.877	637.817	636.640		635.710		637.487	638.430	639.383
1/29/22	649.420	637.932	637.839	636.652		635.702		637.482	638.424	639.365

Date	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10
1/30/22	649.433	637.976	637.849	636.657		635.692		637.474	638.415	639.340
1/31/22	649.405	637.983	637.825	636.646		635.678		637.462	638.400	639.316
2/1/22	649.386	637.968	637.784	636.632		635.665		637.449	638.385	639.281
2/2/22	649.371	637.934	637.734	636.614		635.651		637.436	638.366	639.242
2/3/22	649.361	637.890	637.679	636.590		635.636		637.419	638.343	639.205
2/4/22	649.357	637.840	637.617	636.563		635.621		637.402	638.322	639.169
2/5/22	649.341	637.788	637.554	636.533		635.610		637.387	638.303	639.151
2/6/22	649.347	637.755	637.509	636.509		635.602		637.378	638.293	639.140
2/7/22	649.364	637.733	637.492	636.490		635.594		637.369	638.281	639.129
2/8/22	649.375	637.766	637.553	636.505		635.614		637.381	638.296	639.193
2/9/22	649.425	637.847	637.702	636.549		635.635		637.401	638.325	639.242
2/10/22	649.532	638.062	638.077	636.786		635.729		637.471	638.394	639.414
2/11/22	649.652	638.348	638.491	637.201		635.863		637.603	638.685	639.737
2/12/22	649.754	638.606	638.760	637.482		635.978		637.769	638.875	639.890
2/13/22	649.773	638.819	638.951	637.642		636.078		637.859	638.901	639.919
2/14/22	649.786	638.985	639.096	637.746		636.147		637.901	638.899	639.919
2/15/22	649.756	639.074	639.168	637.797		636.174		637.910	638.876	639.899
2/16/22	649.771	639.146	639.254	637.843		636.192		637.913	638.866	639.892
2/17/22	649.844	639.231	639.383	637.917		636.229		637.928	638.875	639.903
2/18/22	649.947	639.362	639.522	638.032		636.309		637.963	638.901	639.937
2/19/22	649.992	639.477	639.623	638.111	637.866	636.359	637.969	637.992	638.911	639.925
2/20/22	650.061	639.611	639.745	638.198	637.885	636.392		638.018	638.924	639.959
2/21/22	649.992	639.664	639.751	638.196	637.879	636.380		638.012	638.911	639.947
2/22/22	649.985	639.636	639.712	638.054	637.839	636.354		637.989	638.882	639.911
2/23/22	649.984	639.618	639.695	638.134	637.793	636.324		637.963	638.850	639.867
2/24/22	649.927	639.585	639.670	638.107	637.758	636.299		637.944	638.819	639.833
2/25/22	649.860	639.547	639.640	638.068	637.711	636.254		637.918	638.784	639.795
2/26/22	649.816	639.520	639.618	638.028	637.669	636.214		637.891	638.753	639.757
2/27/22	649.783	639.494	639.598	637.981	637.633	636.182		637.865	638.721	639.720
2/28/22	649.862	639.559	639.734	638.078	637.789	636.316		637.955	638.818	639.822
3/1/22	650.203	639.831	640.019	638.323	638.087	636.501		638.176	638.985	640.054
3/2/22	650.286	640.016	640.130	638.392	638.123	636.511		638.199	639.005	640.095
3/3/22	650.396	640.072	640.178	638.416	638.123	636.506		638.174	638.996	640.087
3/4/22	650.423	640.073	640.161	638.398	638.110	636.490		638.148	638.983	640.073
3/5/22	650.345	639.995	640.094	638.361	638.085	636.470		638.114	638.959	640.033
3/6/22	650.262	639.915	640.028	638.334	638.045	636.454		638.088	638.935	639.988
3/7/22	650.203	639.859	639.987	638.321	638.022	636.460		638.079	638.921	639.962
3/8/22	650.169	639.821	639.967	638.320	638.023	636.453		638.076	638.915	639.948
3/9/22	650.122	639.772	639.931	638.307	637.988	636.433		638.056	638.896	639.910
3/10/22	650.079	639.722	639.884	638.291	637.958	636.415		638.035	638.873	639.869
3/11/22	650.054	639.681	639.849	638.282	637.935	636.411		638.026	638.858	639.841
3/12/22	650.055	639.659	639.832	638.281	637.929	636.414		638.024	638.848	639.825
3/13/22	650.035	639.612	639.787	638.265	637.916	636.412		638.023	638.838	639.809
3/14/22	650.011	639.583	639.774	638.284	637.954	636.435		638.043	638.851	639.820
3/15/22	650.030	639.592	639.805	638.315	638.000	636.474		638.096	638.890	639.865
3/16/22	650.047	639.604	639.814	638.327	638.001	636.474		638.107	638.903	639.884
3/17/22	650.066	639.607	639.808	638.313	637.966	636.447		638.073	638.877	639.846
3/18/22	650.080	639.596	639.788	638.301	637.942	636.435		638.053	638.858	639.814
3/19/22	650.090	639.578	639.760	638.291	637.929	636.429		638.045	638.846	639.795
3/20/22	650.066	639.530	639.702	638.274	637.914	636.420		638.033	638.833	639.772
3/21/22	650.063	639.495	639.661	638.273	637.918	636.419		638.025	638.823	639.752

Date	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10
3/22/22	650.067	639.472	639.629	638.268	637.911	636.423		638.030	638.820	639.745
3/23/22	650.091	639.472	639.632	638.275	637.922	636.441		638.053	638.826	639.752
3/24/22	650.086	639.458	639.618	638.270	637.918	636.443		638.068	638.829	639.754
3/25/22	650.094	639.450	639.598	638.265	637.910	636.434		638.053	638.822	639.742
3/26/22	650.093	639.425	639.558	638.252	637.903	636.428		638.041	638.810	639.720
3/27/22	650.101	639.411	639.534	638.255	637.914	636.437		638.059	638.815	639.720
3/28/22	650.094	639.378	639.493	638.242	637.909	636.443		638.082	638.824	639.738
3/29/22	650.063	639.331	639.433	638.220	637.895	636.435		638.078	638.823	639.745
3/30/22	650.044	639.280	639.362	638.191	637.874	636.423		638.063	638.809	639.722
3/31/22	650.035	639.225	639.283	638.157	637.855	636.412		638.042	638.797	639.692
4/1/22	650.028	639.162	639.192	638.115	637.832	636.398		638.020	638.781	639.656
4/2/22	650.000	639.081	639.086	638.058	637.797	636.379		637.996	638.759	639.620
4/3/22	650.000	639.016	639.002	638.016	637.770	636.369		637.978	638.745	639.591
4/4/22	650.013	638.971	638.950	638.033	637.832	636.414		638.013	638.774	639.608
4/5/22	650.007	638.904	638.884	638.011	637.826	636.423		638.033	638.790	639.616
4/6/22	649.979	638.809	638.781	637.933	637.756	636.368		637.983	638.744	639.562
4/7/22	649.980	638.763	638.734	637.902	637.732	636.355		637.966	638.730	639.542
4/8/22	649.990	638.640	638.714	637.889	637.727	636.357		637.966	638.725	639.536

APPENDIX B

TRANSIENT MODEL INPUTS

Stress Periods

A stress period in a transient MODFLOW model is a period of time for which boundary conditions remain constant. The groundwater flow model has 61 monthly stress periods beginning March 1, 2017, and ending on March 31, 2022. Visual MODFLOW Flex 7.0 requires a fixed start date and performs calculations based on the number of days after that fixed date. Monthly stress periods in terms of the number of days are shown in Table B1.

Table B1.

Monthly Stress Periods for the Transient MODFLOW Model

Stress Period	Start Date	End Date	Start Day	End Day
1	3/1/17	3/31/17	0	31
2	4/1/17	4/30/17	31	61
3	5/1/17	5/31/17	61	92
4	6/1/17	6/30/17	92	122
5	7/1/17	7/31/17	122	153
6	8/1/17	8/31/17	153	184
7	9/1/17	9/30/17	184	214
8	10/1/17	10/31/17	214	245
9	11/1/17	11/30/17	245	275
10	12/1/17	12/31/17	275	306
11	1/1/18	1/31/18	306	337
12	2/1/18	2/28/18	337	365
13	3/1/18	3/31/18	365	396
14	4/1/18	4/30/18	396	426
15	5/1/18	5/31/18	426	457
16	6/1/18	6/30/18	457	487
17	7/1/18	7/31/18	487	518
18	8/1/18	8/31/18	518	549
19	9/1/18	9/30/18	549	579
20	10/1/18	10/31/18	579	610
21	11/1/18	11/30/18	610	640
22	12/1/18	12/31/18	640	671
23	1/1/19	1/31/19	671	702
24	2/1/19	2/28/19	702	730
25	3/1/19	3/31/19	730	761
26	4/1/19	4/30/19	761	791
27	5/1/19	5/31/19	791	822
28	6/1/19	6/30/19	822	852
29	7/1/19	7/31/19	852	883
30	8/1/19	8/31/19	883	914
31	9/1/19	9/30/19	914	944
32	10/1/19	10/31/19	944	975
33	11/1/19	11/30/19	975	1005
34	12/1/19	12/31/19	1005	1036
35	1/1/20	1/31/20	1036	1067
36	2/1/20	2/29/20	1067	1096
37	3/1/20	3/31/20	1096	1127
38	4/1/20	4/30/20	1127	1157
39	5/1/20	5/31/20	1157	1188
40	6/1/20	6/30/20	1188	1218
41	7/1/20	7/31/20	1218	1249
42	8/1/20	8/31/20	1249	1280
43	9/1/20	9/30/20	1280	1310
44	10/1/20	10/31/20	1310	1341
45	11/1/20	11/30/20	1341	1371
46	12/1/20	12/31/20	1371	1402
47	1/1/21	1/31/21	1402	1433
48	2/1/21	2/28/21	1433	1461
49	3/1/21	3/31/21	1461	1492
50	4/1/21	4/30/21	1492	1522
51	5/1/21	5/31/21	1522	1553
52	6/1/21	6/30/21	1553	1583
53	7/1/21	7/31/21	1583	1614
54	8/1/21	8/31/21	1614	1645
55	9/1/21	9/30/21	1645	1675
56	10/1/21	10/31/21	1675	1706
57	11/1/21	11/30/21	1706	1736
58	12/1/21	12/31/21	1736	1767
59	1/1/22	1/31/22	1767	1798
60	2/1/22	2/28/22	1798	1826
61	3/1/22	3/31/22	1826	1857

Recharge Inputs

In the MODFLOW model, recharge was applied to the topmost active layer (the setting NRCHOP = 3). The RCH boundary condition requires a flux, in mm·y^{-1}, as its input. Monthly precipitation amounts, in mm, from the PRISM (2022) data set were multiplied by 365.25 divided by the number of days in the stress period to obtain the yearly flux. An additional multiplication factor of 1.35 was applied so that the flux could meet the volume demands of the mass balance. Different zones for precipitation, irrigation, and upland recharge were specified (see Figure 9), with irrigation and upland recharge additive to precipitation (i.e., precipitation recharges everywhere, irrigation and upland recharge are applied in addition to precipitation within their respective zones). In Visual MODFLOW Flex 7.0, Zone 1 designates inactive cells (cells within the grid but not part of the model domain), Zones 2 through 4 are upland recharge, precipitation, and irrigation, respectively, and Zone 5 is a second area of precipitation only. In initial model runs, Zone 5 represented recharge from Fred Creek. The final calibrated model represents Fred Creek with the SFR2 boundary condition, so Zone 5 defaults to precipitation. Table B2 contains the RCH boundary condition fluxes.

Table B2.
Recharge Flux Inputs

Start Date	Stress Period		**Zone 1** Inactive Cells	Upland Amount (mm)	**Zone 2** Upland (mm·y^{-1})	Precip Amount (mm)	Precip Flux (mm·mo^{-1})	**Zone 3** Precip (mm·y^{-1})	Irrigation Amount (mm·y^{-1})	**Zone 4** Irrigation (mm·y^{-1})	**Zone 5** Precip2 (mm·y^{-1})
3/1/17	0	31	0	2000	4065	129.82	175.26	2065	0	2065	2065
4/1/17	31	61	0	3900	5045	69.65	94.03	1145	0	1145	1145
5/1/17	61	92	0	0	589	37.06	50.03	589	400	989	589
6/1/17	92	122	0	0	370	22.53	30.42	370	400	770	370
7/1/17	122	153	0	0	0	0	0	0	400	400	0
8/1/17	153	184	0	0	33	2.06	2.78	33	400	433	33
9/1/17	184	214	0	0	184	11.19	15.11	184	400	584	184
10/1/17	214	245	0	0	2176	136.79	184.67	2176	0	2176	2176
11/1/17	245	275	0	0	2213	134.62	181.74	2213	0	2213	2213
12/1/17	275	306	0	0	1685	105.93	143.01	1685	0	1685	1685
1/1/18	306	337	0	2000	4097	131.81	177.94	2097	0	2097	2097
2/1/18	337	365	0	2000	3485	84.3	113.81	1485	0	1485	1485
3/1/18	365	396	0	2000	2785	49.36	66.64	785	0	785	785
4/1/18	396	426	0	3900	5183	78.07	105.39	1283	0	1283	1283
5/1/18	426	457	0	0	498	31.29	42.24	498	400	898	498
6/1/18	457	487	0	0	335	20.38	27.51	335	400	735	335

Start Date	Stress Period		**Zone 1** Inactive Cells	Upland Amount (mm)	**Zone 2** Upland ($mm{\cdot}y^{-1}$)	Precip Amount (mm)	Precip Flux ($mm{\cdot}mo^{-1}$)	**Zone 3** Precip ($mm{\cdot}y^{-1}$)	Irrigation Amount ($mm{\cdot}y^{-1}$)	**Zone 4** Irrigation ($mm{\cdot}y^{-1}$)	**Zone 5** Precip2 ($mm{\cdot}y^{-1}$)
7/1/18	487	518	0	0	0	0	0	0	400	400	0
8/1/18	518	549	0	0	0	0	0	0	400	400	0
9/1/18	549	579	0	0	63	3.82	5.16	63	400	463	63
10/1/18	579	610	0	0	1209	76	102.60	1209	0	1209	1209
11/1/18	610	640	0	0	1361	82.78	111.75	1361	0	1361	1361
12/1/18	640	671	0	0	2904	182.6	246.51	2904	0	2904	2904
1/1/19	671	702	0	2000	3568	98.58	133.08	1568	0	1568	1568
2/1/19	702	730	0	2000	3670	94.83	128.02	1670	0	1670	1670
3/1/19	730	761	0	2000	2287	18.05	24.37	287	0	287	287
4/1/19	761	791	0	3900	4581	41.44	55.94	681	0	681	681
5/1/19	791	822	0	0	840	52.79	71.27	840	400	1240	840
6/1/19	822	852	0	0	250	15.19	20.51	250	400	650	250
7/1/19	852	883	0	0	206	12.92	17.44	206	400	606	206
8/1/19	883	914	0	0	252	15.86	21.41	252	400	652	252
9/1/19	914	944	0	0	1057	64.31	86.82	1057	400	1457	1057
10/1/19	944	975	0	0	1221	76.79	103.67	1221	0	1221	1221
11/1/19	975	1005	0	0	564	34.29	46.29	564	0	564	564
12/1/19	1005	1036	0	0	1652	103.84	140.18	1652	0	1652	1652
1/1/20	1036	1067	0	2000	5302	207.62	280.29	3302	0	3302	3302
2/1/20	1067	1096	0	2000	3158	68.09	91.92	1158	0	1158	1158
3/1/20	1096	1127	0	2000	2608	38.21	51.58	608	0	608	608
4/1/20	1127	1157	0	3900	4204	18.49	24.96	304	0	304	304
5/1/20	1157	1188	0	0	557	35.01	47.26	557	400	957	557
6/1/20	1188	1218	0	0	443	26.98	36.42	443	400	843	443
7/1/20	1218	1249	0	0	0	0	0	0	400	400	0
8/1/20	1249	1280	0	0	6	0.38	0.51	6	400	406	6
9/1/20	1280	1310	0	0	706	42.97	58.01	706	400	1106	706
10/1/20	1310	1341	0	0	1717	107.96	145.75	1717	0	1717	1717
11/1/20	1341	1371	0	0	1835	111.62	150.69	1835	0	1835	1835
12/1/20	1371	1402	0	0	1694	106.47	143.73	1694	0	1694	1694
1/1/21	1402	1433	0	2000	4594	163.08	220.16	2594	0	2594	2594
2/1/21	1433	1461	0	2000	4483	141.02	190.38	2483	0	2483	2483
3/1/21	1461	1492	0	2000	2456	28.65	38.68	456	0	456	456
4/1/21	1492	1522	0	3900	4071	10.4	14.04	171	0	171	171
5/1/21	1522	1553	0	0	196	12.31	16.62	196	400	596	196
6/1/21	1553	1583	0	0	275	16.76	22.63	275	400	675	275
7/1/21	1583	1614	0	0	0	0	0	0	400	400	0
8/1/21	1614	1645	0	0	192	12.04	16.25	192	400	592	192
9/1/21	1645	1675	0	0	299	18.2	24.57	299	400	699	299
10/1/21	1675	1706	0	0	1094	68.78	92.85	1094	0	1094	1094
11/1/21	1706	1736	0	0	2429	147.77	199.49	2429	0	2429	2429
12/1/21	1736	1767	0	0	2069	130.09	175.62	2069	0	2069	2069
1/1/22	1767	1798	0	2000	3930	121.34	163.81	1930	0	1930	1930
2/1/22	1798	1826	0	2000	2677	38.44	51.89	677	0	677	677
3/1/22	1826	1857	0	2000	3064	66.91	90.33	1064	0	1064	1064

Evapotranspiration Inputs

Like the RCH boundary condition, the EVT boundary condition requires a flux as its input, in $mm{\cdot}y^{-1}$. EVT is applied over the entire model domain and is not split into zones. Here, it was applied to the topmost active layer (NEVTOP = 3). Monthly actual evapotranspiration amounts, in mm, from the MODIS data set (Running et al., 2021) were multiplied by 365.25 and then divided by the number of days in the stress period to obtain the yearly flux. The additional multiplication factor to satisfy the mass balance for calibration was 2.5. The extinction depth was set at 4 meters per Table 10 (from Shah et al., 2007); this is effectively the top of the sandstone unit. Table B3 gives the evapotranspiration flux inputs.

Table B3.
Evapotranspiration Flux Inputs

Start Date	Stress Period		ET measured (mm·mo^{-1})	ET for calibration (mm·mo^{-1})	ET (mm·y^{-1})		Start Date	Stress Period		ET measured (mm·mo^{-1})	ET for calibration (mm·mo^{-1})	ET (mm·y^{-1})
3/1/17	0	31	32.14	80.36	947		10/1/19	944	975	14.71	36.77	433
4/1/17	31	61	28.33	70.83	862		11/1/19	975	1005	17.59	43.97	535
5/1/17	61	92	73.07	182.68	2152		12/1/19	1005	1036	11.24	28.11	331
6/1/17	92	122	90.34	225.86	2750		1/1/20	1036	1067	16.47	41.17	485
7/1/17	122	153	75.74	189.34	2231		2/1/20	1067	1096	22.41	56.03	706
8/1/17	153	184	59.28	148.21	1746		3/1/20	1096	1127	26.54	66.36	782
9/1/17	184	214	35.42	88.54	1078		4/1/20	1127	1157	39.18	97.94	1192
10/1/17	214	245	15.28	38.19	450		5/1/20	1157	1188	49.62	124.05	1462
11/1/17	245	275	13.49	33.73	411		6/1/20	1188	1218	75.39	188.47	2295
12/1/17	275	306	12.08	30.20	356		7/1/20	1218	1249	79.42	198.54	2339
1/1/18	306	337	13.61	34.03	401		8/1/20	1249	1280	58.88	147.19	1734
2/1/18	337	365	20.60	51.49	672		9/1/20	1280	1310	40.54	101.34	1234
3/1/18	365	396	28.14	70.36	829		10/1/20	1310	1341	22.16	55.40	653
4/1/18	396	426	30.97	77.43	943		11/1/20	1341	1371	10.17	25.42	309
5/1/18	426	457	84.23	210.58	2481		12/1/20	1371	1402	11.58	28.94	341
6/1/18	457	487	80.59	201.48	2453		1/1/21	1402	1433	13.21	33.03	389
7/1/18	487	518	73.85	184.63	2175		2/1/21	1433	1461	23.81	59.52	776
8/1/18	518	549	57.19	142.98	1685		3/1/21	1461	1492	26.07	65.17	768
9/1/18	549	579	34.27	85.67	1043		4/1/21	1492	1522	25.70	64.25	782
10/1/18	579	610	16.09	40.23	474		5/1/21	1522	1553	55.79	139.48	1643
11/1/18	610	640	14.86	37.16	452		6/1/21	1553	1583	74.29	185.72	2261
12/1/18	640	671	9.42	23.56	278		7/1/21	1583	1614	79.01	197.53	2327
1/1/19	671	702	15.94	39.86	470		8/1/21	1614	1645	63.24	158.11	1863
2/1/19	702	730	18.58	46.46	606		9/1/21	1645	1675	36.97	92.43	1125
3/1/19	730	761	30.92	77.29	911		10/1/21	1675	1706	16.12	40.31	475
4/1/19	761	791	28.31	70.78	862		11/1/21	1706	1736	16.65	41.62	507
5/1/19	791	822	62.65	156.63	1845		12/1/21	1736	1767	12.46	31.16	367
6/1/19	822	852	84.01	210.03	2557		1/1/22	1767	1798	14.47	36.16	426
7/1/19	852	883	76.47	191.18	2253		2/1/22	1798	1826	21.09	52.73	688
8/1/19	883	914	58.59	146.48	1726		3/1/22	1826	1857	28.76	71.91	847
9/1/19	914	944	37.64	94.09	1146							

Freds Creek SFR2 Inputs

SFR2 inputs for the calibrated model are provided in Table B4 and for the pond scenarios in Table B5. The SFR2 boundary condition also requires vector geometry input, which is shown in Figure 16.

Table B4.
SFR2 Inputs for Freds Creek in the Calibrated Model

Stress Period	Segment	Length (m)	Upstream Elevation (masl)	Downstream Elevation (masl)	Upstream Width (m)	Downstream Width (m)	Thickness (m)	K ($m \cdot s^{-1}$)	Depth (m)	THTS[a]	THTI[b]	EPS[c]
Jan-Mar	1	182.8	645.81	641.6	2	2	0.4	0.23	0.24	0.3	0.9	3
April	1	182.8	645.81	641.6	2	2	0.4	0.23	0.49	0.3	0.2	3
May-Dec	1	182.8	645.81	641.6	2	2	0.4	0.23	0.01	0.3	0.9	3
Jan-Mar	2	176.8	641.6	639.64	2	1.5	0.4	0.23	0.24	0.3	0.9	3
April	2	176.8	641.6	639.64	2	1.5	0.4	0.23	0.49	0.3	0.2	3
May-Dec	2	176.8	641.6	639.64	2	1.5	0.4	0.23	0.01	0.3	0.9	3
Jan-Mar	3	23.24	639.64	639.52	1.5	1.5	0.4	0.23	0.24	0.3	0.9	3
April	3	23.24	639.64	639.52	1.5	1.5	0.4	0.23	0.49	0.3	0.2	3
May-Dec	3	23.24	639.64	639.52	1.5	1.5	0.4	0.23	0.01	0.3	0.9	3
Jan-Mar	4	117.6	639.52	638.64	1.5	1.5	0.4	0.23	0.24	0.3	0.9	3
April	4	117.6	639.52	638.64	1.5	1.5	0.4	0.23	0.49	0.3	0.2	3
May-Dec	4	117.6	639.52	638.64	1.5	1.5	0.4	0.23	0.01	0.3	0.9	3

[a]THTS = saturated water content in the unsaturated zone beneath the upstream end of the current segment, [b]THTI = the initial water content beneath the upstream end of the current segment, [c]EPS = the Brooks-Corey exponent (Waterloo Hydrogeologic, 2021).

Table B5.
SFR2 Inputs for Freds Creek in the Pond Scenarios

Stress Period	Segment	Length (m)	Upstream Elevation (masl)	Downstream Elevation (masl)	Upstream Width (m)	Downstream Width (m)	Thickness (m)	K ($m \cdot s^{-1}$)	Depth (m)	THTS[a]	THTI[b]	EPS[c]
Jan-Mar	1	192.2	645.81	641.63	2	2	0.3	0.23	0.24	0.3	0.9	3
April	1	192.2	645.81	641.63	2	2	0.3	0.23	0.43	0.3	0.2	3
May-Dec	1	192.2	645.81	641.63	2	2	0.3	0.23	0.01	0.3	0.9	3
Jan-Mar	2	110	641.43	639.02	varies	varies	0.1	0.23	0.44	0.3	0.9	3
April	2	110	641.43	639.02	varies	varies	0.1	0.23	0.63	0.3	0.2	3
May-Dec	2	110	641.43	639.02	varies	varies	0.1	0.23	0.01	0.3	0.9	3
Jan-Mar	3	72.6	639.22	638.54	2.5	2	0.3	0.23	0.24	0.3	0.9	3
April	3	72.6	639.22	638.54	2.5	2	0.3	0.23	0.43	0.3	0.2	3
May-Dec	3	72.6	639.22	638.54	2.5	2	0.3	0.23	0.01	0.3	0.9	3
Jan-Mar	4	77.8	638.54	638	2	1.5	0.3	0.23	0.24	0.3	0.9	3
April	4	77.8	638.54	638	2	1.5	0.3	0.23	0.43	0.3	0.2	3
May-Dec	4	77.8	638.54	638	2	1.5	0.3	0.23	0.01	0.3	0.9	3

[a]THTS = saturated water content in the unsaturated zone beneath the upstream end of the current segment, [b]THTI = the initial water content beneath the upstream end of the current segment, [c]EPS = the Brooks-Corey exponent (Waterloo Hydrogeologic, 2021).

General Head Boundary Condition Inputs

GHB conditions were used at the east and west edges of the model domain (Figure 12). Monthly head elevations were computed by the equation of the best-fit plane at the coordinates of the corners of the site (Table 4). Linear interpolation is employed by Visual MODFLOW Flex 7.0 to establish head elevations between the specified corner elevations.

Table B6.
GHB Head Elevations at the West (Upgradient) End of the Site

Start Date	Stress Period		Point0 (SW corner)	Point1 (NW corner)		Start Date	Stress Period		Point0 (SW corner)	Point1 (NW corner)
3/1/17	0	31	646.1	648.8		10/1/19	944	975	645.8	646.5
4/1/17	31	61	646.1	647.9		11/1/19	975	1005	646.4	647.2
5/1/17	61	92	645.7	647.1		12/1/19	1005	1036	646.2	647.3
6/1/17	92	122	645.3	646.6		1/1/20	1036	1067	647.0	649.7
7/1/17	122	153	643.4	644.6		2/1/20	1067	1096	646.5	649.5
8/1/17	153	184	644.1	645.0		3/1/20	1096	1127	646.1	648.8
9/1/17	184	214	645.5	646.5		4/1/20	1127	1157	646.1	647.9
10/1/17	214	245	645.8	646.5		5/1/20	1157	1188	645.7	647.1
11/1/17	245	275	646.4	647.2		6/1/20	1188	1218	645.3	646.6
12/1/17	275	306	646.2	647.3		7/1/20	1218	1249	643.4	644.6
1/1/18	306	337	647.0	649.7		8/1/20	1249	1280	644.1	645.0
2/1/18	337	365	646.5	649.5		9/1/20	1280	1310	645.5	646.5
3/1/18	365	396	646.1	648.8		10/1/20	1310	1341	645.8	646.5
4/1/18	396	426	646.1	647.9		11/1/20	1341	1371	646.4	647.2
5/1/18	426	457	645.7	647.1		12/1/20	1371	1402	646.2	647.3
6/1/18	457	487	645.3	646.6		1/1/21	1402	1433	647.0	649.7
7/1/18	487	518	643.4	644.6		2/1/21	1433	1461	646.5	649.5
8/1/18	518	549	644.1	645.0		3/1/21	1461	1492	646.1	648.8
9/1/18	549	579	645.5	646.5		4/1/21	1492	1522	646.1	647.9
10/1/18	579	610	645.8	646.5		5/1/21	1522	1553	645.7	647.1
11/1/18	610	640	646.4	647.2		6/1/21	1553	1583	645.3	646.6
12/1/18	640	671	646.2	647.3		7/1/21	1583	1614	643.4	644.6
1/1/19	671	702	647.0	649.7		8/1/21	1614	1645	644.1	645.0
2/1/19	702	730	646.5	649.5		9/1/21	1645	1675	645.5	646.5
3/1/19	730	761	646.1	648.8		10/1/21	1675	1706	645.8	646.5
4/1/19	761	791	646.1	647.9		11/1/21	1706	1736	646.4	647.2
5/1/19	791	822	645.7	647.1		12/1/21	1736	1767	646.2	647.3
6/1/19	822	852	645.3	646.6		1/1/22	1767	1798	647.0	649.7
7/1/19	852	883	643.4	644.6		2/1/22	1798	1826	646.5	649.5
8/1/19	883	914	644.1	645.0		3/1/22	1826	1857	646.1	648.8
9/1/19	914	944	645.5	646.5						

Table B7.
GHB Head Elevations at the East (Downgradient) End of the Site

Start Date	Stress Period		Point0 (SE corner)	Point1 (NE corner)	Start Date	Stress Period		Point0 (SE corner)	Point1 (NE corner)
3/1/17	0	31	635.1	638.8	10/1/19	944	975	634.2	633.6
4/1/17	31	61	635.2	637.1	11/1/19	975	1005	634.5	634.0
5/1/17	61	92	635.0	636.0	12/1/19	1005	1036	634.4	634.7
6/1/17	92	122	634.4	635.3	1/1/20	1036	1067	634.2	637.6
7/1/17	122	153	634.0	634.8	2/1/20	1067	1096	634.8	639.1
8/1/17	153	184	633.8	634.0	3/1/20	1096	1127	635.1	638.8
9/1/17	184	214	633.8	633.7	4/1/20	1127	1157	635.2	637.1
10/1/17	214	245	634.2	633.6	5/1/20	1157	1188	635.0	636.0
11/1/17	245	275	634.5	634.0	6/1/20	1188	1218	634.4	635.3
12/1/17	275	306	634.4	634.7	7/1/20	1218	1249	634.0	634.8
1/1/18	306	337	634.2	637.6	8/1/20	1249	1280	633.8	634.0
2/1/18	337	365	634.8	639.1	9/1/20	1280	1310	633.8	633.7
3/1/18	365	396	635.1	638.8	10/1/20	1310	1341	634.2	633.6
4/1/18	396	426	635.2	637.1	11/1/20	1341	1371	634.5	634.0
5/1/18	426	457	635.0	636.0	12/1/20	1371	1402	634.4	634.7
6/1/18	457	487	634.4	635.3	1/1/21	1402	1433	634.2	637.6
7/1/18	487	518	634.0	634.8	2/1/21	1433	1461	634.8	639.1
8/1/18	518	549	633.8	634.0	3/1/21	1461	1492	635.1	638.8
9/1/18	549	579	633.8	633.7	4/1/21	1492	1522	635.2	637.1
10/1/18	579	610	634.2	633.6	5/1/21	1522	1553	635.0	636.0
11/1/18	610	640	634.5	634.0	6/1/21	1553	1583	634.4	635.3
12/1/18	640	671	634.4	634.7	7/1/21	1583	1614	634.0	634.8
1/1/19	671	702	634.2	637.6	8/1/21	1614	1645	633.8	634.0
2/1/19	702	730	634.8	639.1	9/1/21	1645	1675	633.8	633.7
3/1/19	730	761	635.1	638.8	10/1/21	1675	1706	634.2	633.6
4/1/19	761	791	635.2	637.1	11/1/21	1706	1736	634.5	634.0
5/1/19	791	822	635.0	636.0	12/1/21	1736	1767	634.4	634.7
6/1/19	822	852	634.4	635.3	1/1/22	1767	1798	634.2	637.6
7/1/19	852	883	634.0	634.8	2/1/22	1798	1826	634.8	639.1
8/1/19	883	914	633.8	634.0	3/1/22	1826	1857	635.1	638.8
9/1/19	914	944	633.8	633.7					

Teanaway River Stage

Inputs for monthly river stage along the 1800-meter reach of the Teanaway River are provided in Tables B8 and B9. The rating curve in Figure 14 and median monthly discharge information from the Teanaway River at Forks near Cle Elum gage (Station ID 12480000) are used to compute the stage at “the Rock,” which is the location of the measure-style gage installed in the river at the southeast corner of the site (Figure 2). Stage is then interpolated upstream as a constant height above the riverbed. Stage is input into the model at each of the nodes of the polyline from a GIS that defines the geometry of the river. Stage is linearly interpolated in model cells between nodes.

Table B8.
Calculated Stage in the TVFF Reach of the Teanaway River, nodes 0 through 14

Date	Median Discharge	Stage at Rock Gage	point_0	point_1	point_2	point_3	point_4	point_5	point_6	point_7	point_8	point_9	point_10	point_11	point_12	point_13	point_14
Riverbed Elevation:		636.0	646.8	646.7	645.9	645.3	646.7	644.0	642.7	643.5	642.4	643.9	643.9	643.4	643.2	642.7	642.3
3/1/17	18.9	636.8	647.61	647.54	646.71	646.11	647.52	644.81	643.50	644.26	643.26	644.71	644.76	644.24	644.04	643.52	643.06
4/1/17	30.0	636.9	647.75	647.68	646.84	646.25	647.66	644.95	643.64	644.39	643.39	644.84	644.89	644.38	644.17	643.66	643.20
5/1/17	27.9	636.9	647.73	647.66	646.82	646.22	647.63	644.92	643.62	644.37	643.37	644.82	644.87	644.35	644.15	643.63	643.17
6/1/17	7.8	636.6	647.43	647.36	646.52	645.92	647.33	644.62	643.32	644.07	643.07	644.52	644.57	644.05	643.85	643.33	642.87
7/1/17	1.2	636.4	647.21	647.14	646.30	645.71	647.12	644.41	643.10	643.86	642.85	644.30	644.35	643.84	643.64	643.12	642.66
8/1/17	0.5	636.4	647.16	647.09	646.25	645.66	647.07	644.36	643.05	643.80	642.80	644.25	644.30	643.79	643.58	643.07	642.61
9/1/17	0.5	636.4	647.16	647.09	646.25	645.66	647.07	644.36	643.05	643.80	642.80	644.25	644.30	643.79	643.58	643.07	642.61
10/1/17	0.9	636.4	647.19	647.12	646.28	645.69	647.10	644.39	643.08	643.84	642.83	644.28	644.33	643.82	643.62	643.10	642.64
11/1/17	4.8	636.5	647.35	647.28	646.44	645.85	647.26	644.55	643.24	644.00	642.99	644.44	644.49	643.98	643.78	643.26	642.80
12/1/17	5.6	636.6	647.37	647.30	646.47	645.87	647.28	644.57	643.26	644.02	643.02	644.46	644.51	644.00	643.80	643.28	642.82
1/1/18	8.2	636.6	647.43	647.36	646.53	645.93	647.34	644.63	643.32	644.08	643.08	644.53	644.58	644.06	643.86	643.34	642.88
2/1/18	13	636.7	647.53	647.46	646.62	646.02	647.43	644.72	643.42	644.17	643.17	644.62	644.67	644.15	643.95	643.43	642.97
3/1/18	12.5	636.7	647.52	647.45	646.61	646.01	647.43	644.72	643.41	644.16	643.16	644.61	644.66	644.14	643.94	643.42	642.96
4/1/18	24.55	636.9	647.69	647.62	646.78	646.19	647.60	644.89	643.58	644.33	643.33	644.78	644.83	644.31	644.11	643.60	643.13
5/1/18	34.8	637.0	647.80	647.73	646.89	646.30	647.71	645.00	643.69	644.44	643.44	644.89	644.94	644.43	644.22	643.71	643.25
6/1/18	3.55	636.5	647.31	647.24	646.41	645.81	647.22	644.51	643.20	643.96	642.96	644.40	644.45	643.94	643.74	643.22	642.76
7/1/18	0.9	636.4	647.19	647.12	646.28	645.69	647.10	644.39	643.08	643.84	642.83	644.28	644.33	643.82	643.62	643.10	642.64
8/1/18	0.6	636.4	647.17	647.10	646.26	645.67	647.08	644.37	643.06	643.81	642.81	644.26	644.31	643.80	643.59	643.08	642.61
9/1/18	0.5	636.4	647.16	647.09	646.25	645.66	647.07	644.36	643.05	643.80	642.80	644.25	644.30	643.79	643.58	643.07	642.61
10/1/18	0.6	636.4	647.17	647.10	646.26	645.67	647.08	644.37	643.06	643.81	642.81	644.26	644.31	643.80	643.59	643.08	642.61
11/1/18	5.5	636.6	647.37	647.30	646.46	645.87	647.28	644.57	643.26	644.02	643.01	644.46	644.51	644.00	643.79	643.28	642.82
12/1/18	6.3	636.6	647.39	647.32	646.48	645.89	647.30	644.59	643.28	644.04	643.03	644.48	644.53	644.02	643.82	643.30	642.84
1/1/19	11.1	636.7	647.49	647.42	646.58	645.99	647.40	644.69	643.38	644.14	643.14	644.58	644.63	644.12	643.92	643.40	642.94
2/1/19	9.25	636.7	647.46	647.39	646.55	645.95	647.36	644.65	643.35	644.10	643.10	644.55	644.60	644.08	643.88	643.36	642.90
3/1/19	7.3	636.6	647.41	647.34	646.51	645.91	647.32	644.61	643.30	644.06	643.06	644.51	644.56	644.04	643.84	643.32	642.86
4/1/19	37.2	637.0	647.82	647.75	646.92	646.32	647.73	645.02	643.71	644.47	643.47	644.91	644.96	644.45	644.25	643.73	643.27
5/1/19	13.9	636.7	647.54	647.47	646.63	646.04	647.45	644.74	643.43	644.19	643.18	644.63	644.68	644.17	643.96	643.45	642.99
6/1/19	2.4	636.5	647.27	647.20	646.36	645.77	647.18	644.47	643.16	643.92	642.91	644.36	644.41	643.90	643.69	643.18	642.72
7/1/19	0.8	636.4	647.18	647.11	646.28	645.68	647.09	644.38	643.07	643.83	642.83	644.28	644.32	643.81	643.61	643.09	642.63
8/1/19	0.5	636.4	647.16	647.09	646.25	645.66	647.07	644.36	643.05	643.80	642.80	644.25	644.30	643.79	643.58	643.07	642.61
9/1/19	0.6	636.4	647.17	647.10	646.26	645.67	647.08	644.37	643.06	643.81	642.81	644.26	644.31	643.80	643.59	643.08	642.61
10/1/19	1.6	636.4	647.23	647.16	646.33	645.73	647.14	644.43	643.12	643.88	642.88	644.32	644.37	643.86	643.66	643.14	642.68
11/1/19	2.95	636.5	647.29	647.22	646.38	645.79	647.20	644.49	643.18	643.94	642.93	644.38	644.43	643.92	643.72	643.20	642.74
12/1/19	3.6	636.5	647.31	647.24	646.41	645.81	647.22	644.51	643.20	643.96	642.96	644.41	644.45	643.94	643.74	643.22	642.76
1/1/20	16.4	636.8	647.58	647.51	646.67	646.08	647.49	644.78	643.47	644.22	643.22	644.67	644.72	644.21	644.00	643.49	643.03
2/1/20	19.5	636.8	647.62	647.55	646.72	646.12	647.53	644.82	643.51	644.27	643.27	644.71	644.76	644.25	644.05	643.53	643.07
3/1/20	18.7	636.8	647.61	647.54	646.70	646.11	647.52	644.81	643.50	644.26	643.26	644.70	644.75	644.24	644.04	643.52	643.06
4/1/20	33.45	637.0	647.79	647.71	646.88	646.28	647.69	644.98	643.68	644.43	643.43	644.88	644.93	644.41	644.21	643.69	643.23
5/1/20	27.5	636.9	647.72	647.65	646.81	646.22	647.63	644.92	643.61	644.37	643.36	644.81	644.86	644.35	644.15	643.63	643.17
6/1/20	5.75	636.6	647.38	647.31	646.47	645.87	647.29	644.58	643.27	644.02	643.02	644.47	644.52	644.00	643.80	643.28	642.82
7/1/20	1.1	636.4	647.20	647.13	646.30	645.70	647.11	644.40	643.09	643.85	642.85	644.30	644.35	643.83	643.63	643.11	642.65
8/1/20	0.3	636.3	647.14	647.07	646.23	645.64	647.05	644.34	643.03	643.78	642.78	644.23	644.28	643.76	643.56	643.05	642.58
9/1/20	0.4	636.3	647.15	647.08	646.24	645.65	647.06	644.35	643.04	643.79	642.79	644.24	644.29	643.78	643.57	643.06	642.60
10/1/20	7.1	636.6	647.41	647.34	646.50	645.91	647.32	644.61	643.30	644.06	643.05	644.50	644.55	644.04	643.83	643.32	642.86
11/1/20	8.05	636.6	647.43	647.36	646.52	645.93	647.34	644.63	643.32	644.08	643.07	644.52	644.57	644.06	643.86	643.34	642.88
12/1/20	8.5	636.6	647.44	647.37	646.53	645.94	647.35	644.64	643.33	644.09	643.08	644.53	644.58	644.07	643.87	643.35	642.89
1/1/21	9.6	636.7	647.46	647.39	646.56	645.96	647.37	644.66	643.35	644.11	643.11	644.56	644.60	644.09	643.89	643.37	642.91
2/1/21	7.95	636.6	647.43	647.36	646.52	645.93	647.34	644.63	643.32	644.08	643.07	644.52	644.57	644.06	643.85	643.34	642.88
3/1/21	12.3	636.7	647.51	647.44	646.61	646.01	647.42	644.71	643.40	644.16	643.16	644.60	644.65	644.14	643.94	643.42	642.96
4/1/21	30.55	637.0	647.76	647.68	646.85	646.25	647.66	644.95	643.64	644.40	643.40	644.85	644.90	644.38	644.18	643.66	643.20
5/1/21	25.5	636.9	647.70	647.63	646.79	646.20	647.61	644.90	643.59	644.34	643.34	644.79	644.84	644.33	644.12	643.61	643.15
6/1/21	10.65	636.7	647.48	647.41	646.58	645.98	647.39	644.68	643.37	644.13	643.13	644.58	644.62	644.11	643.91	643.39	642.93
7/1/21	1.2	636.4	647.21	647.14	646.30	645.71	647.12	644.41	643.10	643.86	642.85	644.30	644.35	643.84	643.64	643.12	642.66
8/1/21	0.5	636.4	647.16	647.09	646.25	645.66	647.07	644.36	643.05	643.80	642.80	644.25	644.30	643.79	643.58	643.07	642.61
9/1/21	0.5	636.4	647.16	647.09	646.25	645.66	647.07	644.36	643.05	643.80	642.80	644.25	644.30	643.79	643.58	643.07	642.61
10/1/21	0.7	636.4	647.18	647.11	646.27	645.67	647.08	644.37	643.07	643.82	642.82	644.27	644.32	643.80	643.60	643.08	642.62
11/1/21	8.8	636.6	647.45	647.38	646.54	645.95	647.36	644.65	643.34	644.09	643.09	644.54	644.59	644.07	643.87	643.36	642.89
12/1/21	5.7	636.6	647.38	647.31	646.47	645.87	647.28	644.57	643.27	644.02	643.02	644.47	644.52	644.00	643.80	643.28	642.82
1/1/22	18.4	636.8	647.61	647.54	646.70	646.11	647.52	644.81	643.50	644.25	643.25	644.70	644.75	644.24	644.03	643.52	643.05
2/1/22	11.55	636.7	647.50	647.43	646.59	646.00	647.41	644.70	643.39	644.15	643.14	644.59	644.64	644.13	643.92	643.41	642.95
3/1/22	22.0	636.9	647.66	647.59	646.75	646.15	647.56	644.85	643.55	644.30	643.30	644.75	644.80	644.28	644.08	643.56	643.10

Table B9.

Calculated Stage in the TVFF Reach of the Teanaway River, nodes 15 through 29

Date	Median Discharge	Stage at Rock Gage	point_15	point_16	point_17	point_18	point_19	point_20	point_21	point_22	point_23	point_24	point_25	point_26	point_27	point_28	point_29
Riverbed Elevation:		636.0	646.8	641.9	641.2	641.1	639.5	639.3	637.9	639.4	635.5	636.5	636.2	635.0	635.0	635.2	635.1
3/1/17	18.9	636.8	642.74	642.02	641.93	640.35	640.12	638.75	640.23	636.35	637.30	637.02	635.81	635.80	636.04	635.87	635.66
4/1/17	30.0	636.9	642.88	642.15	642.06	640.48	640.25	638.88	640.37	636.48	637.43	637.16	635.95	635.94	636.17	636.00	635.79
5/1/17	27.9	636.9	642.86	642.13	642.04	640.46	640.23	638.86	640.35	636.46	637.41	637.13	635.92	635.91	636.15	635.98	635.77
6/1/17	7.8	636.6	642.56	641.83	641.74	640.16	639.93	638.56	640.05	636.16	637.11	636.83	635.62	635.61	635.85	635.68	635.47
7/1/17	1.2	636.4	642.34	641.61	641.53	639.94	639.71	638.34	639.83	635.94	636.89	636.62	635.41	635.40	635.63	635.47	635.25
8/1/17	0.5	636.4	642.29	641.56	641.47	639.89	639.66	638.29	639.78	635.89	636.84	636.57	635.36	635.35	635.58	635.41	635.20
9/1/17	0.5	636.4	642.29	641.56	641.47	639.89	639.66	638.29	639.78	635.89	636.84	636.57	635.36	635.35	635.58	635.41	635.20
10/1/17	0.9	636.4	642.32	641.59	641.51	639.92	639.69	638.33	639.81	635.92	636.88	636.60	635.39	635.38	635.61	635.45	635.24
11/1/17	4.8	636.5	642.48	641.75	641.67	640.08	639.85	638.48	639.97	636.08	637.03	636.76	635.55	635.54	635.77	635.61	635.39
12/1/17	5.6	636.6	642.50	641.77	641.69	640.10	639.87	638.51	639.99	636.10	637.06	636.78	635.57	635.56	635.80	635.63	635.42
1/1/18	8.2	636.6	642.56	641.84	641.75	640.17	639.94	638.57	640.05	636.17	637.12	636.84	635.63	635.62	635.86	635.69	635.48
2/1/18	13	636.7	642.66	641.93	641.84	640.26	640.03	638.66	640.14	636.26	637.21	636.93	635.72	635.71	635.95	635.78	635.57
3/1/18	12.5	636.7	642.65	641.92	641.83	640.25	640.02	638.65	640.14	636.25	637.20	636.93	635.71	635.70	635.94	635.77	635.56
4/1/18	24.55	636.9	642.82	642.09	642.00	640.42	640.19	638.82	640.31	636.42	637.37	637.10	635.88	635.87	636.11	635.94	635.73
5/1/18	34.8	637.0	642.93	642.20	642.11	640.53	640.30	638.93	640.42	636.53	637.48	637.21	636.00	635.98	636.22	636.05	635.84
6/1/18	3.55	636.5	642.44	641.71	641.63	640.04	639.81	638.45	639.93	636.04	637.00	636.72	635.51	635.50	635.73	635.57	635.36
7/1/18	0.9	636.4	642.32	641.59	641.51	639.92	639.69	638.33	639.81	635.92	636.88	636.60	635.39	635.38	635.61	635.45	635.24
8/1/18	0.6	636.4	642.30	641.57	641.48	639.90	639.67	638.30	639.79	635.90	636.85	636.58	635.37	635.35	635.59	635.42	635.21
9/1/18	0.5	636.4	642.29	641.56	641.47	639.89	639.66	638.29	639.78	635.89	636.84	636.57	635.36	635.35	635.58	635.41	635.20
10/1/18	0.6	636.4	642.30	641.57	641.48	639.90	639.67	638.30	639.79	635.90	636.85	636.58	635.37	635.35	635.59	635.42	635.21
11/1/18	5.5	636.6	642.50	641.77	641.69	640.10	639.87	638.50	639.99	636.10	637.05	636.78	635.57	635.56	635.79	635.63	635.41
12/1/18	6.3	636.6	642.52	641.79	641.71	640.12	639.89	638.52	640.01	636.12	637.07	636.80	635.59	635.58	635.81	635.65	635.43
1/1/19	11.1	636.7	642.62	641.89	641.81	640.22	639.99	638.63	640.11	636.22	637.18	636.90	635.69	635.68	635.91	635.75	635.54
2/1/19	9.25	636.7	642.59	641.86	641.77	640.19	639.96	638.59	640.08	636.19	637.14	636.86	635.65	635.64	635.88	635.71	635.50
3/1/19	7.3	636.6	642.54	641.82	641.73	640.15	639.92	638.55	640.03	636.15	637.10	636.82	635.61	635.60	635.84	635.67	635.46
4/1/19	37.2	637.0	642.95	642.22	642.14	640.55	640.32	638.96	640.44	636.55	637.51	637.23	636.02	636.01	636.24	636.08	635.87
5/1/19	13.9	636.7	642.67	641.94	641.86	640.27	640.04	638.67	640.16	636.27	637.22	636.95	635.74	635.73	635.96	635.79	635.58
6/1/19	2.4	636.5	642.40	641.67	641.58	640.00	639.77	638.40	639.89	636.00	636.95	636.68	635.47	635.46	635.69	635.52	635.31
7/1/19	0.8	636.4	642.31	641.58	641.50	639.92	639.69	638.32	639.80	635.92	636.87	636.59	635.38	635.37	635.61	635.44	635.23
8/1/19	0.5	636.4	642.29	641.56	641.47	639.89	639.66	638.29	639.78	635.89	636.84	636.57	635.36	635.35	635.58	635.41	635.20
9/1/19	0.6	636.4	642.30	641.57	641.48	639.90	639.67	638.30	639.79	635.90	636.85	636.58	635.37	635.35	635.59	635.42	635.21
10/1/19	1.6	636.4	642.36	641.63	641.55	639.96	639.73	638.37	639.85	635.96	636.92	636.64	635.43	635.42	635.66	635.49	635.28
11/1/19	2.95	636.5	642.42	641.69	641.61	640.02	639.79	638.42	639.91	636.02	636.97	636.70	635.49	635.48	635.71	635.55	635.33
12/1/19	3.6	636.5	642.44	641.71	641.63	640.05	639.81	638.45	639.93	636.05	637.00	636.72	635.51	635.50	635.74	635.57	635.36
1/1/20	16.4	636.8	642.71	641.98	641.89	640.31	640.08	638.71	640.20	636.31	637.26	636.99	635.78	635.77	636.00	635.83	635.62
2/1/20	19.5	636.8	642.75	642.02	641.94	640.35	640.12	638.76	640.24	636.35	637.31	637.03	635.82	635.81	636.05	635.88	635.67
3/1/20	18.7	636.8	642.74	642.01	641.93	640.34	640.11	638.75	640.23	636.34	637.30	637.02	635.81	635.80	636.03	635.87	635.66
4/1/20	33.45	637.0	642.92	642.19	642.10	640.52	640.29	638.92	640.40	636.52	637.47	637.19	635.98	635.97	636.21	636.04	635.83
5/1/20	27.5	636.9	642.85	642.12	642.04	640.45	640.22	638.86	640.34	636.45	637.41	637.13	635.92	635.91	636.14	635.98	635.77
6/1/20	5.75	636.6	642.51	641.78	641.69	640.11	639.88	638.51	640.00	636.11	637.06	636.79	635.57	635.56	635.80	635.63	635.42
7/1/20	1.1	636.4	642.33	641.61	641.52	639.94	639.71	638.34	639.82	635.94	636.89	636.61	635.40	635.39	635.63	635.46	635.25
8/1/20	0.3	636.3	642.27	641.54	641.45	639.87	639.64	638.27	639.76	635.87	636.82	636.55	635.33	635.32	635.56	635.39	635.18
9/1/20	0.4	636.3	642.28	641.55	641.46	639.88	639.65	638.28	639.77	635.88	636.83	636.56	635.35	635.34	635.57	635.40	635.19
10/1/20	7.1	636.6	642.54	641.81	641.73	640.14	639.91	638.54	640.03	636.14	637.09	636.82	635.61	635.60	635.83	635.66	635.45
11/1/20	8.05	636.6	642.56	641.83	641.75	640.16	639.93	638.57	640.05	636.16	637.12	636.84	635.63	635.62	635.85	635.69	635.48
12/1/20	8.5	636.6	642.57	641.84	641.76	640.17	639.94	638.57	640.06	636.17	637.12	636.85	635.64	635.63	635.86	635.70	635.48
1/1/21	9.6	636.7	642.59	641.86	641.78	640.20	639.96	638.60	640.08	636.20	637.15	636.87	635.66	635.65	635.89	635.72	635.51
2/1/21	7.95	636.6	642.56	641.83	641.74	640.16	639.93	638.56	640.05	636.16	637.11	636.84	635.63	635.62	635.85	635.68	635.47
3/1/21	12.3	636.7	642.64	641.91	641.83	640.25	640.01	638.65	640.13	636.25	637.20	636.92	635.71	635.70	635.94	635.77	635.56
4/1/21	30.55	637.0	642.88	642.16	642.07	640.49	640.26	638.89	640.37	636.49	637.44	637.16	635.95	635.94	636.18	636.01	635.80
5/1/21	25.5	636.9	642.83	642.10	642.01	640.43	640.20	638.83	640.32	636.43	637.38	637.11	635.90	635.88	636.12	635.95	635.74
6/1/21	10.65	636.7	642.61	641.88	641.80	640.22	639.98	638.62	640.10	636.22	637.17	636.89	635.68	635.67	635.91	635.74	635.53
7/1/21	1.2	636.4	642.34	641.61	641.53	639.94	639.71	638.34	639.83	635.94	636.89	636.62	635.41	635.40	635.63	635.47	635.25
8/1/21	0.5	636.4	642.29	641.56	641.47	639.89	639.66	638.29	639.78	635.89	636.84	636.57	635.36	635.35	635.58	635.41	635.20
9/1/21	0.5	636.4	642.29	641.56	641.47	639.89	639.66	638.29	639.78	635.89	636.84	636.57	635.36	635.35	635.58	635.41	635.20
10/1/21	0.7	636.4	642.31	641.58	641.49	639.91	639.68	638.31	639.80	635.91	636.86	636.58	635.37	635.36	635.60	635.43	635.22
11/1/21	8.8	636.6	642.58	641.85	641.76	640.18	639.95	638.58	640.07	636.18	637.13	636.86	635.64	635.63	635.87	635.70	635.49
12/1/21	5.7	636.6	642.51	641.78	641.69	640.11	639.88	638.51	640.00	636.11	637.06	636.78	635.57	635.56	635.80	635.63	635.42
1/1/22	18.4	636.8	642.74	642.01	641.92	640.34	640.11	638.74	640.23	636.34	637.29	637.02	635.80	635.79	636.03	635.86	635.65
2/1/22	11.55	636.7	642.63	641.90	641.82	640.23	640.00	638.63	640.12	636.23	637.18	636.91	635.70	635.69	635.92	635.75	635.54
3/1/22	22.0	636.9	642.79	642.06	641.97	640.39	640.16	638.79	640.28	636.39	637.34	637.06	635.85	635.84	636.08	635.91	635.70