Effect of Large Wood Restoration on Alluvial Aquifer Storage in Yakima Basin Headwater Tributaries

A Report for Washington State Department of Ecology Project # NTA C210007 and the Groundwater Subcommittee of the Yakima Basin Integrated Plan

May 2023

By Carey A. Gazis and Lisa L. Ely
Central Washington University

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. Executive Summary

Enhancing groundwater storage is a practical strategy to increase late-summer water supplies within the Yakima River watershed. In the Yakima River basin, one potential target for groundwater storage is the floodplains of its tributaries. The hydrologic function of these tributaries has been degraded by past and current land uses. Through the collaboration of multiple stakeholders, recent stream restoration projects have placed large wood into multiple tributaries of the Yakima River to increase sedimentation in channels and divert more water onto adjacent floodplains. One intended hydrologic effect of wood emplacement is to increase groundwater recharge and storage in alluvial aquifers during spring high flows, resulting in a natural release of water into streams later in the season. Benefits of wood restoration in streams for aquatic and riparian habitats are well documented (Roni et al., 2015). However, the impact of wood restoration on groundwater storage is not yet well understood or quantified (Nash et al., 2018; Boylan, 2019a, b). Relatively few long-term, field measurements of this approach to enhance groundwater recharge and storage have been conducted.

The Teanaway River is one of the northernmost tributaries of the Yakima River and has been substantially altered by past land use practices including logging and agriculture. The logging practices removed trees from the watershed and caused incision of the Teanaway River and its tributaries, reducing the hydraulic connection between stream and floodplain (Schanz et al., 2019). Agricultural practices have diverted water from the streams and ponds, recharging the shallow aquifer in some locations and reducing natural recharge in others.

This project focused on two sites in the Teanaway River basin: Indian Creek and Teanaway Valley Family Farm. Indian Creek is a small tributary on the North Fork of the Teanaway River where large wood (LW) was emplaced in stages from 2016 to 2018. We assessed whether the restoration of instream LW had consistent, detectable effects on the recharge and storage of groundwater in the alluvial floodplain aquifer at Indian Creek. Possible changes to the groundwater in the floodplain before and after the LW installation were investigated through analysis of the floodplain stratigraphy and sediment grain-size, stream-flow modeling, and monitoring of groundwater levels from 2014-2021.

Teanaway Valley Family Farm (TVFF), a property on the floodplain along the main stem of the Teanaway River represents a different setting in the Teanaway River basin. At this site, the Teanaway River has been incised into the sandstone bedrock. TVFF and the neighboring properties have been farmed for timothy hay for decades. Changing irrigation practices over the past twenty years have altered the hydraulic characteristics of the site. TVFF was purchased by the Washington Department of Fish and Wildlife in 2017 and is now being restored to promote more natural function. As part of this effort, ten monitoring wells were installed at TVFF to inform restoration decisions. We analyzed pressure transducer data from these monitoring wells to describe groundwater recharge and flow patterns. This information was supplemented with stable isotope analyses of groundwater and surface water samples, which were used to determine the extent to which Teanaway River water infiltrates into the floodplain.

Examination of sediments at both sites reveals the presence of fine-grained sediment (clay to silt), which is relatively impermeable and thus serves as confining layers within the floodplain aquifer. At TVFF, examination of tailings during well installation revealed that a thick and continuous clay unit dominates the northern side of the floodplain. This unit is up to 5 meters thick, likely the remnants of a glacial lake deposit (Tabor et al., 1982) that has been eroded away on the lower side of the floodplain by the modern river. At Indian Creek, the clay layers are thinner and interspersed with sand layers. Stratigraphic descriptions of the stream banks reveal a ubiquitous silt/clay dominant layer (60-90 cm thick) at a depth of 1 meter or less, overlying a sand and gravel layer (15-50 cm thick), a clay/silt layer (~30 cm thick), and another sand and gravel layer. These relatively continuous clay layers extend at least 2.2 km upstream from the mouth of Indian Creek on both sides of the channel. Similar clay units have been mapped elsewhere in the region as glacial drift or lacustrine deposits (Tabor et al., 1982).

The presence of clay has a number of implications for groundwater storage. When it is present as a massive unit as at TVFF, it occupies a volume that is not accessible for water storage. Although the clay is often saturated with water, it can not transmit water at a useful rate. When present as thinner horizons, the clay serves to create small, perched aquifers and pathways of fluid flow. It also appears to control the course and incision rate of streams.

At Indian Creek, the groundwater levels in the monitoring wells before and after the LW emplacement show no detectable sustained effect of the LW restoration on seasonal or longer-term groundwater levels in the five years following the initial LW emplacement in Indian Creek. Groundwater levels in the floodplain piezometers return to base levels within days of monthly precipitation exceeding 70 mm, suggesting relatively rapid groundwater outflow, possibly through the permeable sand and gravel layers interbedded with the clay and silt layers. The highest spring groundwater elevations precede peak stream discharge, indicating that flow from the Indian Creek channel into the adjacent floodplain during the peak discharge is not the main source of recharge to the floodplain aquifer. A 1-dimensional hydraulic model run with and without channel obstructions (representing LW) at the monthly average discharge in spring and the peak discharge during the study period suggests that the addition of LW log jams may increase the water surface elevation by ~10-50 cm during high flows, below the bank elevation in the modeled reach.

These results of the research at Indian Creek suggest that the wood in the stream is yet to have an impact on the groundwater recharge and storage in the Indian Creek floodplain. The large wood restoration project at Indian Creek is still relatively recent, and restoration work is still being performed at the site. Over time, increased sediment aggradation in the channel or a flood that reorganizes the channel wood could conceivably alter the future surface water-groundwater interactions. However, due to the channel incision of up to 2 m on Indian Creek and the main Teanaway River, significant channel aggradation would be necessary to facilitate this interaction. The assessment of stratigraphy coupled with groundwater data and stream-flow modeling reported here provides initial insight into the role of the floodplain stratigraphy on the potential groundwater recharge associated with LW restoration at one site. Further investigation of the stratigraphy of other headwater tributaries of the Yakima River could expand our understanding of the regional effectiveness of instream large wood on groundwater recharge and storage.

At TVFF, groundwater elevation data from the ten monitoring wells at define three aquifers in the study area. A cobble-rich alluvial aquifer occupies the lower two-thirds of the floodplain. Stable isotope data indicates that Teanaway River water infiltrates fully into this aquifer and completely flushes through the aquifer in the riparian forest along the river. In the upper third of the floodplain, there is a confined aquifer below the thick clay deposit there. The hydraulic head of that aquifer is controlled by snowmelt and streamflow in the hillslopes. This floodplain confined aquifer likely provides inputs to the alluvial aquifer seasonally. Just above the floodplain, in the valley of a small tributary, John Creek, there is another confined aquifer that is recharged only by snowmelt and streamflow in the John Creek subbasin. The potentiometric surface of this John Creek aquifer, based on groundwater elevations for a well at the bottom of this valley, is consistently >10 m above the potentiometric surface of the confined aquifer in the upper floodplain.

Groundwater and Teanaway River elevations over a three-year period characterize an annual cycle with three hydrologic periods: 1) a period of episodic groundwater recharge in late October until early March; 2) a snowmelt period during which groundwater elevations begin to decline while river flow is sustained by snowmelt (early March to June); 3) the summer baseflow season, when groundwater levels decline rapidly and reach their minimum as they maintain streamflow in the Teanaway River. Groundwater flow patterns at the TVFF site shift throughout these seasons. During baseflow period, flow is roughly parallel to the river, carrying groundwater down the floodplain towards the mouth of the river. As the unconfined aquifer is recharged, groundwater collects on the northern (upper) side of the aquifer and the direction of flow is shifted towards the Teanaway River. Thus, the river is more strongly gaining during and immediately after groundwater recharge.

The cobble-rich nature of the alluvial aquifer and the rapid decline of groundwater elevations at the beginning of the baseflow period indicate that this aquifer is highly transmissible and easily drained by the Teanaway River. Because of the incision that has occurred, the river functionally serves as a drain during the summer months. The seasonal draining of the alluvial aquifer is further compounded by pumping from a series of ponds that are upstream of TVFF. The ponds appear to be an abandoned channel that serves as a preferential flow path through the alluvial aquifer. Two wells downgradient of the ponds go dry in the late summer indicating that the alluvial aquifer is no longer saturated in that area. Cottonwood mortality in the riparian forest on TVFF is likely due at least in part to lack of groundwater during the late summer.

The refined understanding of aquifer stratigraphy in the Teanaway River floodplain allows for updates to estimates of aquifer storage capacity. The sometimes thick sequences of clay reduce the overall storage capacity of the floodplain volume and complicate the patterns of groundwater recharge and flow. Even if additional volume within the unconfined aquifer is available to store water in the summer months, the groundwater would be rapidly drained by the incised streams. Increased sediment aggradation over time in the channels or floods that reorganize the channel wood could conceivably increase the connectivity between the rivers and the floodplain and allow for increased storage.

II. Indian Creek: Effects of Instream Large Wood on Floodplain Aquifer Recharge and Storage

INTRODUCTION

Enhancing groundwater storage is a practical strategy to increase late-summer water supplies within the Yakima River watershed. Through the collaboration of multiple stakeholders, numerous stream restoration projects have placed large wood (LW) into multiple tributaries of the Yakima River over the last decade to enhance and diversify aquatic habitats. The benefits of wood restoration in streams for aquatic and riparian habitats are well documented (Jones et al., 2014; Roni et al., 2015), as are the effects on geomorphic features and hyporheic exchange (Gurnell and Sweet, 1998; Sawyer and Cardenas, 2012; Wohl, 2013; Scott et al., 2019). However, the potential

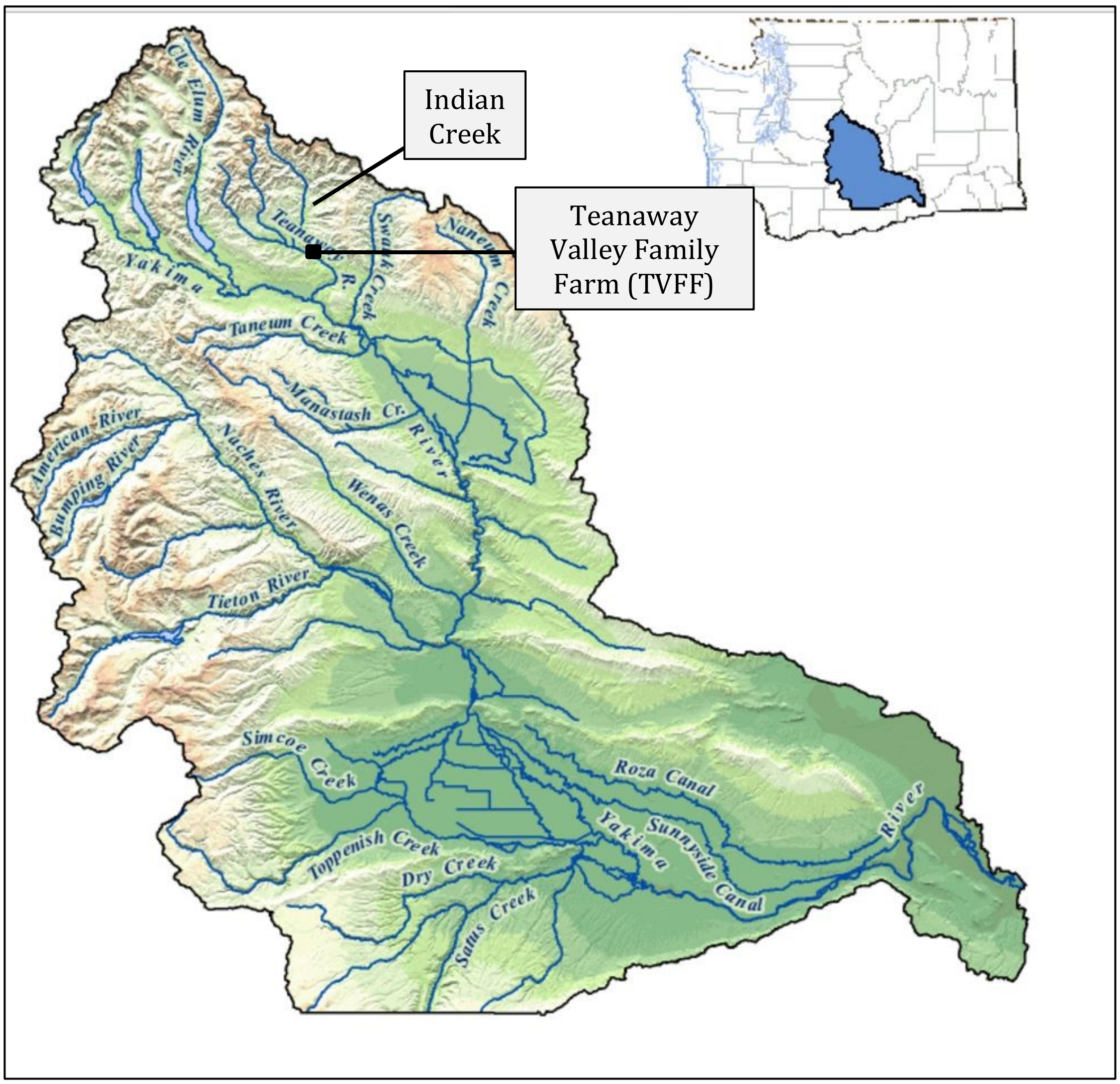

Figure 1. Yakima Basin watershed with study sites labeled. Study areas highlighted in red box. Modified from Washington Department of Ecology.

additional benefit of wood restoration on groundwater recharge and storage is not yet well understood or quantified (Nash et al., 2018; Boylan, 2019a, b). One reason for this gap in our knowledge is the lack of useful monitoring data available for restoration areas (Tague et al., 2008). The numerous LW restoration projects underway in the Yakima Basin present an opportunity to assess the effect of LW restoration on storage and recharge of the shallow floodplain aquifers.

This portion of the study investigated whether the restoration of instream LW from 2017-2018 had consistent, detectable effects on the recharge and storage of groundwater in the alluvial floodplain aquifer at Indian Creek, a tributary to the Teanaway Basin in the headwaters of the Yakima River basin (Figures 1, 2 and 3). The assessment involved the description of aquifer stratigraphy, the manual recording of groundwater levels and the analysis of groundwater levels in piezometers from 2014-2021. It also included a one-dimensional streamflow model to investigate the likelihood of increased floodplain inundation in reaches with LW additions. The study builds on the previous hydrological modeling of the Indian Creek floodplain aquifer by Boylan (2019 a, b). This section of the report is based on the data and analysis from the CWU Master's Thesis by Bartlett (2022).

One goal of restoring instream LW is to increase sedimentation in channels and divert more water onto the adjacent floodplains. The intended hydrologic effect of wood emplacement is to thus increase groundwater recharge and storage in alluvial aquifers during spring high flows, resulting in a natural release of water into streams during the drier summer months. At this time, how soon after emplacement instream LW may affect floodplain groundwater recharge and storage is not well quantified (Emmons, 2013; Nash et al., 2020). Indian Creek was used as an example study site because of the existence of monitoring wells that span the period before and after LW restoration.

Often, LW wood restoration projects are implemented with little consideration of the sedimentary composition of the adjacent aquifer, which affects how, where and when the groundwater interacts with the streamflow (Huggenberger and Aigner, 1999). Understanding the hydrologic dynamics between the floodplain and stream in the region or setting can help project managers determine the sites where LW might best increase the interaction between the surface water in the channel and the floodplain, and thus be most effective for groundwater recharge and storage. A recent study of wood restoration and aquifer recharge at Indian Creek (Boylan, 2019 a, b) modeled groundwater flow in an aquifer of uniform composition and an assumed thickness. The current study builds on those results by investigating the interactions of the surface water and groundwater and how the stratigraphy of the aquifer affects the dynamics of the hydrology.

Indian Creek Study Site

Indian Creek is a tributary to the North Fork Teanaway River (NFTR) in the headwaters of the Yakima River basin (Figures 1 and 3). The bedrock of Indian Creek is composed of the Roslyn Formation sandstone (47 million years ago; Tabor et al., 1984). The stream valleys are filled by Pleistocene glacial deposits and outwash that are tens of thousands of years old (Figure 4; Eddy et al., 2017). The glacial and outwash deposits are characterized by poorly defined layers of boulders, pebbles, sand, silt, and lacustrine clay. Although the glacial lacustrine sediment is only shown in the lower reaches of the Teanaway River valley on the geologic map (Figure 4), the lacustrine clay occurs in the floodplain stratigraphy farther up the Teanaway valley and its tributaries, including Indian Creek.

Most of the precipitation at Indian Creek falls between October and March (Prism Climate Group). Stream discharge rises rapidly in the early spring, usually peaking between early April and early May (Washington Department of Ecology stream gauge ID: 39T060). During the peak discharge, in areas where the creek banks are less than 40-cm high, water overtops the banks and flows out onto the floodplain (Figure 5). Discharge then rapidly subsides in early May. The stream bed is mostly dry by the middle of summer, excluding some stagnant ponds and reaches of trickling flow.

The Yakama Nation, a stakeholder in the YBIP, has conducted numerous LW restoration projects in the Teanaway basin and other tributaries of the Yakima River. The primary purpose of these LW restorations is to restore aquatic habitat, specifically for improved production of Yakama Nation treaty reserved fish species (DeKnikker, 2016). The LW wood is emplaced to reduce stream velocity, encourage deposition of sediment, and increase stream complexity.

The LW restoration project at Indian Creek involved the placement of LW throughout the stream channel and the adjacent floodplain over an approximate 3-km reach. Emplacement of the wood began in the summer of 2014, mostly on the floodplain. The largest installation of wood into the channel was from 2017-2018, with additions continuing through 2021. The instream LW was placed in many large dense groupings from near the mouth of Indian Creek to approximately 1.5 km upstream (Figure 2). Individual logs or small LW groups were placed in other areas of the stream or between areas of dense LW log jams.

The floodplain of Indian Creek is equipped with eight groundwater monitoring wells. Four wells were installed by the Washington Department of Natural Resources in 2013. Three more wells were installed in 2018 by Boylan (2019a), one of which (MP-7) is no longer present at the site. The six wells remaining from those two installations are in two triangular configurations (Figure 3) located 0.5 and 1.5 km upstream from the mouth of Indian Creek. Two new wells were installed in 2021 in the Teanaway River valley at the mouth of Indian Creek (Figure 3).

Boylan (2019a, b) investigated the changes in groundwater level, flow direction, and gradients at the two well sites. No notable increase to the overall groundwater table was discovered at any of the wells in the study. Groundwater flow direction at the upstream well cluster was found to be away from or parallel with the stream at different times. Direction of flow in the downstream well cluster was towards the stream. The groundwater gradient at the downstream wells was shown to increase toward the stream in the years following wood placement. At the upstream wells, the gradient between the stream and MP-3 possibly decreased between 2014 and 2018, although it continued to slope away from the stream. The gradient between the stream and MP-4, at the far edge of the floodplain near the hillslope, increased. The overall direction of groundwater flow was therefore away from the stream at the location of the upstream wells.

Figure 2. Aerial photo of instream large wood restoration on Indian Creek near North Fork Teanaway Road just upstream of the Department of Ecology gauge (Figure 3). (Image credit: Isaac Mitchell).

Figure 3 A and B. Study area of Indian Creek. The horizontal image at the top of the figure shows the entire study reach. The yellow boxes outline the locations of the close-up images of sections with stream gages, wells or stratigraphy sites. A.) Downstream reach near the North Fork Teanaway River and two wells installed in 2021. B.) Downstream well cluster.

Figure 3 C and D. Study area of Indian Creek. The horizontal image at the top of the figure shows the entire study reach. The yellow boxes outline the locations of the close-up images of sections with stream gauges, wells or stratigraphy sites. C.) Middle reach. D.) Upstream reach and well cluster. Blue markers represent the groundwater monitoring wells. Green markers represent the floodplain stratigraphy sites. Yellow markers represent the stream bank stratigraphy sites. Red markers represent stream gauges.

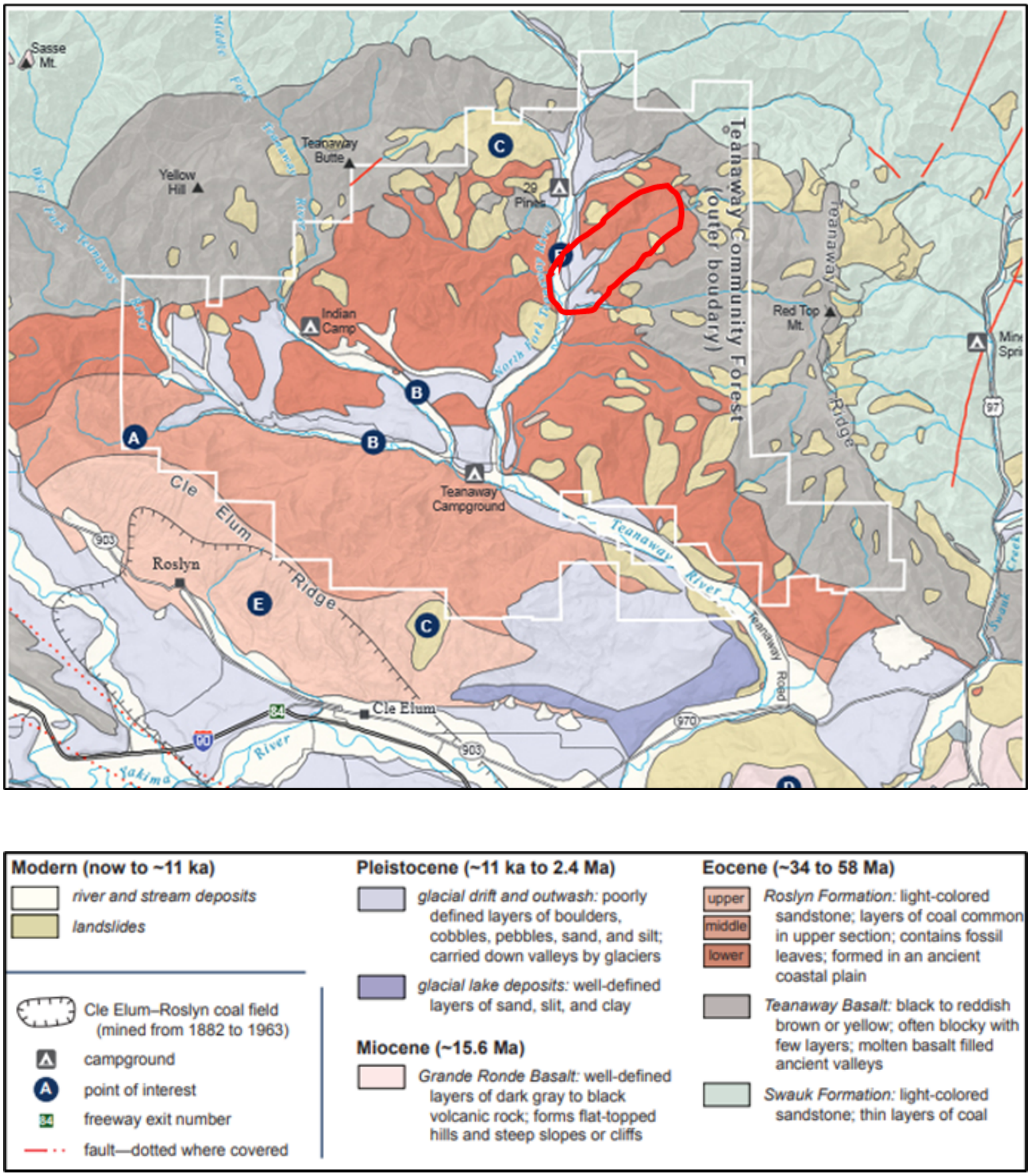

Figure 4. Geology of the Teanaway Community Forest by the Washington State Geological Survey. Map modified from Tabor et al. (1984).

Figure 5. Floodplain inundation of surface water during peak discharge on 04/17/2020. The floodplain is just downstream of the gauge in Image C. Photo by Stephen Bartlett.

Figure 6. Dry Indian Creek stream channel during summer. View looking upstream in Image A at an instream large wood jam in the Indian Creek channel on 8/22/2020. Most of the stream channel is dry. Photo by Stephen Bartlett.

METHODS

Groundwater and Stream Flow

Groundwater levels were documented using manual measurements and pressure transducers installed in each groundwater monitoring well (Table 1). Wells MP-1, 2, 3, and 4 are equipped with vanEssen Micro-Diver pressure transducers installed in 2014 by Kittitas Community Trust and Washington State Department of Ecology (DOE) (Boylan, 2019a). The pressure transducers record measurements at 15-minute intervals. A barometric data logger of the same brand was placed hanging in a nearby tree at each of the two well clusters to compensate for atmospheric pressure.

Wells MP-5, 6, and 7 were installed October 26, 2018, by Boylan (2019a). Both wells are now equipped with HOBO U20 Water Level Loggers. These data loggers collect a measurement every 15 minutes. MP-7 is no longer in existence on the floodplain of Indian Creek and was not present when this project began in the spring of 2020.

Table 1. Piezometer specifications of wells MP-1 through 6. Coordinates and pressure transducer depths for MP-1, 2, 4, and 5 were taken from Boylan (2019a). Measurements are the distance in meters below the top of the pipe (m bTOP).

Piezometer ID	Type	Latitude	Longitude	Piezometer Depth (m bTOP)	Transducer Depth (m bTOP)	Length of Pipe (m)
MP-1	3/4" OD steel	47.30491 N	120.84885 W	2.05	2.02	0.6035
MP-2	3/4" OD steel	47.30517 N	120.84930 W	2.83	2.72	0.201
MP-3	3/4" OD steel	47.31395 N	120.83617 W	1.48	1.40	0.552
MP-4	3/4" OD steel	47.31411 N	120.83648 W	2.89	2.82	0.12
MP-5	2" OD PVC	47.30438 N	120.84967 W	1.86	1.70	0.378
MP-6	2" OD PVC	47.31353 N	120.84925 W	2.59	2.46	0.643

Groundwater level data from the pressure transducers for 2014 to 2018 were obtained from Boylan (2019a). Pressure transducer data after 6/18/2019 were downloaded and processed by the Central Washington University Geological Sciences Department. Manual groundwater level data from 10/27/2018 to 4/4/2019 were obtained from Boylan (2019a); additional manual groundwater level data were collected in this study from 6/28/2020-11/7/2021.

Pressure transducer data were compensated with atmospheric pressure to produce a pressure head in centimeters. The pressure transducer immersed in water records the changes in total pressure, water pressure plus atmospheric pressure. Atmospheric pressure is measured by a transducer placed above ground in the area. Atmospheric pressure is then subtracted from the total pressure recorded by the immersed devices to get the change in relative water pressure. The relative water pressure is then converted into water depth.

Manual groundwater levels beginning 6/28/2020 were taken using an electronic water level tape that measures depth to groundwater.

Water levels for the pressure transducer data and manual measurements were converted to elevation above mean sea level (m a.m.s.l) in meters. Manual measurements were converted using the following equation:

$$E_w = E_s - (d_f)*(0.3048) + p$$

where E_w is the water elevation above sea level in meters; E_s is the surface elevation of the well obtained from the topographic survey; d_f is the depth to water from top of pipe, in feet; and p is the length of the pipe above ground in meters.

Upon downloading data from pressure transducers, several problems with the data became apparent. Data from MP-1 acquired from Boylan (2019a) and recent data had a continuous downward drift that dropped readings to levels below the pressure transducer. The data were plotted on an elevation vs. time graph. The slope was numerically adjusted in Microsoft Excel to create a horizontal trend. When the prior data from Boylan (2019a) and the recent data were graphed together a 0.22597 m difference existed between the datasets. To adjust this difference, 0.22597 m was subtracted from the data between 6/12/2014 and 5/21/2018.

Several equipment problems were encountered during the data collection and processing. Recent data from MP-2 showed a malfunction with the pressure transducer. The device did not record changes in pressure beyond 6/18/2019, rendering all readings after that period unusable. The cable holding the pressure transducer in well MP-3 corroded and broke on 7/2/2020; the transducer fell to the bottom of the well and is irretrievable. It was replaced near the end of this study, but no new pressure transducer data was retrieved after 7/2/2020. Much of the recent data therefore consist of manual measurements.

Topographic Elevation Survey

A Topcon Real Time Kinematic (RTK) Global Positioning System was used to obtain elevation and position data. The RTK system consists of a stationary base station and a rover device. Each device communicates with multiple satellites and with each other. The rover is set up at each desired location, given time to locate its position using the satellites, and the position is recorded using a handheld tablet.

For the first trip, the base station was placed in an open field just west of MP-5 (Figure 3). Each monitoring well, stratigraphic column site, and Washington Department of Ecology (DOE) stream gauge were surveyed for position and elevation. The Washington Department of Natural Resources (DNR) section corner monument T21N R16E located downstream/west of MP-5 was also surveyed. Due to incomplete and inconsistent data at the upstream monitoring wells, surveying was performed a second time. The second base station position was farther upstream at a higher elevation near the road that runs the length of the area.

The two topographic surveys with the RTK yielded different elevations for some points. We therefore used a transit level to obtain more precise relative elevations of the groundwater monitoring wells within each cluster. The transit level consists of a stationary tripod that holds a monocular sight. Crosshairs are used to pinpoint the level on a measuring staff. The tripod was set up in a central location in each of the two triangular well clusters.

To adjust the elevations of the wells with the transit level data, an elevation reference point from the RTK data was chosen at each well cluster. The elevation of MP-6 was used as reference for the upstream well cluster. The elevation for MP-5 was used as reference for the downstream well cluster and the DNR section corner. These two points were chosen as reference elevations because they had the smallest standard deviation, 0.007 m or less.

Using the reference elevations, the elevation of the tripod location was determined by subtracting the staff reading from the height of the tripod and adding the difference to the reference elevation. The following equation was then used to calculate the adjusted elevations.

$$(h-P)/100 + R = PE$$

Where PE is the elevation of the point of interest, h = the height of the base, R is the reference point elevation and P is the reading taken by the transit level, and 100 is to convert centimeters to meters. The analyses and interpretations in this study are based on the adjusted well elevations.

Stratigraphy

The stratigraphy of the floodplain aquifer was described at three banks along Indian Creek and one bank of the NFTR near the mouth of Indian Creek (Figure 3). Six locations throughout the floodplain were also described using a 7.5-cm diameter auger (Figure 3). These locations were determined based on proximity to the groundwater well clusters and height of the stream bank. Sites 3-1, 3-2, and 4-1 were chosen as intermediate sites between the well clusters.

Characteristics described in the field were sediment color using a Munsell color chart, grain size, mottling, presence of roots, and oxidized rhizomes. Contacts between stratigraphic units were determined by changes in sediment size and/or consolidation. These changes included deposition of gravels with an increase in sand or the decrease in coarse-grained sediment with abrupt increases in fine-grained sediment. These units were grouped into larger zones of similar sediment characteristics for stratigraphic interpretation. Sediment samples were collected from each zone for grain-size analysis.

Sediment Analysis

Sediment samples from stream bank site 1-1 (Figure 3) were used for grain-size analysis. The strata identified there were common throughout the stream bank sections and provided a general representation. At least one sample was collected from each identified stratigraphic zone. Multiple samples were taken from zones that contained enough variation throughout their thickness to warrant the extra analysis of the units within. All samples were analyzed using sieves and the Mastersizer 3000 LV for comparison.

All samples were dried in an oven at 100˚ C for 24 hours. The entire mass of each sample was then crushed gently using a pestle and mortar to eliminate or reduce consolidated clumps of fine-grained sediment. The full samples were weighed prior to being placed in the sieves. The mass retained in each sieve was weighed and recorded. Sieve sizes used were 4, 2, 1, 0.5, 0.25, 0.125, 0.063, 0.045 and 0.032mm. Sediment that sieved through 0.032 mm was weighed and labeled as <0.032 mm.

The fine-grained component of all samples was analyzed in the Mastersizer 3000 LV. Samples were first weighed, then sieved through a 0.5 mm screen. After the sieving, the mass retained and passed was recorded. The mass of the sample to be used in the Mastersizer was determined by the Standard Operating Procedure for fine sediment. These amounts ranged from 0.10 to 0.13 g. The samples were placed in vials in a 30 ml of solution of water and sodium hexametaphosphate and mixed at a ratio of 5.5g/L to disperse flocculated clay and silt particles. The vials were shaken for 2 minutes and left to sit for 24 hours prior to analysis. The Mastersizer 3000 LV performs three analyses per run. Each sample was run three times, yielding nine total analyses per sample. The nine outputs were averaged. The outputs used were the d10, d50, and d90.

Streamflow Model

The Army Corps of Engineers Hydrologic Engineering Center River Analysis Systems 5.0.7 (HEC-RAS) was used to model the possible effects of the addition of large wood jams in the stream channel. HEC-RAS was used to model multiple discharges through a short example reach of the channel of Indian Creek where wood has been placed. This was to gain insight into what effect the addition of the wood has on the stage and velocity of the stream.

Discharges used in the HEC-RAS model were 6.0, 13.4, 15.9, and 36.4 ft^3/s. These discharges are average high discharge for the months of March, April, May, and the highest recorded discharge since 2014, respectively. Each discharge was run without obstructions and then run with in-channel obstructions. The scenarios were run using the “steady flow analysis” tool. Manning’s ‘n’ hydraulic roughness values were set to 0.03 for the model without obstructions and 0.06 for the model with obstructions. Manning’s ‘n’ hydraulic roughness values were determined using the ‘USGS Guide for Selecting Manning’s Roughness Coefficients for Natural Channels and Floodplains (Freeman et al., 1998).

Lidar imagery from 2015 (Washington State Department of Natural Resources (DNR) Lidar Portal) provided the channel geometry and topography for the HEC-RAS modeling. Because wood was not in the stream at the time the Lidar was collected, it allowed the model comparison to be done by adding virtual obstructions in the numerical model of the stream channel. Using the HEC-RAS mapper tool, an approximately 1,040-foot channel profile was drawn down the middle of the current stream channel. This section is the area where most of the large wood was placed into the stream channel (Figure 2). Cross sections were generated automatically 100 feet apart, beginning 115 feet upstream of the bottom of the modeled reach, and 100 feet wide.

Using the “add obstructions” tool in HEC-RAS geometry editor, obstructions were placed throughout the channel of each cross section based on where the wood was observed on the 2019 drone imagery (Figure 2). The density of obstructions placed within each cross-section was chosen based on the results from Spreitzer et al., (2020), which showed a common average porosity of large wood jams to be approximately 66%. To simulate the density of wood piles, the obstructions were built as vertical blocks of varying height and thickness until the channel reached an approximate fill of 33%.

RESULTS AND DISCUSSION

Floodplain Stratigraphy and Sediment Characteristics

The stratigraphic sites described along the stream banks and within the floodplain of Indian Creek from the mouth to 1.4 km upstream are remarkably similar (Figures 7 and 8). Each site is characterized by well-defined zones of silt, mixed silt/clay, sand and gravel, and gray clay. The thickness of the zones varies throughout the sites, and each zone contains slight variations in sediment composition and compaction from site to site. The lower gray clay zone was not encountered at all floodplain sites, either because the auger cores were not deep enough or there had been disturbance of the original stratigraphy.

Below are general descriptions of the stratigraphic zones exposed in the streambank and floodplain sections (Figures 7 and 8). Detailed descriptions of the floodplain stratigraphy are in Bartlett (2022).

Zone 1: Surface Silty Soil

The uppermost zone is the surface soil, which is 15-25 cm thick, and is composed of silt with some gravel clasts. The soil is highly vegetated with roots throughout the entire thickness. The presence of gravels in the soil zone increases both in size and density upstream from the NFTR confluence to profile 3-1 (Figures 3 and 8).

Zone 2: Silt

The silt zone begins beneath the surface soil, except at the NFTR bank where there is a 16 cm layer of sand and gravel beginning at 20 cm depth. This zone is up to 60 cm thick and thins upstream. The silt zone is generally medium to light brown, becoming gray and red toward the base as the amount of clay increases. Some fine sand and gravel up to 7 cm diameter are mixed into the silt matrix.

Zone 3: Silt/Clay

The third zone down is the thickest layer within the floodplain aquifer above the stream bed, ranging from 60-83 cm. It is generally a matrix of silt containing nodules of clay. The concentration of clay in this zone increases with depth at all stream bank sites, at some sites exceeding 70%. The lower portion of the zone is predominantly a gray color at all sites. Oxidation is abundant throughout the zone, characterized by vertical streaks of brownish red clay in a gray clay matrix. The upper and lower contacts contain sand and gravel.

Zone 4: Sand, Silt, and Gravel

The fourth zone is composed of sand, silt, and gravel. The zone ranges from 15-50 cm thick. Gravel sizes at the NFTR and site 1-1 are not larger than 1.5 cm. Sites 2-1 and 3-1 each contain cobbles up to 10 cm.

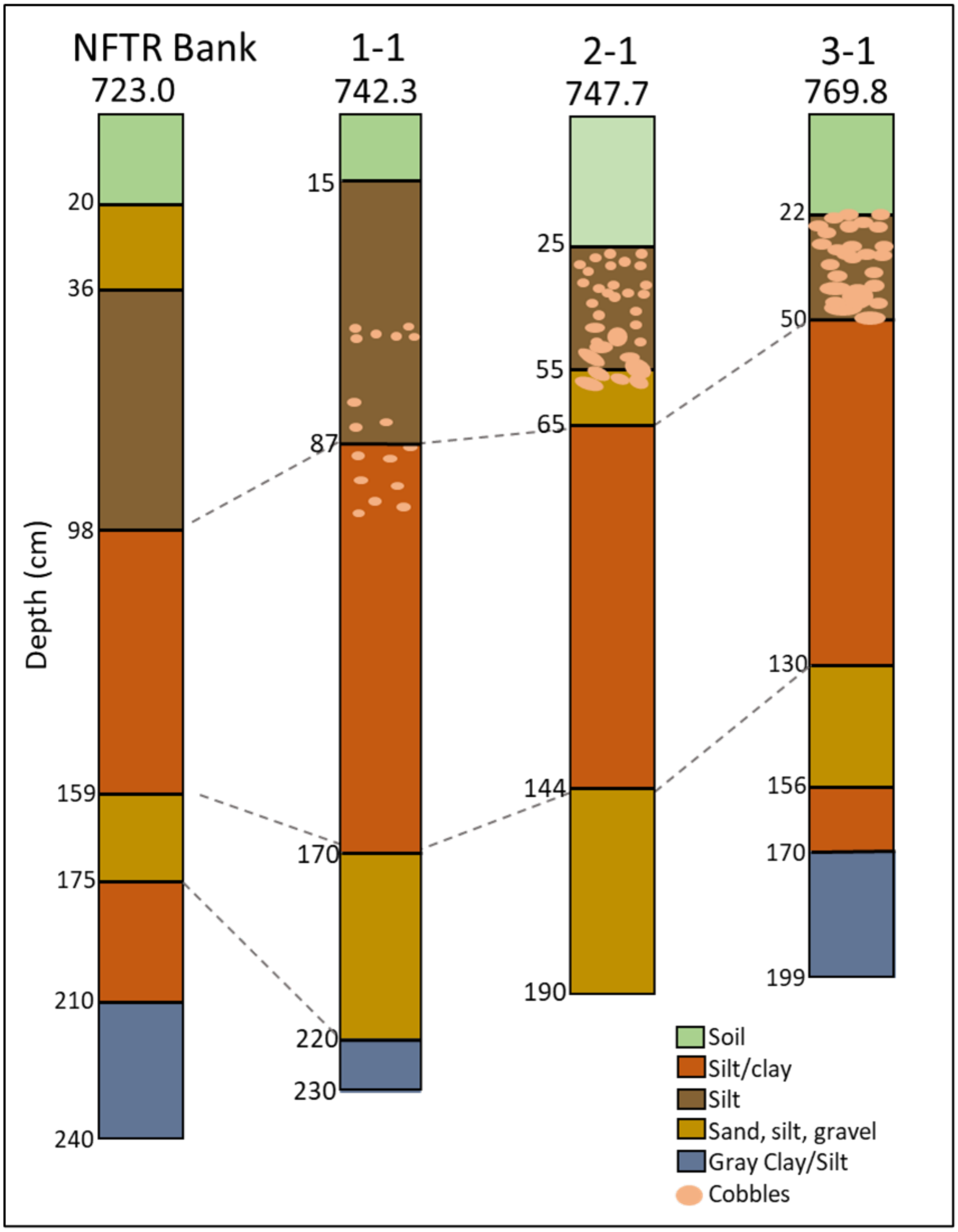

Figure 7. Streambank stratigraphy from the mouth of Indian Creek at the North Fork Teanaway River to 1.4 km upstream of Indian Creek. Locations are in Figure 3**.**

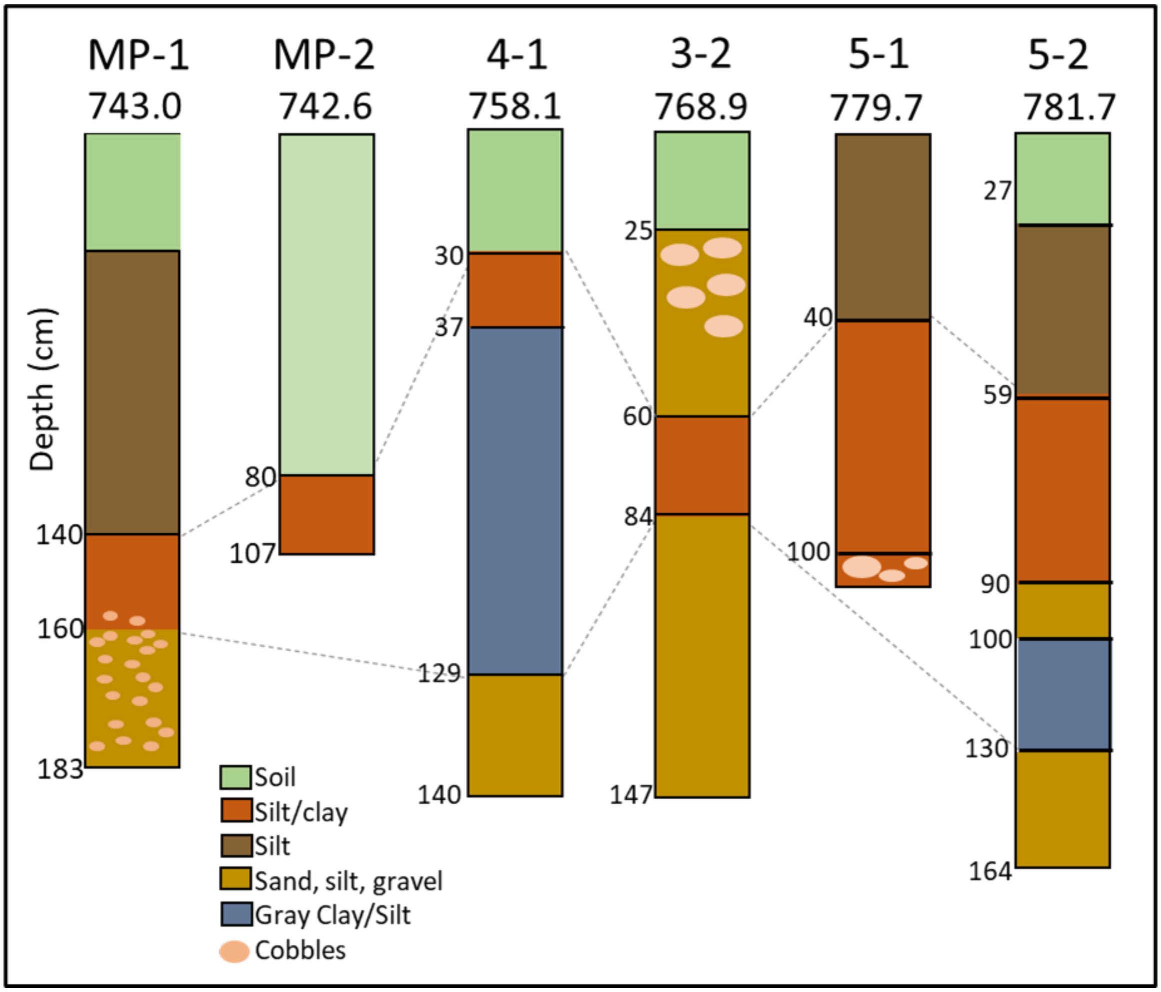

Figure 8. Floodplain stratigraphy at and between well clusters on Indian Creek. Locations are in Figure 2.

Zone 5: Gray Clay

The fifth zone is a bluish gray silty clay, 10-90 cm thick. Where described, it is sticky, plastic saturated clay. Some sites contain small pebbles at the top of the zone or fine sand within it. This zone is at or slightly below the elevation of the channel bottom of Indian Creek and the Teanaway River, and it forms the channel bed in some locations along Indian Creek and the Teanaway River at the confluence. (No excavation into the stream bed occurred at 2-1, so the zone was not observed there.)

Zone 6: Sand, Gravel and Cobbles

Below the gray clay is a layer of sand, gravel, and cobbles observed at the NFTR, 1-1, and 3-1 sites.

The stratigraphy at Indian Creek affects the recharge, storage, and movement of groundwater throughout the reach. The sediment layers within the described areas of the reach have differences in permeability that can retard the flow of water through the banks and down from the surface. If the aquifer were to be recharged from bank infiltration, it would most likely occur through the sand and gravel layers above and below the gray clay layer. The gray clay may be acting as a semi-confining layer throughout much of the floodplain, causing water to be perched in the sand and gravel above it, or at least not move downward as readily as it could through the more permeable layers of coarser sediment.

The differences in sediment composition can account for considerable differences in aquifer properties such as porosity, permeability, and hydraulic conductivity depending on other factors such as compaction and saturation (Richard et al., 2001). The sediment analyzed for grain size was collected from the stream bank at site 1-1 (Figure 9) and is not necessarily representative of the ratios of silt and clay in similar zones throughout the floodplain. For example, it was clear in the field that the mixed silt/clay zone at sites 5-1 and MP-3 contained more silt/clay nodules and less sand than the equivalent zone represented by samples 5, 6 and 7 at site 1-1 (Figure 9). Because the permeability and hydraulic conductivity of silt and clay is several orders of magnitude less than sand and gravel, it is likely that the silt/clay and gray clay zones impede the flow of water throughout much of the thickness of the floodplain aquifer. However, as indicated by the sediment-size analysis in Figure 9, mixed sand and sand lenses are present within all layers of the stratigraphy and could provide conduits for groundwater flow.

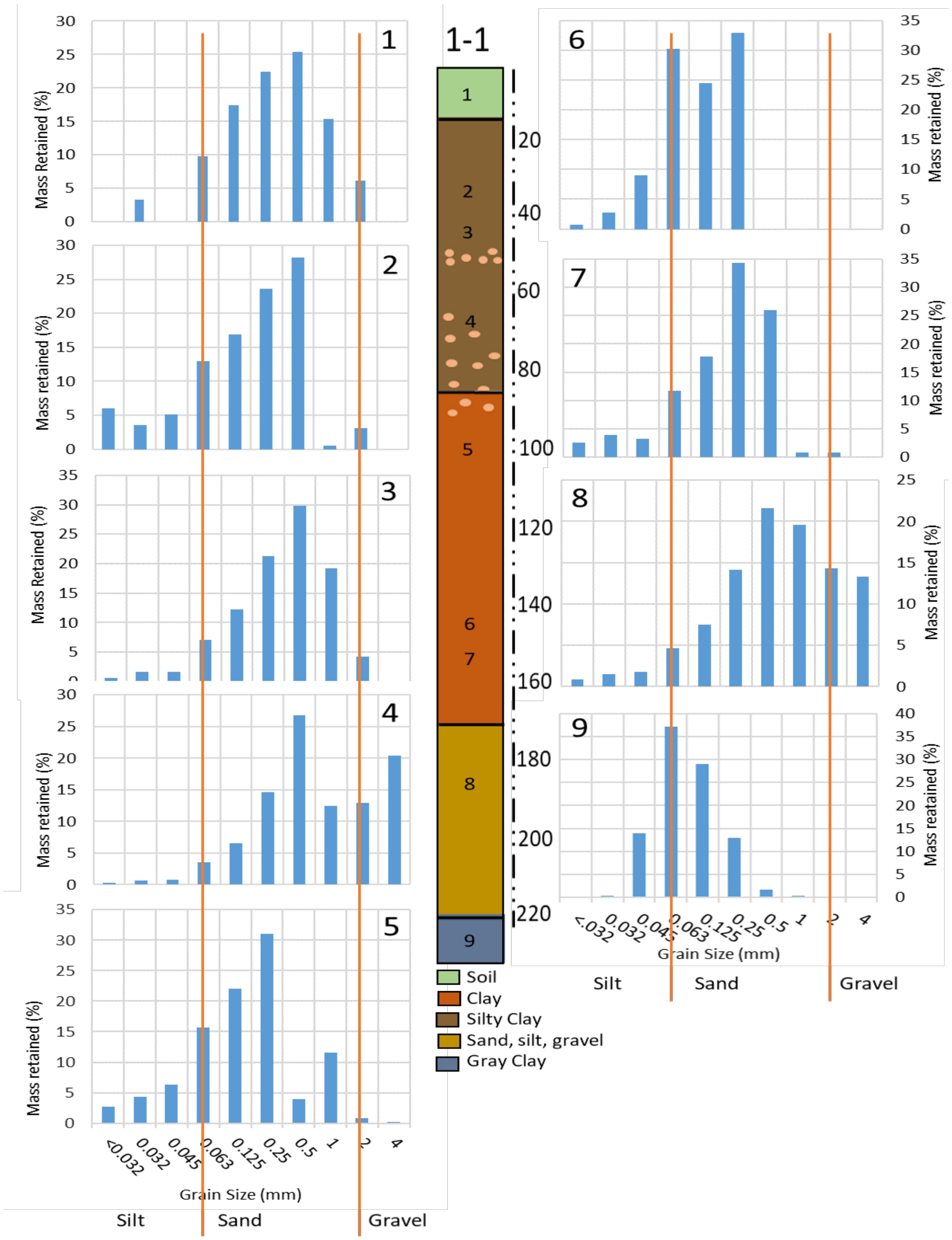

Figure 9. Sediment grain sizes from Stratigraphic Section 1-1 associated with the depth from which they were collected. Numbers in the upper left corner of the graphs correlate to the sample numbers on the stratigraphic column. Graphs show the grain size analysis as mass percent for each sieve range. Sieve sizes are in millimeters. Clay is <0.004 mm and contained within the <0.032 bin. See Bartlett (2022) for complete sediment-size data.

Potential Floodplain Aquifer Storage Capacity

Porosity estimates for section 1-1 (Figure 9) were calculated to create a rough estimate of the storage potential of the floodplain aquifer (Figure 10). Estimated porosity values for the stratigraphic layers represented by sediment samples 1-4, 7 and 8 were calculated using HydrogeosieveXL. Average porosity for these samples is approximately 0.35. The porosity values for samples 5, 6 and 9 (Figure 9), are based on estimates from Schwartz and Zhang (2003), with a mean value of 0.38. Although samples 5, 6 and 9 have higher porosity estimates, they contain the highest percentage of fine sediment, and thus have a low permeability. These fine-grained layers are not necessarily effective groundwater aquifers, as they can hold water but do not readily transmit or release it. The porosity estimates for this stratigraphic column do not necessarily reflect the entire floodplain. The stratigraphy of the floodplain is generally consistent throughout the study area, although the sediment composition of the zones varies to some degree (Figures 7 and 8).

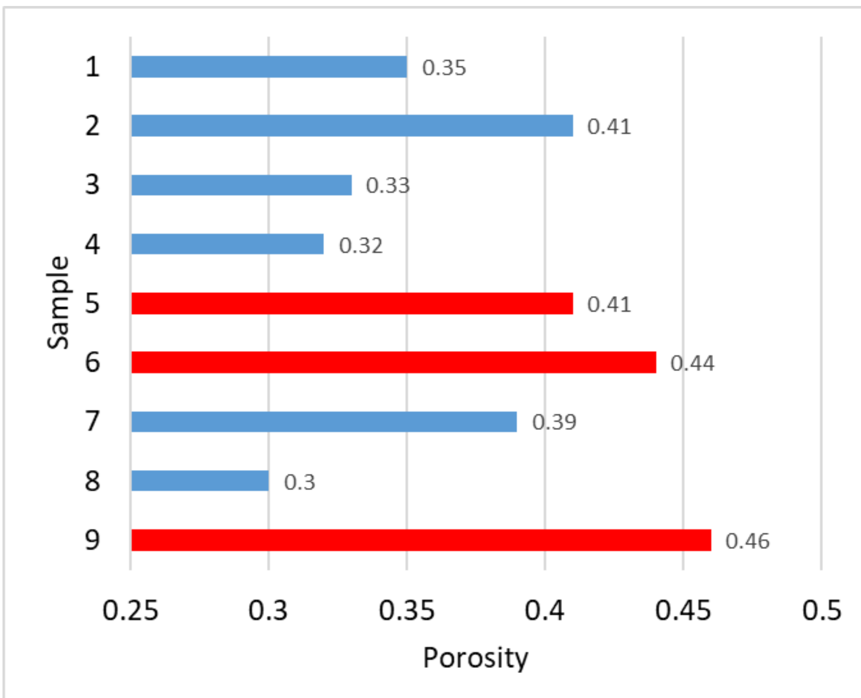

Figure 10. Porosity for site 1-1. Values in blue were calculated using HydrogeosieveXL. Values in red were calculated using values from Schwartz and Zang (2003).

The potential storage capacity of the shallow floodplain aquifer above the stream-channel bed was calculated for different scenarios (Tables 2 and 3). The values for the thickness, depth and porosity of the stratigraphic layers were based on streambank stratigraphic section 1.1 (Figures 15 and 17). Because the purpose of this study is to assess whether installing large wood in the Indian Creek channel increases the elevation or duration of groundwater storage in the floodplain, the elevation of the channel bed was used as the maximum depth for the floodplain aquifer storage calculations. In much of the study area, the gray clay stratigraphic layer is close to the same elevation as the channel bed and is assumed to be at least a partial impediment to vertical groundwater flow. The average depth of the lowest groundwater levels in the summer dry season is 1.5m, so the aquifer is currently draining to a depth of about 0.5-0.7 m above the channel bed every summer. The area used for the storage calculations is from the furthest downstream well, MP-5, to the furthest upstream wells, MP-3 and 4, and the width of the valley floor. The area was estimated by drawing a polygon on Google Earth Pro and was rounded to 126,000 m^2 (Figure 11).

Figure 11. Area polygon used for potential storage capacity. The polygon extends from the furthest upstream well to the furthest downstream well and from the approximate location of the stream channel to the northern hillside.

Table 2. High and low annual average water levels in Indian Creek wells.

Well #	Surface elevation (masl)	Average high water from 2014-2021 (masl)	Average low water from 2014-2021 (masl)	High – low difference (m)	Depth of high GW peak below surface	Depth of low GW below surface
Downstream wells						
1	742.992	742.2	741.6	0.6	0.8	1.4
2	742.627	742.5	741.0	1.5	0.1	1.6
5	740.772	740.2	739.3	0.9	0.6	1.5
Upstream wells						
3	781.682	781.6	780.9	0.6	0.1	0.8
4	782.01	780.7	779.7	1.0	1.3	2.3
*6	779.81	779.2	778.6	0.6	0.6	1.2
				Avg of wells #1-5	**Avg of wells #1-5**	**Avg of wells #1-5**
				0.9	**0.6**	**1.5**
* masl = meters above mean sea level						
** = Well #6 has 1 year of record in a dry year; not considered representative and excluded from mean						

The thickness and composition of the stratigraphic layers that compose the floodplain affect the maximum effective storage capacity of the floodplain aquifer. For this study area and aquifer depth, the fine-grained sediment layers are estimated to reduce the effective maximum storage capacity by about 30-35%, depending on the porosity values used. Currently, at the peak water-table elevations in the spring, approximately 40% of the available 2.2 m floodplain aquifer depth is saturated, again excluding 0.7m of ineffective storage in the fine-grained sediment as well as 0.6m of unsaturated sediment above the peak groundwater elevations. If the addition of LW in the channel were able to raise the peak water table to the elevation of the ground surface across the entire flooplain, it could increase the effective storage by up to 65%. However, in reality the physical limit based on the detailed topography would be lower than these maximum estimates here, even under the most optimistic predictions of floodplain inundation.

The groundwater storage capacity estimates here are for a single point in time, at the maximum spring high streamflow and groundwater levels. The duration that the stored groundwater is retained in the floodplain aquifer into the summer dry months is not considered in these calculations. That factor is addressed in a separate section of this report.

Table 3. Potential Storage Capacity of Indian Creek Floodplain. Calculated estimates of the potential storage capacity of the Indian Creek floodplain aquifer for the area shown in Figure 11 (126,000 m2). Estimated aquifer depth of 2.2m is the approximate average depth of the Indian Creek channel bed below the incised floodplain surface.

Stratigraphic Units	**Thickness (m)**	**Area (m^2)**	**Porosity (%)**	**Storage Capacity (m^3)**	**Storage Capacity (ac-ft)**
Total potential storage from ground surface to depth of gray clay and stream channel	2.2	126,000	0.38	105,300	85
Effective storage from ground surface to gray clay and stream channel bed, excluding fine-grained portion of clay/silt layer	1.5 (0.7m ineffective fine-grained sediment)	126,000	0.35	66,200	54
Current maximum groundwater storage amount, based on average annual peak groundwater elevation in spring to depth of gray clay and stream channel bed, excluding fine-grained portion of clay/silt layer	0.9 (average depth of peak GW is 0.6m below surface)	126,000	0.35	36,700	32
Additional maximum groundwater storage if saturated to surface	0.6	126,000	0.35	26,500	21

Groundwater Elevations Through Time

The UTM coordinates and elevations of the wells, stratigraphic sections and gauging stations are in Table 4. The elevations of the wells were adjusted relative to a reference elevation in each well cluster using a transit level. Locations of each point are shown on the map in Figure 3. Points that were only surveyed with the RTK were not adjusted.

Groundwater levels from pressure transducer data were converted to elevation in meters above mean sea level (masl) based on the adjusted RTK elevations of the ground surface at each well (Tables 4 and 5. Manual measurements obtained from Boylan (2019a) and those obtained during this research period are shown in elevation above mean sea level (a.m.s.l).

Table 4. Topographic survey results. All elevations are in meters above mean sea level. Site locations are shown in Figure 5. * = Elevations represent the reference elevations from the RTK data used to create the adjusted surface elevations for the other wells in the clusters.

Point	Northing	Easting	RTK Elevation	Adjusted Elevation
Section Corr	5241096.613	662425.501	736.614	736.714
MP-1	5241289.986	662598.678	742.795	742.992
MP-2	5241311.598	662576.512	746.884	742.627
MP-3	5242327.818	663531.568	780.843	781.682
MP-4	5242341.372	663508.562	782.037	782.01
MP-5	5241238.905	662544.086	740.772*	740.772*
MP-6	5242279.114	663477.186	779.81*	779.81*
1-1	5241259.52	662578.653	744.926	742.168
3-1	5241919.069	663242.895	769.728	
3-2	5241930.324	663222.017	769.961	
4-1	5241736.848	663045.2	758.127	
5-1	5242257.372	663439.567	779.68	
DOE Gauge	5240851.958	662192.8540	729.412	
Upstream Ga	5242302.381	663529.6610	784.635	780.429

Table 5. Manual measurements to the water table in the six monitoring wells. Measurements are depth to water in feet below the top of the well pipe. (Data prior to 2020 from Boylan (2019a).

Date	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6
10/8/2018	Dry	6.39	3.98	7.95	5.91	5
10/26/2018	Dry	4.98	4.41	6.22	5.69	5.2
4/4/2019	4.80	1.75	2.49	5.37	3.29	3.61
6/28/2020	Dry	5.82	3.91	7.85	6.07	5.19
8/26/2020	Dry	6.10	4.41	8.22	6.35	5.61
10/21/2020	Dry	5.71	3.16	7.5	6.07	5.15
4/11/2021	5.90	3.56	2.91	5.64	3.51	3.65
4/28/2021	6.44	5.01	2.92	5.95	4.92	3.78
5/9/2021	6.67	5.19	3.12	6.48	5.14	4.1
5/29/2021	6.74	5.57	3.48	7.19	6.08	4.71
6/10/2021	Dry	5.65	3.67	7.48	6.1	4.92
10/31/2021	Dry	5.54			5.97	
11/7/2021			3.65	9.3		4.7

MP-1 pressure transducer data provide the clearest and longest signal of the water-level changes in the downstream well cluster (Figure 12). MP-1 goes dry every year in the spring and remains dry until late autumn or early winter (Table 5). Based primarily on MP-1, which is the closest well to the restoration area of the stream, pressure transducer data show the groundwater levels increasing from October-January. Groundwater usually increases from the annual low as the autumn precipitation arrives or when snow melt occurs (Table 5). The groundwater then rapidly decreases when the surface snow cover is nearly gone.

Pressure transducer data and manual measurements from MP-2 show that the groundwater level increases and declines at approximately the same times as MP-1 (Figure 12). MP-2 does not appear to go dry at any time throughout the year, and at base level the water remains about 1.5 meters above the bottom of the well. Manual measurements show that the groundwater elevation is often lower than the readings from the pressure transducer except shortly after its installation. Data after the spring of 2017 is unreliable due to a malfunction of the pressure transducer.

MP-5 pressure transducer data is minimal; however the manual measurements coincide well with those from the other wells. The manual measurements taken by Boylan (2019a) around the time of installation show a water-level increase, but there was no reaction from the pressure transducer. In January 2020 the water increased rapidly with an increase in precipitation. Manual measurements then show it near base level in May.

The pressure transducer data for the water levels in the upstream wells show dissimilar patterns from one another. In the 2015-16 water year the water level in MP-3 began to increase from base level in early December 2015 (Figure 13) and returned to base level by mid-March 2016. In that same year, pressure transducer data for MP-4 showed the water level increasing in early January 2016 (Figure 13). The water then gradually declined, returning to a base level sometime in October 2016.

Boylan (2019a) noted that the data for MP-3 appear to show an overall increase in water level from the beginning of recording. However, later manual measurements contradict such an increase of the base groundwater level and show the recent groundwater level to be consistent with the earlier base level readings from the pressure transducer. The MP-3 pressure transducer may have malfunctioned during the 2017 water year, as the data show no change to water level in the spring of 2017. No data are available after spring 2020.

MP-4 data show the water level increasing in March 2017 and declining to base level in October. The 2020 water year shows a clear increase to a peak water elevation of 781.1 meters a.m.s.l. with a rapid return to base level by July. The accurate elevation for this period is the 8/26/2020 manual measurement at 779.65 meters a.m.s.l.

When plotted together for comparison, the manual measurements show synchronous timing in the annual increase and decrease in the groundwater levels in all wells throughout the Indian Creek floodplain study area (Figure 14).

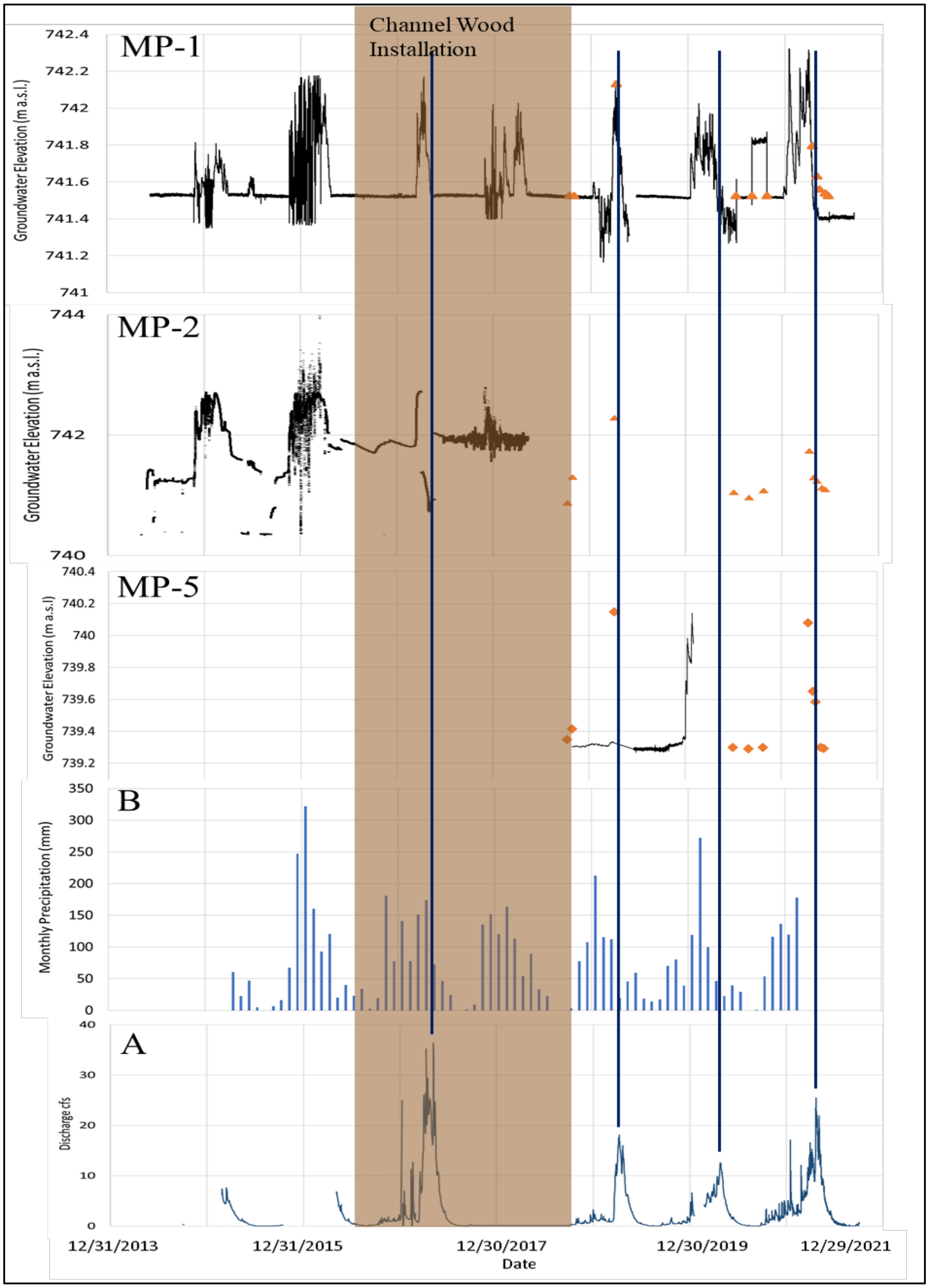

Figure 12. Pressure transducer data of groundwater elevations in the downstream well cluster compared to (A) Indian Creek discharge and (B) monthly regional precipitation. Light gray vertical grid lines mark the beginning of each calendar year. Brown shading represents the timeframe of large wood installation in Indian Creek. Vertical blue lines mark peak annual stream discharge. Orange diamonds represent manual measurements of water levels in wells. Precipitation data are from the Oregon State University Prism Climate Group and stream discharge data are from the DOE stream gauge on Indian Creek.

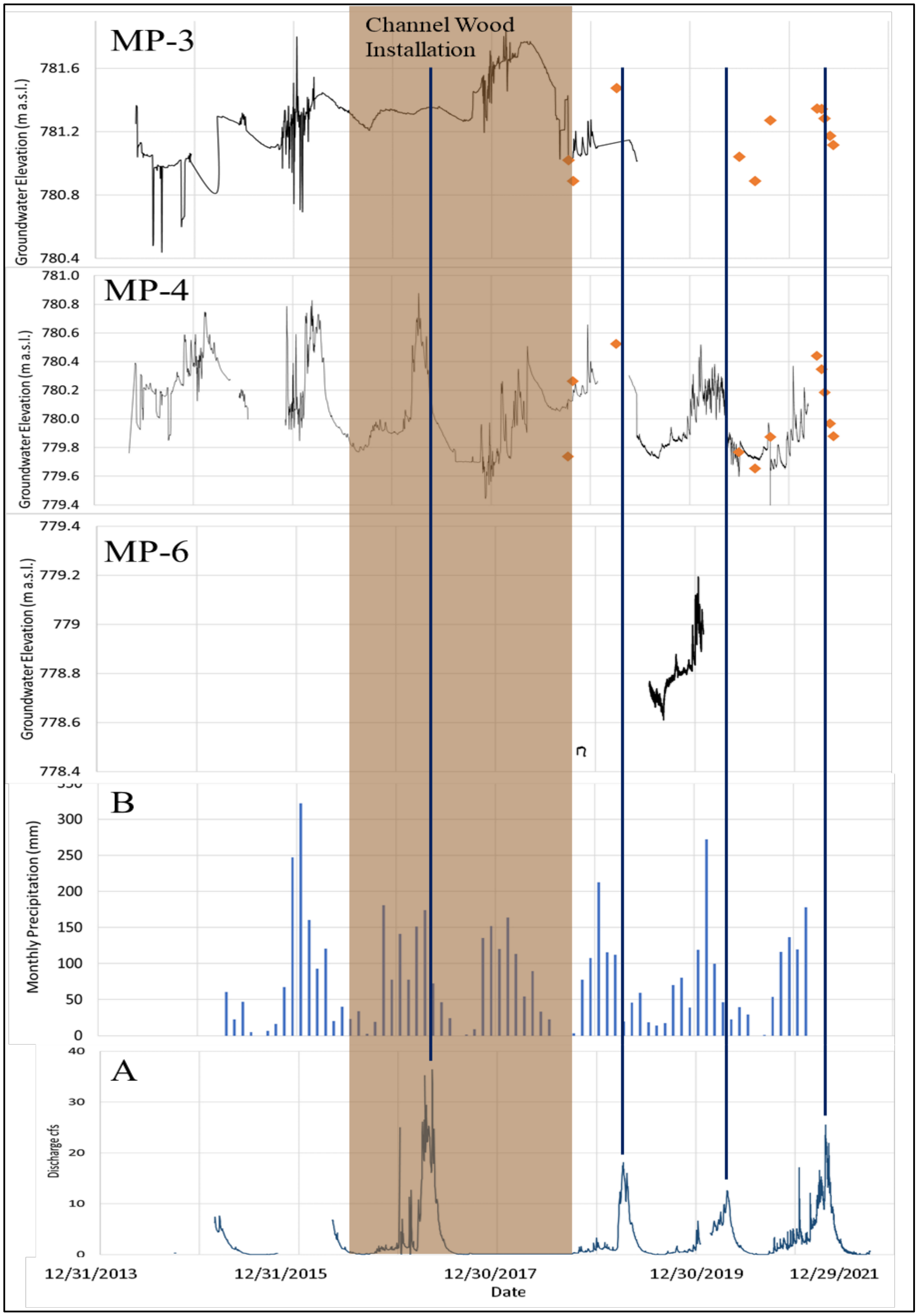

Figure 13. Pressure transducer data of groundwater elevations in the upstream well cluster compared to (A) Indian Creek discharge and (B) monthly regional precipitation. Light gray vertical grid lines mark the beginning of each calendar year. Brown shading represents the timeframe of large wood installation in Indian Creek. Vertical blue lines mark peak annual stream discharge. Orange diamonds represent manual measurements of water levels in wells. Precipitation data are from the Oregon State University Prism Climate Group and stream discharge data are from the DOE stream gauge on Indian Creek.

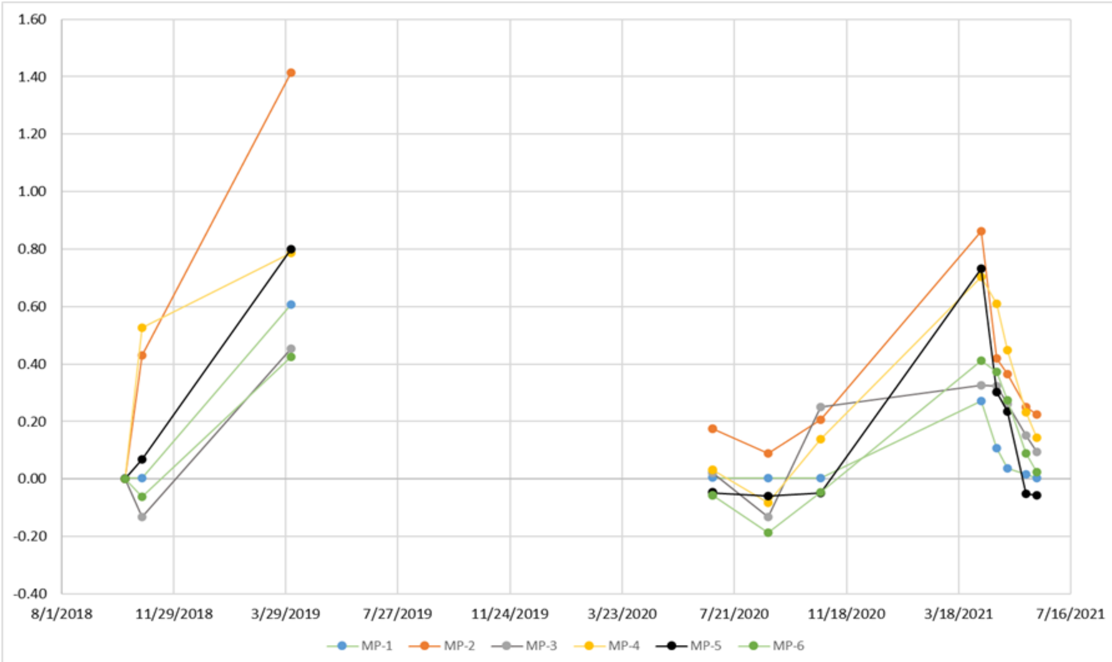

Figure 14. Comparison of manual measurements from the upstream and downstream well clusters. The first measurement, dated 10/08/2018, has been set to 0. Measurements prior to 2020 are from Boylan (2019a). These plots show consistent timing in the relative rise and decline in the groundwater wells across the floodplain study area.

Comparison of Groundwater Levels among the Indian Creek Floodplain Wells

The rapid decline from high to low groundwater levels over a period of days to weeks in the late spring suggests that the water is readily moving through a highly permeable zone (Figures 12 and 13). Most of the wells penetrate into or below the sand and gravel layer above the gray clay. MP-4 and MP-2 very likely extend through the gray clay while MP-3, 5 and 6 end in the sand and gravel. These layers of coarse sediment could serve as conduits for preferential groundwater flow.

Regional precipitation and snowmelt are the dominant contributors to the groundwater recharge and streamflow. The rise in the water-table elevations at all wells follows high monthly precipitation values. The source of the water that recharges the groundwater is likely a combination of inflow from the surrounding hills and higher elevations, direct rainfall, melting of snow on the floodplain surface and overflow from Indian Creek in the reaches where the channel is not too incised. A comparison of groundwater elevations with stream discharge and monthly regional precipitation shows that the groundwater levels commonly increase immediately after increased monthly precipitation (Figures 12 and 13). The data also show that the groundwater levels are commonly in decline prior to the peak in stream discharge in Indian Creek.

The timing of the groundwater variations and stream discharge indicate that the peak stream flow in Indian Creek is not a significant driver of recharge to the floodplain groundwater. Where the data are available, the peak discharge in the stream consistently occurs after the highest groundwater levels in the wells (Figures 12 and 13). The manual measurements show that the groundwater is already in rapid decline during the final rise and peak in the streamflow. In the spring of 2017, MP-1 was nearly dry by the time of the stream peak discharge (Table 4). This pattern of the peak stream discharge lagging the highest groundwater levels is observed both before and after the wood installation in the channel.

Two new monitoring wells, CWU-8 and CWU-9, were installed near the confluence of Indian Creek and the North Fork Teanaway River as part of this project (Figures 3 and 15). Delays in the installation until October 2021 meant that the recording of the groundwater levels in these wells started after the analysis was completed for the wells in the Indian Creek drainage. However, the groundwater levels were compared with overlapping records from two wells in the Indian Creek floodplain during the 2022 Water Year (Figure 15). The seasonal variations and even some shorter-terms fluctuations in the groundwater levels of the new wells are remarkably consistent with those of Wells 2 and 4 located 0.9 and 2.2 km upstream on Indian Creek (Figures 3 and 15).

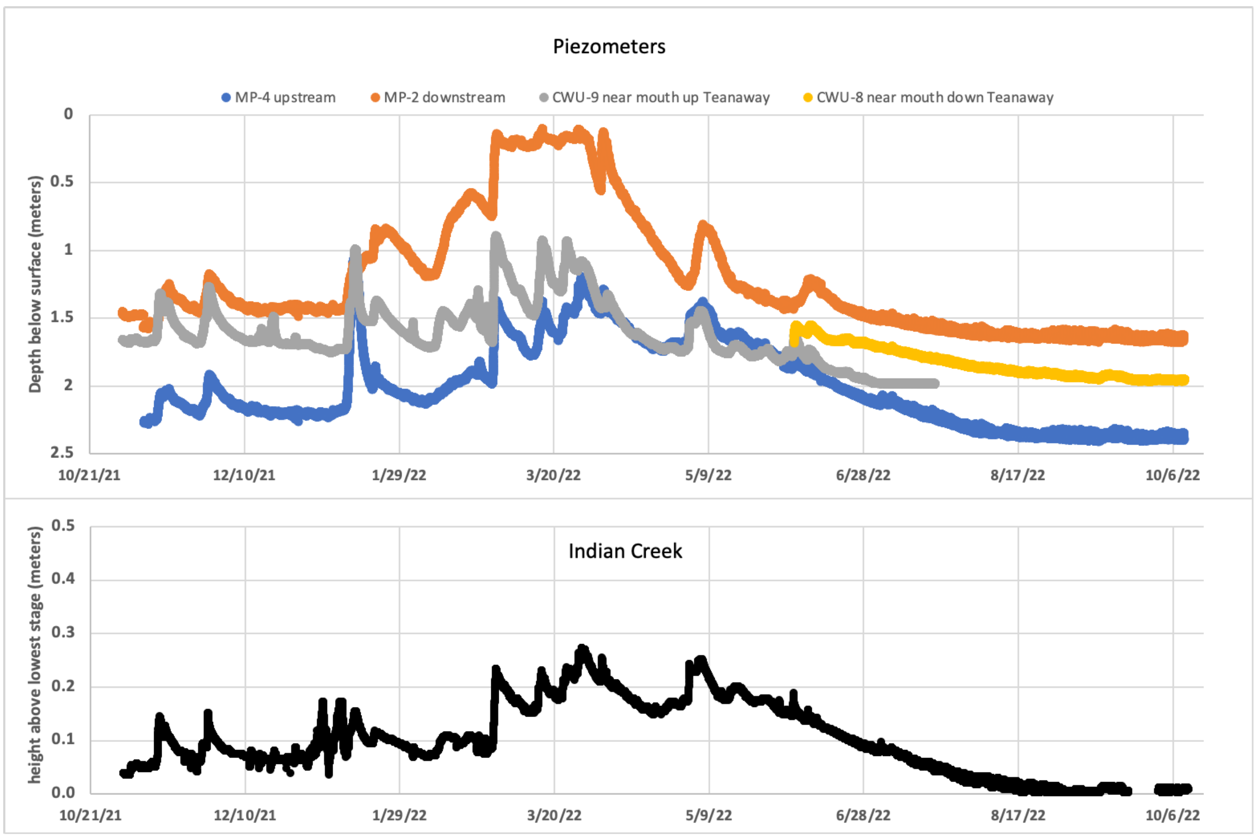

Figure 15. Groundwater depths in two new monitoring wells installed near the confluence of Indian Creek and the Teanaway River (CWU-8 and CWU-9). Locations for these wells are shown in Figure 3A. The seasonal and even some shorter-terms variations in the groundwater levels are similar to those of Wells 2 and 4 located 0.9 and 2.2 km upstream on Indian Creek (Figure 3B and 3D).

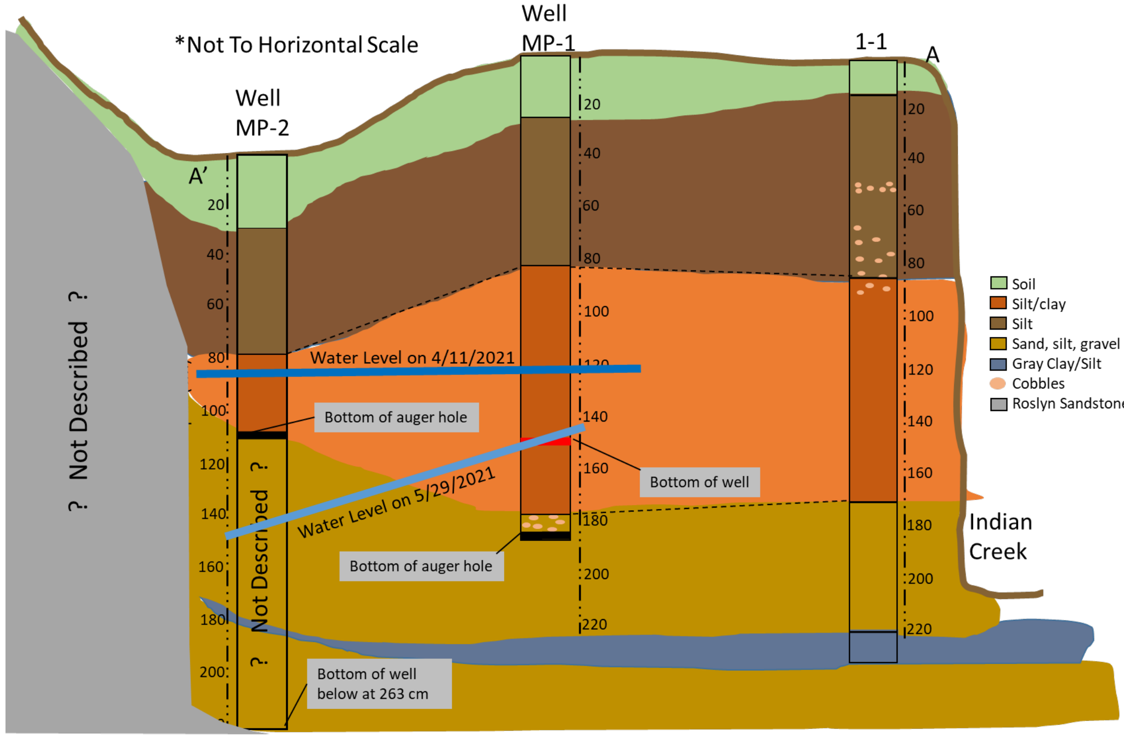

Figure 16. Cross-sectional interpretation of the stratigraphy of the floodplain at the downstream wells from the hillside to the streambank. Water lines show the depth of the water in MP-1 and MP-2 on 4/11/2021 and 5/29/2021. The dates of the groundwater levels shown here are the same as in the groundwater gradient figure (Figure 17).

Comparison of water-level measurements from the wells within each of the two clusters determined the general direction of the groundwater gradient (Table 3). Manual measurements from early April and late May 2021 were used as an example to compare the flow gradients during peak spring recharge and early summer, after groundwater levels have dropped (Figures 16 and 17). The groundwater gradient at the downstream well cluster indicates down-valley flow at both peak and low water levels, with a slight shift in direction away from the stream channel in the summer (Figure 17). In the upstream wells, the gradient slopes more directly away from the stream toward the edge of the valley, with a slight shift more upstream in the summer (Figure 17). These results indicate that groundwater could flow from Indian Creek into the shallow aquifer at the upstream well cluster, which was also found by Boylan (2019 a, b). However, the highest spring groundwater levels precede the peak stream discharges in multiple years at both the upstream and downstream wells, thus the stream flow is not the main control on the timing of the shallow aquifer recharge at either site.

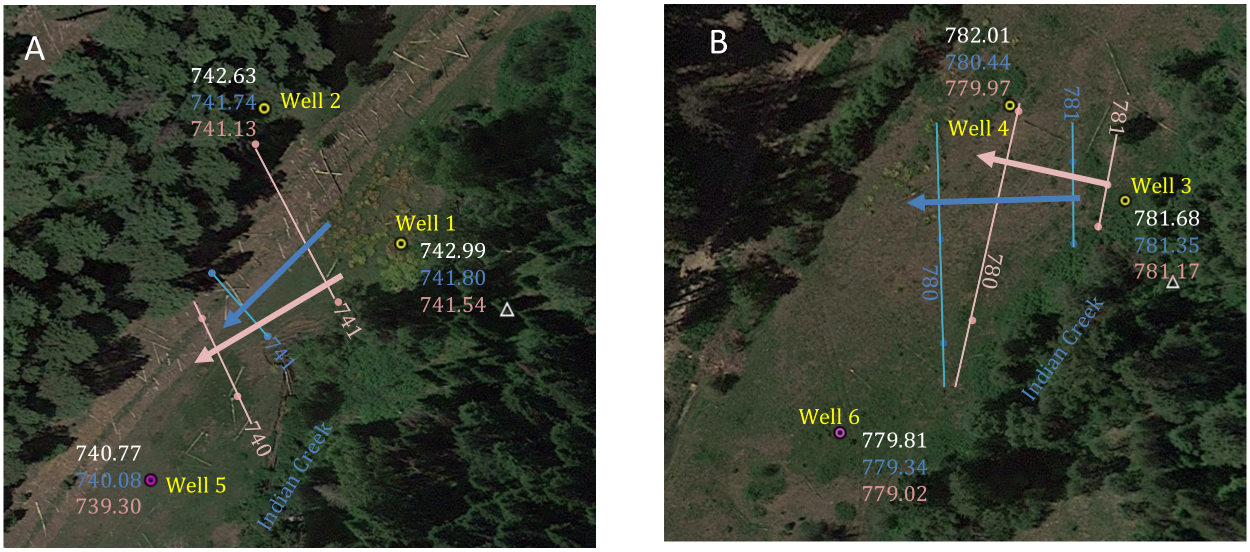

Figure 17. Changes in groundwater levels from early to late spring 2021. Image A shows the downstream wells. Image B shows the upstream wells. White numbers are surface elevations. Blue numbers are groundwater elevations measured close to the peak water levels on 4/11/2021. Orange numbers are groundwater elevations measured on 5/29/2021, after water levels had dropped. Colored arrows correlate to the colored numbers and represent the general groundwater gradient directions. As the water levels drop, the gradient slopes slightly more away from Indian Creek.

Influence of Large Wood on Seasonal Duration and Elevation of Groundwater in the Floodplain

If the wood in the stream channel is currently influencing groundwater recharge and storage in the floodplain, the data after the LW emplacement should show an overall increase in groundwater levels and/or duration before returning to summer low levels. Increases in the height of the peak groundwater levels would be seen in the early spring or late winter during the snow melt. A sustained duration of high groundwater levels would be seen in the late spring or early summer.

Some reaches of the channel are shallow with banks not exceeding 20 cm, especially in the upstream portion of the study area. These areas currently experience annual overbank flow during the high discharge season, with and without instream wood, which causes large amounts of water to flow across the surface of the floodplain after the snow has melted (Figure 5). These areas of shallow banks are not in the reaches where dense LW was installed and thus floodplain inundation is likely due to factors other than the channel wood.

The differences and similarities between the two well clusters allowed a comparison of the spatial and temporal variations in groundwater levels, which contributed to the interpretation of the possible effects of instream LW. The two clusters are separated by about 1.5 km (Figure 3) distance and around 40 m in elevation (Table 4). The downstream cluster is located approximately 0.1 km upstream of the most densely placed instream wood of the LW restoration project (Figures 2 & 3). There has been no instream LW emplaced within 0.5 km of the upstream cluster. This difference in proximity to the instream LW implies that the downstream cluster should be more likely to experience changes to groundwater recharge or storage from the wood restoration.

There are no observable trends in the groundwater data from any of the floodplain monitoring wells before and after the large wood was placed in the Indian Creek channel in 2017-2018. The range of seasonal variations between the high and low groundwater levels is similar throughout the period of monitoring well records from 2014-2021. The base levels during the dry periods are largely consistent. The spring high peaks display a similar amount of variability before and after the LW emplacement. If anything, the high groundwater levels in Wells 2, 3 and 4 appear to decrease in elevation in the three years after the wood was installed, although this could be due to systematic uncertainties in the measurements or differences in seasonal precipitation values. The high precipitation months in early 2016 could have contributed to high groundwater levels in some of the wells immediately preceding the wood installation.

The well data also do not indicate a change in the duration of the seasonal high spring groundwater levels since the wood emplacement began in 2016. The duration that groundwater remains above the summer low levels varies from year to year (Figures 12 and 13; Table 6). Using well MP-1 as an example (Table 6), the date that MP-1 goes dry each year ranges from early April to late May. Short- and long-duration periods of high groundwater levels at well MP-1 occurred both before and after the LW installation, with the shortest period of sustained high water after the LW and the longest documented period before the LW. Similar patterns were noted for the groundwater levels in well MP-4 (Figure 13).

Table 6. Duration of wet and dry periods at Well MP-1. Dates that MP-1 increased from dry, peaked, and returned to dry. * = Date when the well went dry in 2020-2021 is not exact; it occurred between manual measurements on 5/29/2021 and 6/10/2021.

	MP-1	Wet	Peak	Dry	Days Wet
	2014-2015	11/24/2014	11/29/2014	4/10/2015	137
	2015-2016	11/17/2015	3/2/2016	4/29/2016	164
Wood installed in channel	2016-2017	3/10/2017	4/7/2017	5/19/2017	69
	2017-2018	11/23/2017	3/30/2018	5/13/2018	171
	2018-2019	3/18/2019	4/4/2019	4/29/2019	42
	2019-2020	1/7/2020	2/8/2020	4/17/2020	101
	2020-2021	12/23/2020	1/14/2021	*6/10/2021	*169

In summary, the installation of large wood in the Indian Creek channel has yet to show a measurable effect on the height or duration of groundwater in the floodplain aquifer as of 2021, four years after the LW was emplaced.

Streamflow Model

HEC-RAS hydraulic flow model of the Indian Creek comparisons were performed to gain a general understanding of the difference in water-surface elevation (WSE) with and without instream LW. The purpose was to determine how far up the 2-meter-tall stream banks the WSE is likely to rise with and without LW under the average and maximum peak spring discharges on Indian Creek. The results help determine whether the addition of LW increases the WSE to levels where it intersects the more permeable layers of the floodplain stratigraphy for a greater vertical distance or a longer duration, or whether it overtops the banks. The channel at Indian Creek contains continuous wood that densely fills the entire channel in much of the modeled reach, which is immediately downstream of Wells 1, 2 and 5. Discharges used in the HEC-RAS model were the average high discharges for the months of March, April and May (6.0, 13.4, 15.9 ft^3/s), and the highest recorded discharge since 2014 of and 1.03 m^3/s (36.4 ft^3/s) on May 5, 2017.

The addition of LW in the stream channel caused a rise in the modeled WSE of up to 0.55 m for the discharge of 1.03 m^3/s, which was the highest flow on record from 2014-2021 (Figure 18). WSE increases were less for the lower discharges. Even at this high flow, the water did not overtop the banks in the modeled reach with or without LW obstructions (Figures 19 and 20). Detailed output results from the modeling are in Bartlett (2022).

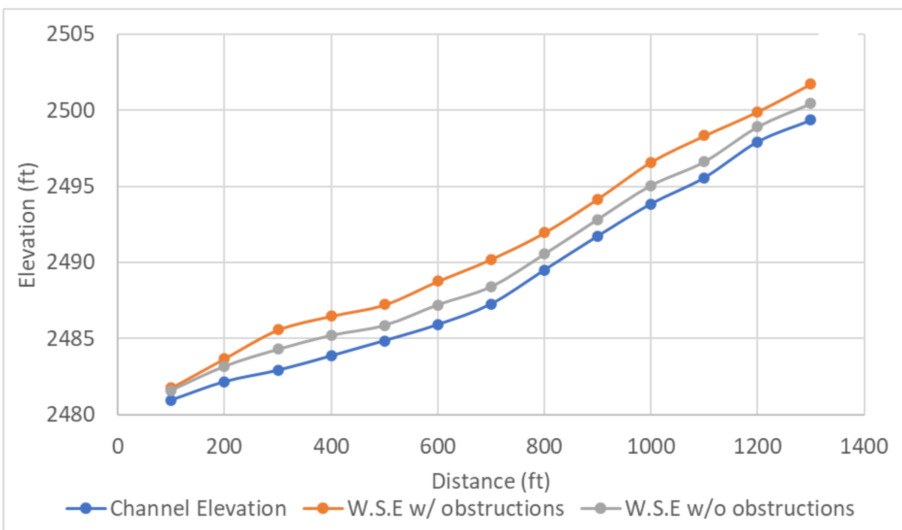

Figure 18. HEC-RAS water-surface profile for the maximum Indian Creek discharge. Discharge = 36.4 ft3/s. The gray line represents the WSE without obstructions. The orange line represents the WSE with obstructions. The blue line represents the minimum channel elevation. Detailed output from the model is in Bartlett (2022).

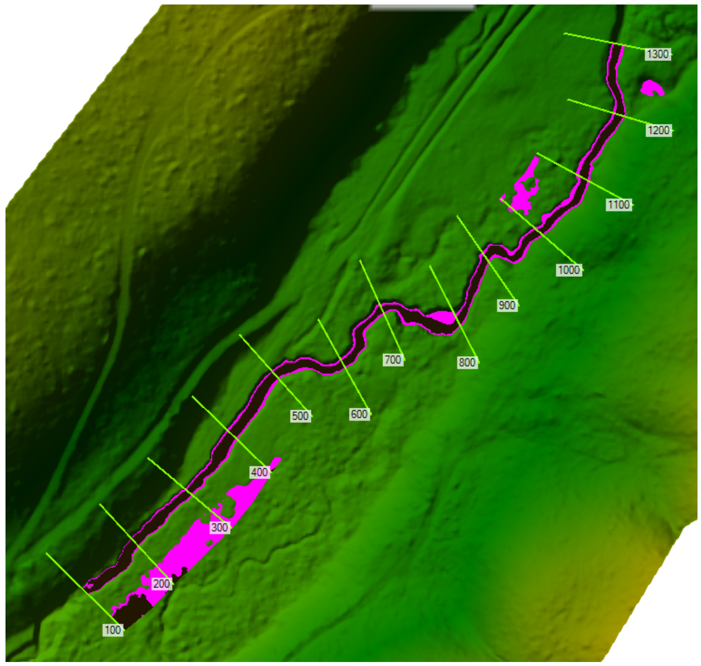

Figure 19. HEC-RAS model inundation results of the maximum discharge on Indian Creek. Discharge = 36.4 ft3/s. The dark color represents the WSE without obstructions, the pink represents the WSE with obstructions. The flow is largely contained within the incised channel.

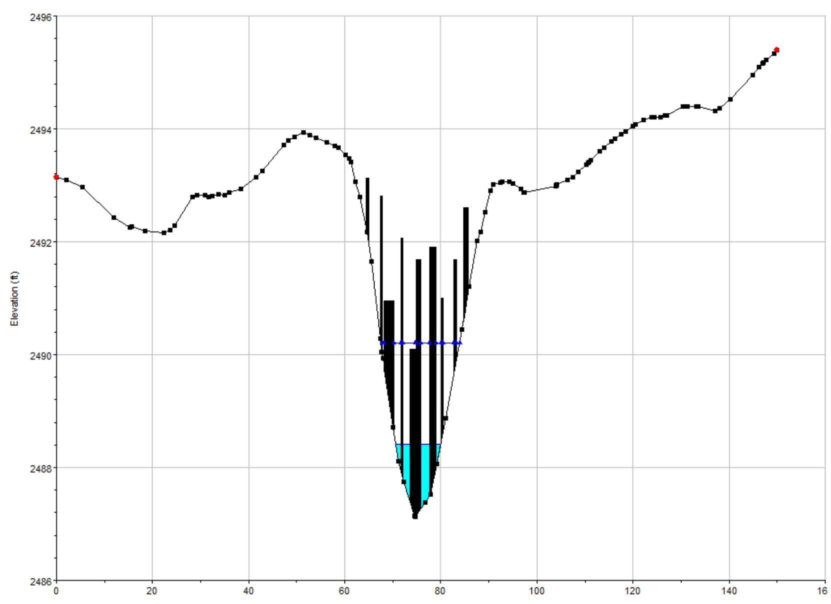

Figure 4. HEC-RAS modeled WSE stage results of the maximum discharge on Indian Creek. HEC-RAS modeled WSE stage results of the 36.4 ft^3/s discharge at the cross section that is 700 feet upstream of the downstream end of the reach. The light blue fill represents the WSE without obstructions, the dark blue line is the WSE with obstructions. The black lines are the obstructions used in the model to represent large wood. The WSE does not overtop the banks of the incised channel.

The streambanks at most areas of the modeled reach are approximately two meters high. The channel depth becomes increasingly shallow downstream and is covered by thick vegetation where the modeled area ends. Throughout the modeled reach the channel contains near continuous instream large wood piles (Figure 2). The water remained within the channel at all modeled discharge volumes.

The HEC-RAS model results indicate that under the current geometry of much of Indian Creek, the increased streamflow obstruction from the LW is unlikely to have a significant effect on the groundwater recharge or floodplain inundation. The hydraulic simulations show that even during the highest recorded discharge during the study period, the 0.5 m increase in the stage is unlikely to fill the channel enough to overtop the bank in the areas where channel depth is more than 50 cm (Figure 20). The increased WSE might intersect more of the permeable sand layers and lenses and slightly increase outflow into the floodplain aquifer. However, the lower permeability of the overlying thick silt/clay layer would likely impede significant lateral bank infiltration (Figures 7, 9 and 16).

The Indian Creek channel is deeply incised throughout much of the study reach, up to 2 m below the adjacent floodplain. This incision is also prevalent along the main Teanaway River. The Teanaway River has eroded down to the bedrock in some reaches, which has been attributed to timber harvesting and the transport of logs down the river through splash damming in the early 20th century (Schanz et al., 2019). Tributaries of the Teanaway River, such as Indian Creek, have incised their channels to coincide with the lowered baselevel of the main river. Some tributaries of the Teanaway, such as Indian Creek, also contained railroad spurs for timber transport that might have channelized floodplain flow. The result is that all of these channels will require significant aggradation or mobilization of wood through a large flood for water to regularly overflow onto the floodplain in the incised reaches.

CONCLUSIONS OF THE INDIAN CREEK STUDY

This study assessed the short-term impact of instream large wood (LW) restoration on the recharge and storage of the floodplain aquifer at Indian Creek. The groundwater was evaluated using pressure transducer data manual measurements from 2014-2021, which spans the main installation of instream LW in 2017-2018. The stratigraphy of the floodplain was described at multiple sites throughout the project reach to investigate how the sediment affects the groundwater recharge and storage potential. Sediment grain-size analysis was performed to better understand the composition of the sediment and estimate porosity values within the floodplain. A streamflow model was run at various known discharges of Indian Creek to understand what changes the instream wood might have on the water surface elevation and floodplain inundation.

The stratigraphy of the floodplain aquifer at stream level and above contains six common zones. A silt zone and a silt/clay zone dominate the upper 2 meters of the floodplain stratigraphy, underlain by a sand and gravel zone located just above the stream level, Below the sand and gravel zone is a gray clay layer that often coincides with the elevation of the channel bed. The gray clay occurs at about the same depth throughout the floodplain and has been found in other locations within the Teanaway Valley. The clay is underlain by more sand and gravel at Indian Creek, although it overlies the bedrock in parts of the Teanaway Valley Family Farm (Chapter 3).

The variation in sediment size within the floodplain stratigraphy of Indian Creek almost certainly affects the storage capacity of the floodplain aquifer. The gray clay and portions of the overlying silt/clay zone probably reduce the effective storage capacity of the floodplain aquifer and could influence the groundwater movement. The coarser sand and gravel layers are more likely to create effective aquifer storage, but their high permeability probably contributes to the rapid draining and decline of the groundwater levels in the late spring.

The comparison of precipitation data and stream discharge with groundwater levels commonly show an annual pattern of high precipitation leading to high groundwater levels, with the peak stream discharge lagging behind the peak in groundwater levels. Groundwater levels are often in decline when the seasonal peak stream discharge occurs in Indian Creek, indicating that infiltration from the stream is not the major control on the groundwater recharge. The groundwater levels drop rapidly in the late spring, indicating efficient transmission through permeable sediment layers in the floodplain, probably the sand and gravel zones. The groundwater gradients slope away from Indian Creek at the upstream cluster of wells, and parallel to the valley at the downstream wells.

Groundwater levels were found to be unaffected by the presence of the instream large wood. Data from six groundwater monitoring wells showed no consistent increased trend in the base levels, seasonal peaks, or duration of high groundwater levels after the emplacement of the large wood.

Streamflow model results showed that the addition of large wood to the existing stream channel is unlikely to cause a large change in flow depth during the maximum spring discharges that would increase the lateral movement of water into the floodplain aquifer or increase the chances of water to overtop streambanks that are more than 0.5 m high. The Indian Creek channel is currently incised up to 2 meters below the floodplain in much of the study site.

The large wood restoration project at Indian Creek is still relatively recent, and restoration work is still being performed at the site. These results suggest that the wood in the stream is yet to have an impact on the groundwater recharge and storage at this site. Over time, increased sediment aggradation in the channel or a flood that reorganizes the channel wood could conceivably alter the future surface water-groundwater interactions. However, due to the deep incision of Indian Creek and the main Teanaway River, significant aggradation would be necessary to facilitate this interaction.

The assessment reported here provides initial insight into the role of the floodplain stratigraphy on the potential groundwater recharge and storage associated with LW restoration at one headwater tributary of the Yakima River. The results from Indian Creek are likely a reasonable representation of other headwater tributaries in the Teanaway Basin, and possibly other formerly glaciated streams in the region. In any case, this study illustrates the importance of the stratigraphy in the behavior of the floodplain aquifer. Further investigation of the floodplain stratigraphy of other headwater tributaries of the Yakima River could expand our understanding of the regional effectiveness of instream large wood on groundwater recharge and storage.

III. Teanaway Valley Family Farm: The Effects of Channel Incision and Land Use on Surface-Water/ Groundwater Interactions

INTRODUCTION

The Teanaway Valley Family Farm (TVFF) is located along the main stem of the Teanaway River below the bifurcations that form the North, West and Middle Forks (Figure 21). TVFF was purchased by Washington Department of Fish and Wildlife in 2017 and is currently being restored by Mid-Columbia Fisheries Enhancement Group (MCFEG). As part of this restoration effort, a network of ten groundwater monitoring wells were installed on this property in November, 2018. In this part of the project, graduate student Joe Petralia monitored water levels, temperature, and stable isotope ratios of groundwater samples from these wells through time in order to understand the patterns of groundwater flow through the study site and the extent of mixing between river water and groundwater within the floodplain aquifer. This information is also used to estimate groundwater storage potential at this site. This section of the report is based on the data and analysis from the CWU Master's Thesis by Petralia (2022).

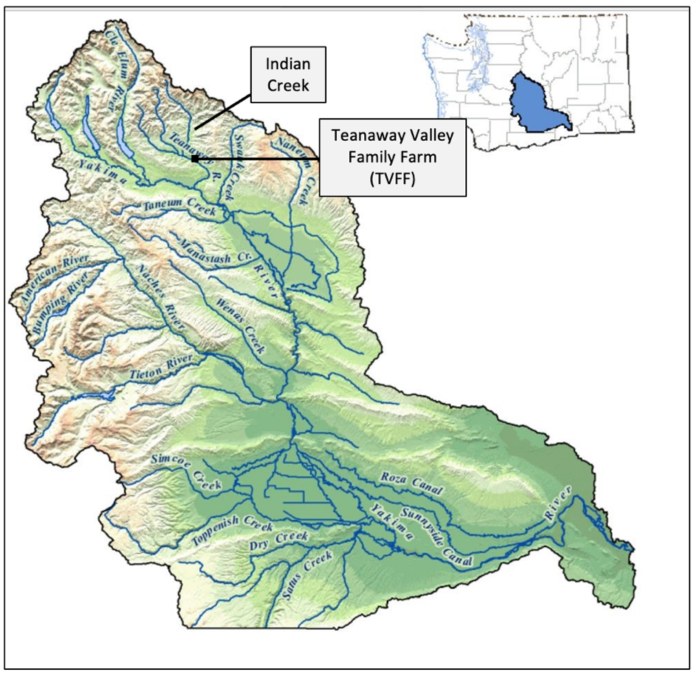

Figure 21. Location map for Teanaway Valley Family Farm (TVFF)

Site Description

Teanaway Valley Family Farm (Figure 22) is an 87-hectare plot of land located at River Mile 8 on the main-stem Teanaway River. The study area is largely on the floodplain of the Teanaway River, but also includes part of the valley of a small tributary named John Creek. Another small tributary, Fred Creek, also drains into the study area. Both of these tributaries are ephemeral, only flowing during the late winter and spring and have been channelized around the agricultural fields in the floodplain. The hydrology at the site is snowmelt dominated with the majority of precipitation falling as snow during the winter months and melting between the months of February and April. The annual precipitation is approximately 63 cm (25 inches).

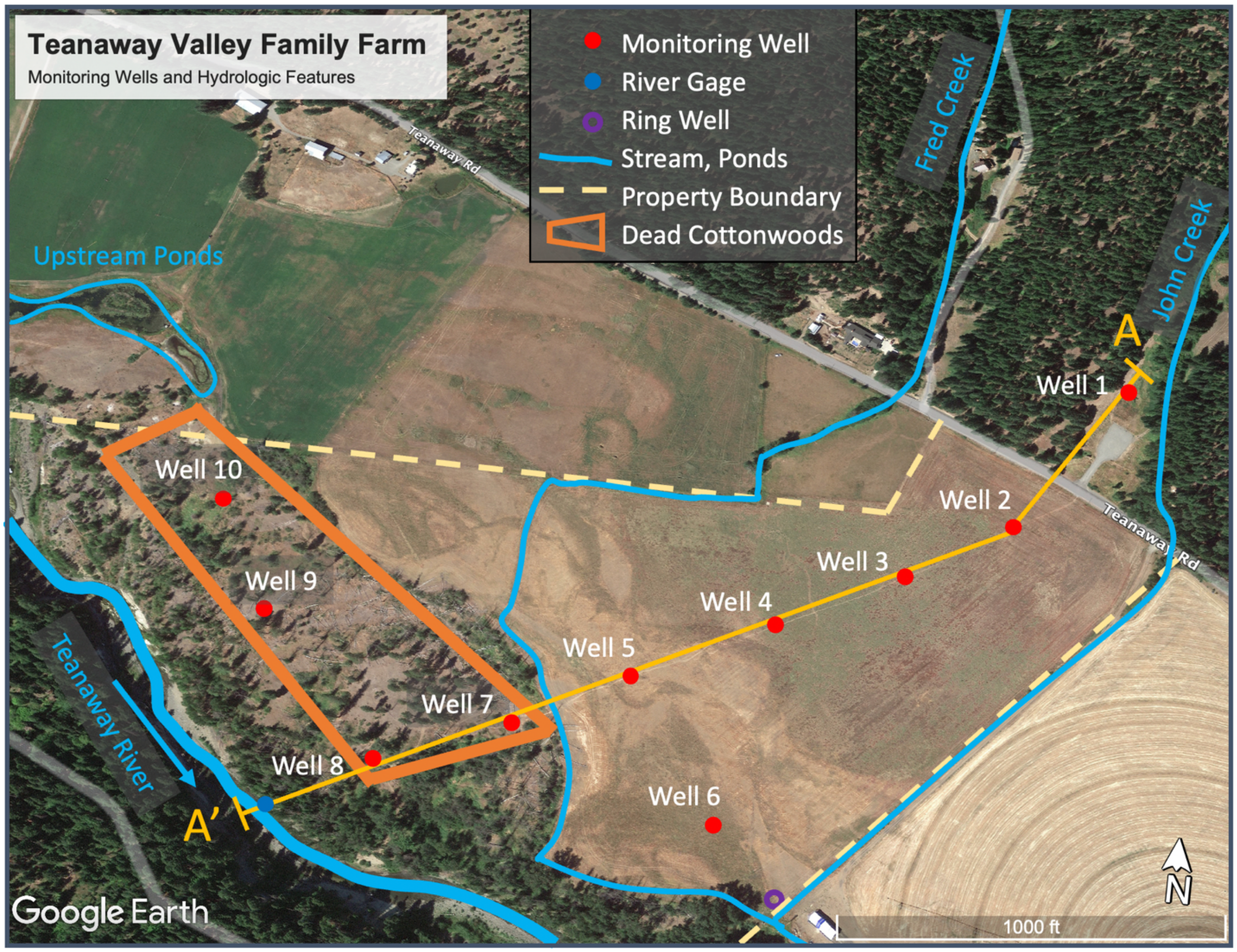

Figure 5. Teanaway Valley Family Farm site map. Red dots are monitoring wells, blue dot is river gage site, orange polygon shows area of cottonwood die-off. Transect A-A' is used for cross sections in Figures 27 and 31.

Prior to being purchased by the Washington Department of Fish and Wildlife, TVFF had been farmed for timothy hay for decades. Irrigation was distributed from a canal, called Ballard Ditch, near the road on the northeast side of the fields. For decades, the primary method of irrigation was flood irrigation. In 1978, the upstream neighbor shifted their water sources to a series of surface water ponds. Ballard Ditch was destroyed due to flooding in years 1996-1997. For TVFF and the downstream neighbor, irrigation shifted from flood irrigation to pivot irrigation pumped from shallow wells in approximately the year 2000. The shallow (<4 m) wells used for this irrigation are located approximately 300 feet from the Teanaway River on the TVFF property and the adjacent downstream property. An irrigation schedule that ends annually in July has been used by the landowners for approximately 14 years. Irrigation on the TVFF property was discontinued as of July 2018. Late season water rights on adjacent properties are now owned by Washington Water Trust.

One distinct feature of TVFF is a grove of dead cottonwood trees within the floodplain of the Teanaway River (Figure 21). After the land was purchased by the Washington Department of Fish and Wildlife, Mid-Columbia Fisheries Enhancement Group took the lead in restoring the land. Because of concerns about cottonwood die-off and to better understand the hydrologic characteristics of the site, they obtained funds to install a network of ten monitoring wells on TVFF to characterize groundwater level variation through time (Figure 21). These wells, drilled in November 2018, are arranged so that seven wells lie along a transect from the hillside to the Teanaway River. The remaining three wells provide a smaller transect that runs subparallel to the river through the dead cottonwood trees.

On the southwest side of TVFF, the Teanaway River has incised into the Roslyn Sandstone bedrock, largely as a result of another past land use, logging. Logging operations began in the 1920s with the removal of log jams, which had been performing a natural function of slowing flow of water and sediment out of the watershed. Logs stripped from the forests were then transported downstream in "log drives" that led to a mill downstream along the Yakima River. This process was highly abrasive to stream banks and stream beds (Collins et al., 2016; Shanz et al., 2019). At present, all reaches of the Teanaway River have experienced rapid erosion to the stream bed and the creation of strath terraces in the lower reaches (Collins et al., 2016).

Stable Isotope Background

The stable isotopes of hydrogen (D and H) and oxygen (^{16}O, ^{17}O, and ^{18}O) can be used to understand an array of hydrological processes. For the purpose of this study, they will be used to determine interactions between groundwater and surface water. A stable isotope is a nuclide of an element that does not undergo radioactive decay. Stable isotopes in water are measured as ratios of a heavy, uncommon isotope (D, ^{18}O) over a lighter, common one (H, ^{16}O) and expressed in the delta notation:

$$\delta = \frac{(R_{smp} - R_{std})}{R_{std}} * 1000$$

where R is the isotope ratio (D/H for δD, $^{18}O/^{16}O$ for $\delta^{18}O$), smp is the sample and std is a standard, Vienna Standard Mean Ocean Water (V-SMOW). The units for this measure are per mil (‰), where one per mil is equivalent to a tenth of a percent difference between the ratio in the sample and the ratio in V-SMOW.

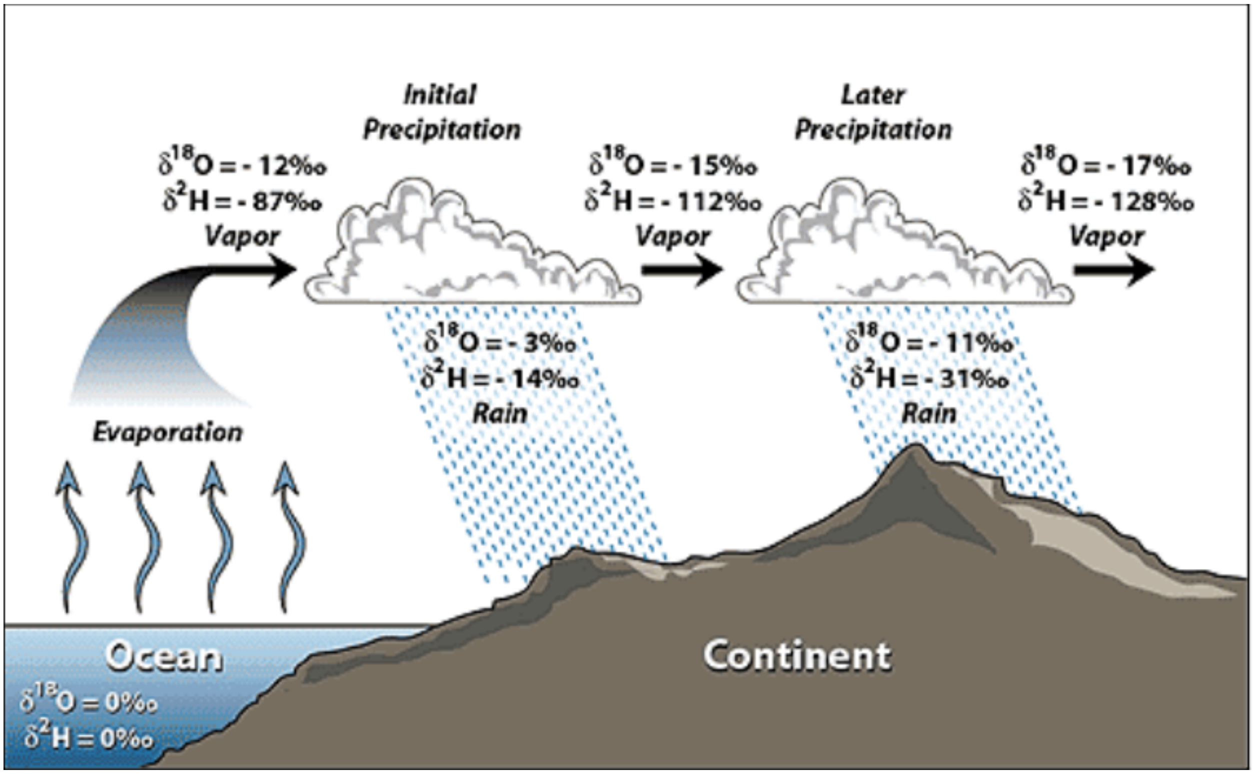

Figure 6. Change in the isotopic composition of an air mass as it moves inland and loses moisture (Sahara, 2005).

When water evaporates, the water molecules with the lighter isotopes preferentially evaporates. When water condenses and precipitates, the heavier composition stable isotope compounds preferentially rain-out (Faure and Mensing, 2005). Figure 23 illustrates how the rainout process gives rise to a wide range in the natural variation of the isotopic composition of surface waters across the landscape. In general, water becomes progressively depleted in heavier isotopes as a moist air mass moves away from its moisture sourc e, often the ocean.

These processes of isotope separation, or fractionation, are similar for isotopes of hydrogen and isotopes of oxygen. As a result, δD and $\delta^{18}O$ are highly correlated. In a given area, precipitation has the widest range of isotopic composition and falls along a line on a δD vs. $\delta^{18}O$ plot called the Local Meteoric Water Line. Isotopic fractionation is dependent on temperature, so winter precipitation tends to be isotopically lighter (have less ^{18}O and D) than summer precipitation. This seasonal variation with a lesser amplitude is also seen in streams and rivers, whose water is derived from recent precipitation. Groundwater, particularly deeper groundwater, tends to remain more constant and is often isotopically distinct from local surface water.

Because of this natural variation, stable isotopes of hydrogen and oxygen are used as a natural tracer of water sources and mixing between different waters. δD and $\delta^{18}O$ are conservative tracers that move at the same speed as the water because H and O are actually part of the water molecule, not a dissolved constituent.

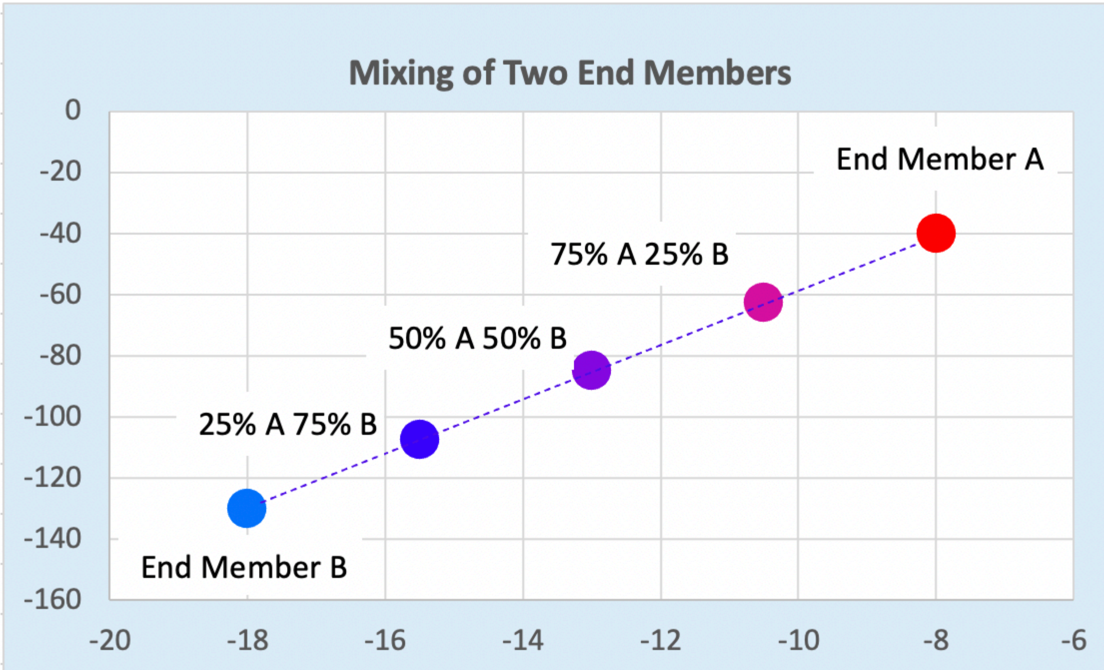

Figure 7. Mixing between two isotopically distinct end members. End members are red and blue, mixture of two end members is purple. Different percentages of mixtures are shown.

Isotopes are useful for determining mixing ratios when two isotopically distinct waters mix (Christophersen and Hooper, 1992). Figure 24 demonstrates mixing between two end members. The isotopic composition of the mixture is simply a weighted average of the two end members. Thus, if the isotopic composition of these end members can be determined or assumed, then the mixing ratios can be calculated for any mixed sample using a simple mass balance equation:

$$\delta_{mixture} = x\delta_A + (1 - x)\delta_B$$

where δ is either $\delta^{18}O$ or δD; the subscripts A and B signify the two end members; the subscript mixture represents the mixture; and x is the fraction of end member A in the mixture.

In the Teanaway River area and elsewhere in the Yakima River basin, this concept can and has been applied to interactions between surface water and groundwater (e.g., Taylor and Gazis, 2006; Sleeper, 2020). In general, stream water is derived from the western side of the basin, where the isotopic composition of precipitation is heavier (higher δD and $\delta^{18}O$) than to the east. Groundwater tends to be isotopically lighter, partly because it is derived from more eastern precipitation. If groundwater at a given depth is isotopically similar to a nearby stream, this suggests that there is a significant amount of surface water that has infiltrated to that level.

METHODS

Monitoring Wells

The ten TVFF monitoring wells were drilled on November 13-14, 2018. During drilling, well tailings were collected and logged. Location and construction information about the ten wells is presented in Table 1. All wells were finished within the sandstone bedrock of the area except for Well 2, which was drilled to 6.95 m, presumably just above the bedrock contact. The borehole width for all wells is 8 inches (20 cm), while the well casings consist of 2-in (5-cm) PVC pipe. The lowermost 1.52 or 3.05 m of pipe contained slits that serve as the well screens (Figure 25A). Wells were sealed with 1.5 m of bentonite and a concrete base and monument were installed to protect the well head (Figure 25B). Latitude, longitude, and surface elevation were obtained using a RTK survey-grade GPS referenced to a benchmark on the northeast side of the property.

Table 7. Monitoring Wells at TVFF. Screened length was placed at bottom of well.

Well #	Ecology Tag #	**WGS 84**		Well depth below surface m	Screen length m	Monument height m m
		Latitude	Longitude			
Well 1	BKL276	47.240529	-120.82100	5.85	3.05	0.72
Well 2	BKL277	47.239189	-120.82262	6.95	3.05	0.69
Well 3	BKL275	47.238667	-120.82397	6.07	3.05	0.75
Well 4	BKL274	47.238204	-120.82538	4.51	1.52	0.73
Well 5	BKL273	47.237681	-120.82700	4.15	1.52	0.61
Well 6	BKL272	47.236619	-120.82613	4.08	1.52	0.61
Well 7	BKL268	47.237328	-120.82836	3.72	1.52	0.72
Well 8	BKL269	47.236950	-120.82969	3.26	1.52	0.92
Well 9	BKL271	47.238003	-120.83102	3.08	1.52	0.99
Well 10	BKL270	47.238850	-120.83154	3.90	1.52	0.71

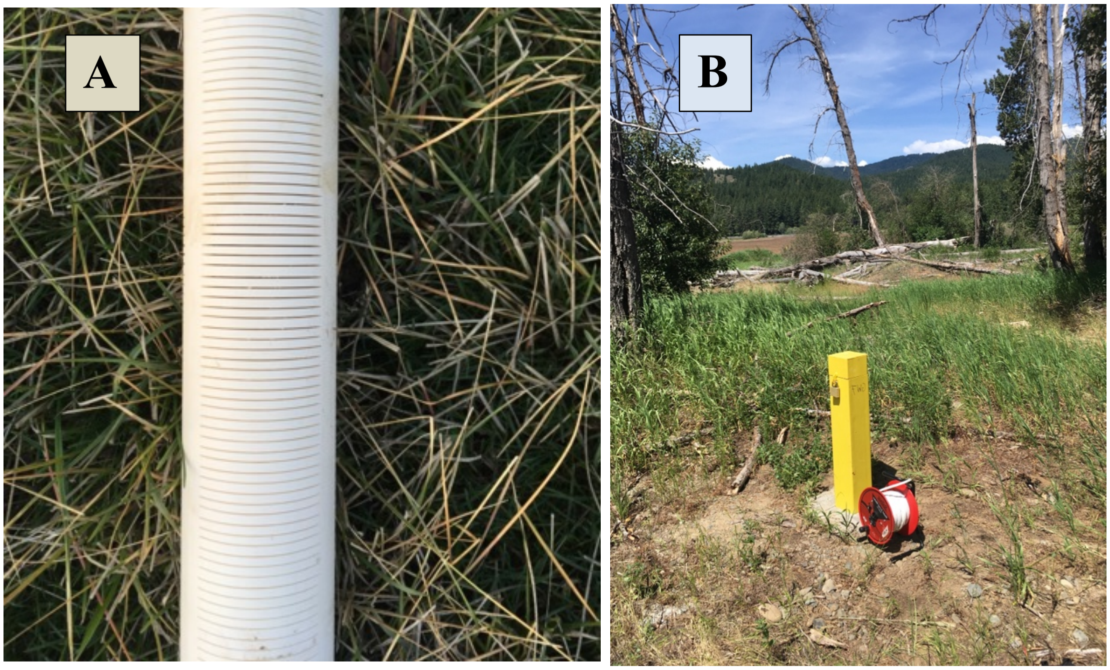

Figure 8. Details of monitoring well construction. A) slits in 2-in PVC pipe that serve as well screen in bottom 1.5 or 3.0 meters of wells, B) well monument.

Water Level Measurements

Each of the ten wells in TVFF was equipped with HOBO pressure transducers (U20-001-01). An additional equivalent transducer was installed at the top of Well 1 to collect barometric data. The pressure transducers were set to take a measurement of pressure and temperature every fifteen minutes. The data from these pressure transducers were downloaded once every 3-6 weeks from October 2019 until February 2021 and then every 4-6 months until November 2022. Pressure measurements were compensated to remove atmospheric pressure variations using the barometric pressure data and converted to elevations in meters above sea level using the ground elevation and the manually measured depth to groundwater at the beginning of the measurement. These data were transferred to Microsoft Excel to organize and compare the data and calculate daily averages.

An additional HOBO pressure transducer was installed with a stage gage in the Teanaway River west-southwest of Well 8 in August, 2019 (Teanaway River site on Figure 22). Readings from this gage were downloaded through December 2019 and then the transducer was lost in the high flows of spring 2020. These data were compared to stage data from the Department of Ecology gaging site on Red Bridge Road (Washington Ecology, 2023). Based on the comparison, the following equation was derived to calculate TVFF river elevations from the Red Bridge data for the time period after the data logger was lost:

$$E_{TVFF} = 634.3549 + G_{RB}*0.23268$$

where E_{TVFF} is the elevation of the river in meters at the TVFF gage site and G_{RB} is the gage height at the Red Bridge station in feet. This calibration is based on relatively low-flow data between August and October 2019. Red Bridge station is 5.5 km downstream of TVFF and one smaller tributary, Mason Creek, enters the Teanaway River between the two sites. During high flow, particularly when inputs from Mason Creek are disproportionate to inputs from upstream tributaries, the calculated elevations of Teanaway River at TVFF are approximations.

At the time of each pressure transducer download, manual water level measurements were made using a 30-meter Solonist electrical water level tape. These manual water level measurements served as a check that the pressure transducer data was not drifting. In general, the difference in water level between the beginning of a data logging interval and a download was within 4 cm of the water level difference measured by the pressure transducer. In the few cases, where it was greater than 4 cm, the discrepancy was determined to be due to one of two causes: rapid change in groundwater elevation at the time of measurement; or an errant manual measurement due to moisture on the end of the water level tape.

Water Sampling

A total of 328 groundwater, Teanaway River, and ephemeral stream samples were collected between November 14, 2018 and November 10, 2022. Samples were collected from all wells that were not dry and from the Teanaway River at the gage site at approximately one-month intervals. Additional Teanaway River samples were collected on 12 additional dates in 2019 and January 2020. Samples were also collected from near the Red Bridge gage station on seven of the sampling dates and from John Creek and/or Fred Creek on seven additional dates. Details of sample collection are given in Table 8.

Well water samples were collected from each well using a plastic bailer and placed in 30 ml polyethylene. Because there are no pumps in the wells, the well casing was not evacuated entirely at each sampling. Therefore, the water samples may at times represent water which had remained stagnant in the well casing.

Stable Isotope Analysis

Water samples were analyzed for stable isotopes of hydrogen and oxygen using a Picarro water isotope analyzer. This instrument uses cavity ring-down spectrometry to measure ratios of stable isotopes in water. D/H and $^{18}O/^{16}O$ ratios of samples are reported as δD and $\delta^{18}O$, respectively. Water samples were filtered with a 0.45 um polypropylene filter prior to analysis. Each water sample analysis consisted of 10-12 injections of the same water sample. The first three injections were discarded because of memory effects and the δD and $\delta^{18}O$ for the remaining injections were averaged. Five internal laboratory standards of know isotopic composition were used to create isotope calibration curves each day that the instrument was run. In addition, a quality control standard of known isotopic composition was run every fifth sample along with a replicate measurement of that sample (unknown isotopic composition). These standards and replicates served to determine the measurement precision and accuracy. Uncertainties are better than 1 per mil for δD and 0.1 per mil for $\delta^{18}O$.

Table 8. Water samples collected at TVFF.

Date	# wells sampled	Teanaway River*	ephemeral streams**	dry wells	Date	# wells sampled	Teanaway River*	ephemeral streams**	dry wells
11/14/18	9	x	JC	Well 2	6/1/20	10	x, RB		
3/31/19	6	x			6/29/20	10	x		
4/7/19	10	x			7/28/20	8	x		Wells 9, 10
4/21/19	10	x			9/1/20	8	RB		Well 2
6/12/19	10	x	JC		11/2/20	9	RB		Well 2
7/17/19	8	x		Wells 9, 10	2/2/21	9	RB		
8/8/19	8	x		Wells 9, 10	3/18/21	10	x	JC	
8/28/19	9	x		Well 2	5/4/21	10	x	JC	
10/3/19	9	x		Well 2	6/16/21	10	x	JC	
10/31/19	9	x		Well 2	8/6/21	7	x		Well 2
12/3/19	9	x		Well 2	9/23/21	9	x		Well 2
2/5/20	7				10/27/21	9	x		Well 2
2/26/20	10	x, RB			2/19/22	10	x	JC, FC	
3/18/20	10	x			4/8/22	10	x	JC, FC	
4/27/20	10	x, RB			10/25/22	3			Well 2
5/7/20	10	x, RB			11/10/22	9	x		Well 2
Totals	**Groundwater samples**		**285**	**Teanaway River samples**		**34**	**John/Fred Creek samples**		**9**

* x = water collected at TVFF Teanaway River gage site; RB = water collected near Red Bridge gage station; additional Teanaway River samples were collected from the TVFF gage site on the following dates: 1/10/19, 1/16/19, 1/28/19, 2/4/19, 2/15/19, 2/22/19. 2/25/19. 4/12/19, 5/8/19, 8/21/19, 11/20/19, 8/26/20

**JC = sample collected from John Creek; FC = sample collected from Fred Creek

RESULTS AND DISCUSSION

Stratigraphy

When the ten TVFF monitoring wells were drilled on November 13-14, 2018, well tailings were collected and logged. Information about the ten wells is presented in Table 9. All wells were finished within the sandstone bedrock of the area except for Well 2, which was drilled to 6.95 m, presumably just above the bedrock contact.

Table 9. Description of Borehole Stratigraphy. These descriptions are based on well tailings retrieved at the time of drilling.

Well #	Depth (m)	Bedrock depth (m)	Description
1	5.85	5.49	0-7 ft – soil, relatively clay-rich 7-18 ft – mostly clay 18 ft – bedrock, sandstone
2	6.95	> 6.95	0-5 ft – soil, relatively clay-rich 5-18 ft – mostly clay 18 ft – thin layer of angular gravel did not reach bedrock at 23 ft
3	16.07	5.79	0-7 ft – soil, relatively clay-rich 7-19 ft – mostly clay, contains some cobbles and pebbles 19 ft – bedrock, sandstone
4	4.51	4.57	0-5 ft – relatively clay-rich greyish soil 5-15 ft – mostly cobbles and pebbles 15 ft – bedrock, sandstone
5	4.15	3.96	0-4 ft – sandy soil with ≈30% cobbles 4-13 ft – pebble to small cobble size, ≈90% 13 ft – bedrock, sandstone
6	4.09	3.96	0-4 ft – sand-silt soil, few cobbles 4-5 ft – soil + cobbles, soil has clay-rich aggregates 5-7.5 ft – cobbles and pebbles (≈95%) 7.5-13 ft – bigger cobbles 13 ft – bedrock, sandstone
7	3.72	3.66	0-3 ft – sand-silt soil + 25% cobbles 3-8 ft – mostly cobbles 8-9 ft – 80% pebbles + some clay 9-10 ft – cobbles 12 ft – bedrock, sandstone
8	3.26	3.20	1-2 ft – sandy soil with ≈40% cobbles and pebbles 2-10.5 ft – cobbles and pebbles (95%) 10.5 ft – bedrock, sandstone
9	3.08	3.05	0-4 ft – mostly cobbles (≈90%), some soil 4-5 ft – cobbles 5-10 ft – cobbles grading to pebbles below 10 ft – bedrock, sandstone
10	3.90	3.81	High point, on local mound 0-3 ft – sand-silt soil, very few cobbles 3-5 ft – darker brown soil, some cobbles (≈10%) 5-12.5 ft – mostly cobbles and pebbles (90-95%) 12.5 ft – bedrock, sandstone

In general, there is a sharp contrast in the substrate of the lower floodplain (Wells 4-10) versus the upper floodplain and John Creek valley (Wells 1-3). Wells 4-10, which are closer to the river, penetrate sediment that is rich in cobbles, while the stratigraphy at Wells 1-3 is dominated by clay (Figure 26). The depth to bedrock decreases from the northeast to the southwest with the sandstone bedrock exposed at the TVFF Teanaway River gage site, where the river has incised into the bedrock (Figure 26).

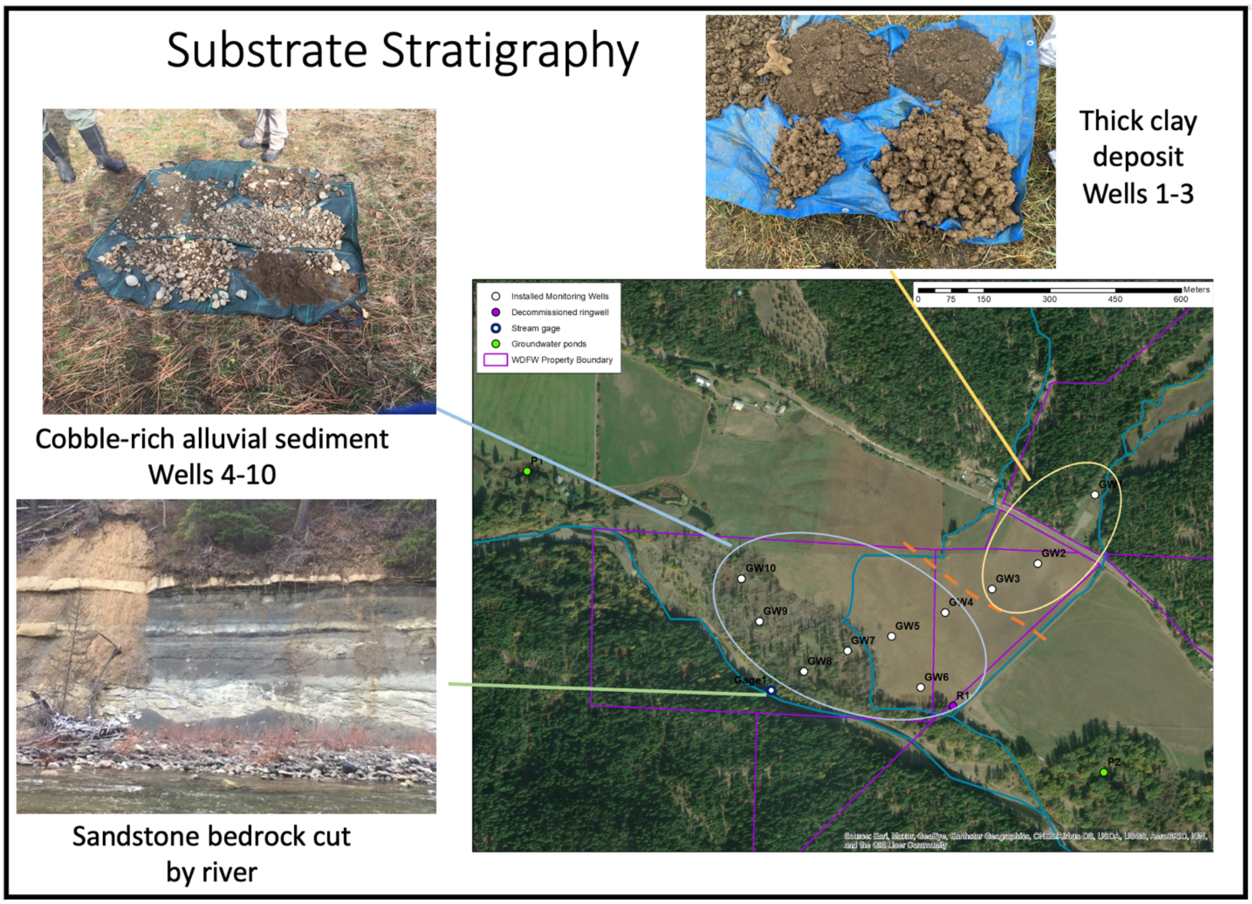

Figure 9. Map and photos of substrate stratigraphy at TVFF. The upper right figure shows two piles of clay-rich sediment (lower two piles in picture) that are dominant on the northeastern (upslope) side of the floodplain. The upper left picture shows cobble-rich sediment typical of the lower part of the floodplain. The bottom left picture is a view towards the southwest of the sandstone bedrock that is cut by the river. The map view shows where these units are on the landscape and the inferred contact between the clay-rich sediment and the cobble-rich sediment (dashed orange line).

Figure 27 is a simplified cross section from Well 1 to the river (A-A' line on Figure 22), showing this change in the sedimentary deposits that overly the bedrock. Clay deposits occupy the majority of lowermost valley formed by John Creek and a substantial part, approximately 25%, of the floodplain volume. They have very low permeability. Although they are largely saturated with water, they do not transmit water and thus serve as a confining layer for any aquifers. Occasional cobble lenses and a gravel horizon at the base of the clay likely serve as small, confined aquifers.

Similar clay deposits to those that were observed in the tailings of Well 1-3 are present throughout the upper Yakima basin, particularly on the north side of the basin in places like the Teanaway Valley (Tabor et al., 1982). They are likely the result of glacial process in which water that is laden with clay-rich sediments is pooled. In this case, the clay likely occupied more of the Teanaway alluvial valley fill but were eroded away by the modern Teanaway River which also laid down the cobble-rich sediment.

Because of past logging practices, the Teanaway River has incised into the bedrock on the southwest side of the cross section and property. The riverbed at the gaging site is now 2.5 meters lower than the ground surface at Well 8, which is 90 meters away. This difference in elevation gives rise to a hydraulic gradient during the summer months, when the incised stream acts as a ditch that more efficiently carries water out of the basin.

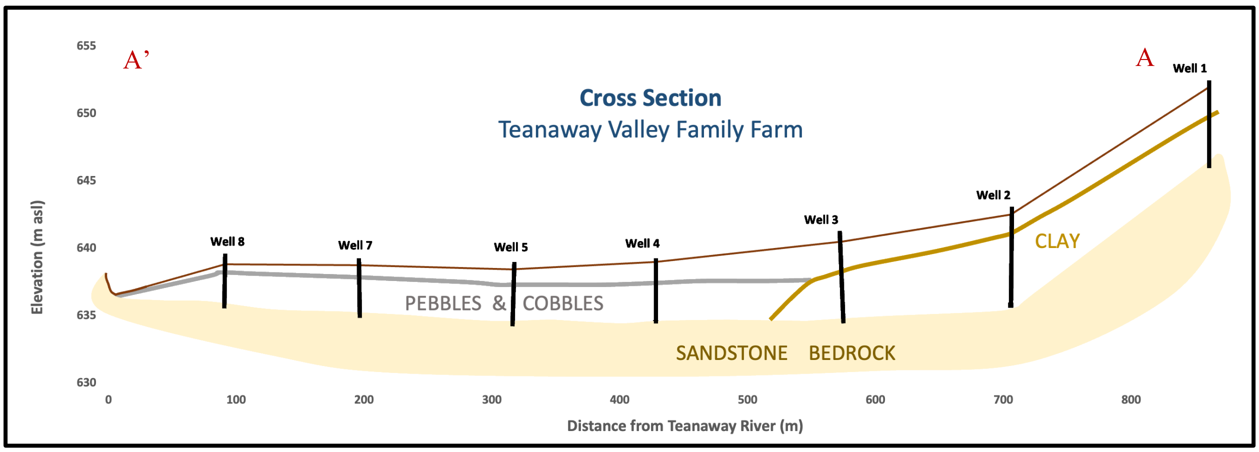

Figure 10. NE-SW cross section at TVFF. A-A' line, running from Well 1 to the Teanaway River, is shown in Figure 22.

Seasonal Groundwater Elevations and Flow Direction

Groundwater levels have been recorded via HOBO data loggers in all wells from 8/21/19 to present. Through this data set, we can infer how groundwater flow varies seasonally at the Teanaway Valley Family Farm and the relative influence of Teanaway River fluctuations versus local snowmelt recharge on the water level in each well.

Figure 28A shows daily average groundwater elevations for pressure transducer data from all wells from August 2019 to November 2022. The elevation of groundwater in Well 1 is significantly higher than the groundwater in all other wells. Well 1 shows a broader recharge peak than other wells; because of its position, its water level is only influenced by snowmelt and streamflow in the John Creek watershed. The stratigraphy in this Well is dominated by clay and the groundwater is likely confined in coarse lenses within the clay, particularly at interface between the clay and the sandstone bedrock. Thus, it is within a confined aquifer and the water level represents the pressure produced at recharge zones higher in the John Creek watershed.

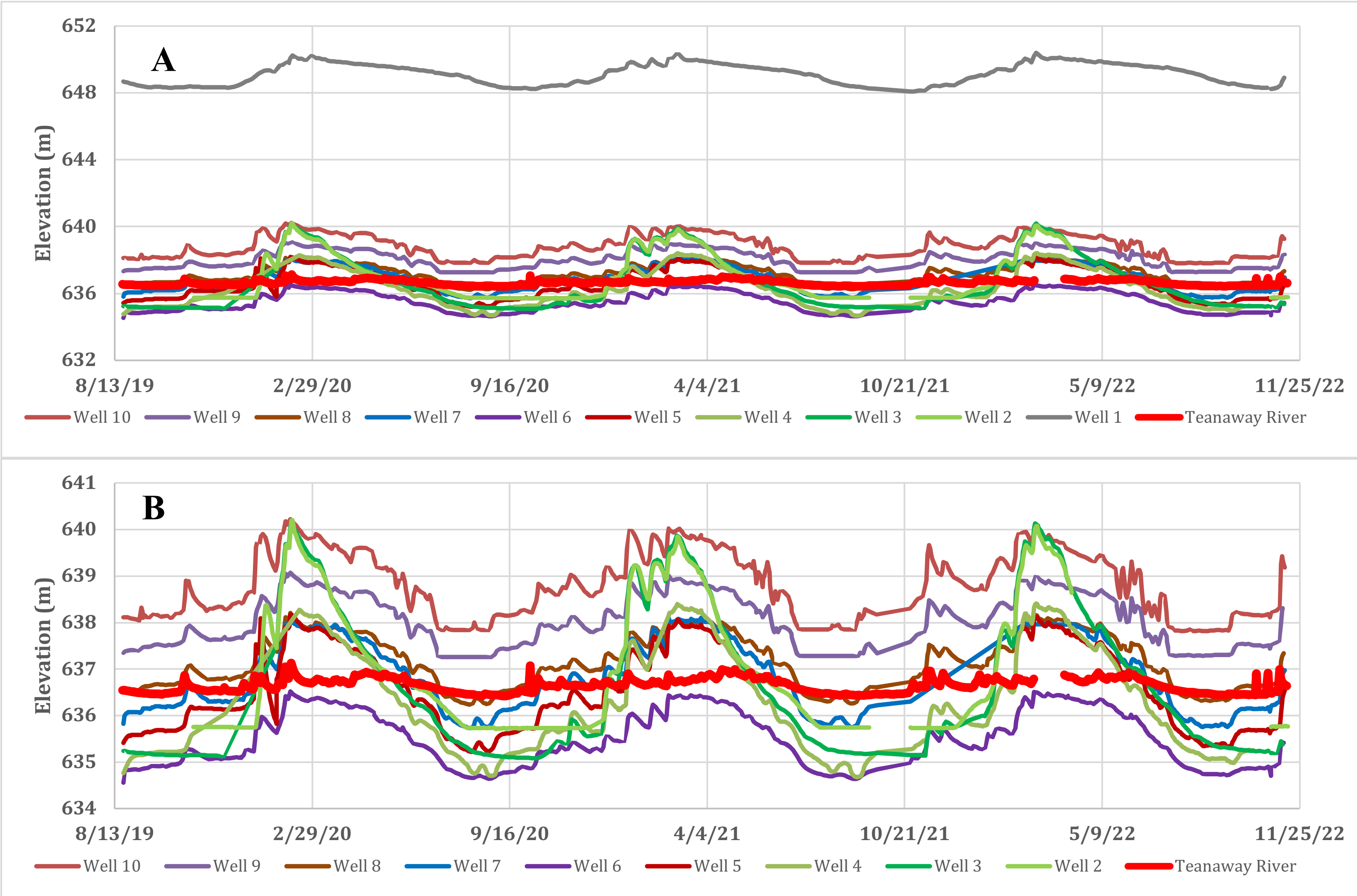

Figure 11. Groundwater elevations at TVFF. Measured using Hobo pressure transducers between 8/22/19 and 11/10/2. A) Elevations for groundwater in all wells and the Teanaway River; B) Elevations for Teanaway River and groundwater in all wells except for Well 1. Scale allows for visualization of the seasonal variations and the different patterns for Wells 2 and 3 (green curves).

Among the remaining wells (Figure 28B), Wells 2 and 3 have a distinctly different groundwater elevation pattern, with a greater amplitude of elevation change and a more rapid decline from the peak values. The groundwater levels in Wells 2 and 3 likely represent the potentiometric surface for another confined aquifer within the upper Teanaway River floodplain where the wells are located. The stratigraphy observed within the wells suggest that this aquifer is a thin cobbly unit right above the bedrock. It is possible that the aquifer extends into the upper part of the bedrock itself.

Groundwater elevations in Wells 5 through 10 generally move up and down as a unit. There is some convergence between Wells 5, 7, and 8 during the February and March, during the peak after groundwater recharge. These groundwater elevations represent the water table for the unconfined alluvial aquifer.

Well 4 has an intermediate pattern. It has a greater range of groundwater elevations and more rapid elevation declines than Wells 5 to 10. Then, during the late spring through fall, groundwater elevations in Well 4 follow a similar pattern to the water table of the alluvial aquifer (Wells 5 to 10).

Figure 29 displays a comparison between groundwater elevation in Well 6, the alluvial aquifer that well that is downgradient of the well transect, and the Teanaway River elevation at the TVFF gage site. The annual variation in elevations has been divided into three periods:

1. *Groundwater Recharge* – the period when groundwater levels rise in a fluctuating manner. The upward surges correlate with large rain events or short thaws, periods with minimum temperatures above freezing, during January through March. River elevations fluctuate and increase slightly during this period. This period generally extends from late October/early November until late February/early March.

2. *Snowmelt* – the period of peak flows in the Teanaway River. Groundwater elevations recede and increasing rates during this period, which extends from late February/early March to June.

3. *Baseflow* – this is the warm summer period, when there is minimal precipitation and the Teanaway River is fed by baseflow from the alluvial aquifer. The groundwater elevations pass through a minimum in this period, typically in late August.

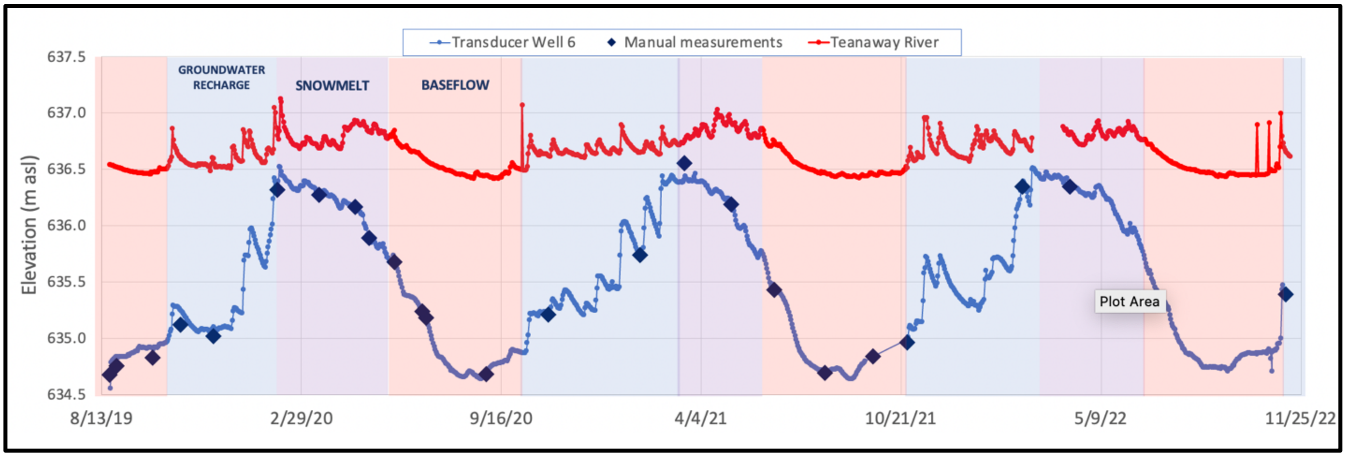

Figure 12. Seasonal variations in groundwater and stream elevation. The annual cycle is divided into three periods based on stream and groundwater elevation patterns. These periods, described in the text, are Groundwater Recharge, Snowmelt, and Baseflow.

Groundwater elevation patterns within Wells 4 to 10 can be used to contour the water table for the alluvial aquifer and understand the changes in groundwater flow throughout the year. Figures 30A and 30B show contour maps of the water table and groundwater flow directions at the end of the baseflow period and at the end of the groundwater recharge period, respectively. They are based on manual measurements from October 3, 2020 (baseflow) and February 5, 2020 (groundwater recharge).

During the baseflow season, groundwater flow is roughly parallel to the river throughout the study area moving downgradient from northwest to southeast. Immediately after recharge, groundwater levels in all wells increase by over a meter and the direction of flow shifts so that it is flowing obliquely towards the river. Thus, the Teanaway River is gaining in this reach at that time. This shift in water table orientation represents a short-term collection of water at the edge of the clay contact (shaded region in Figure 30 B).

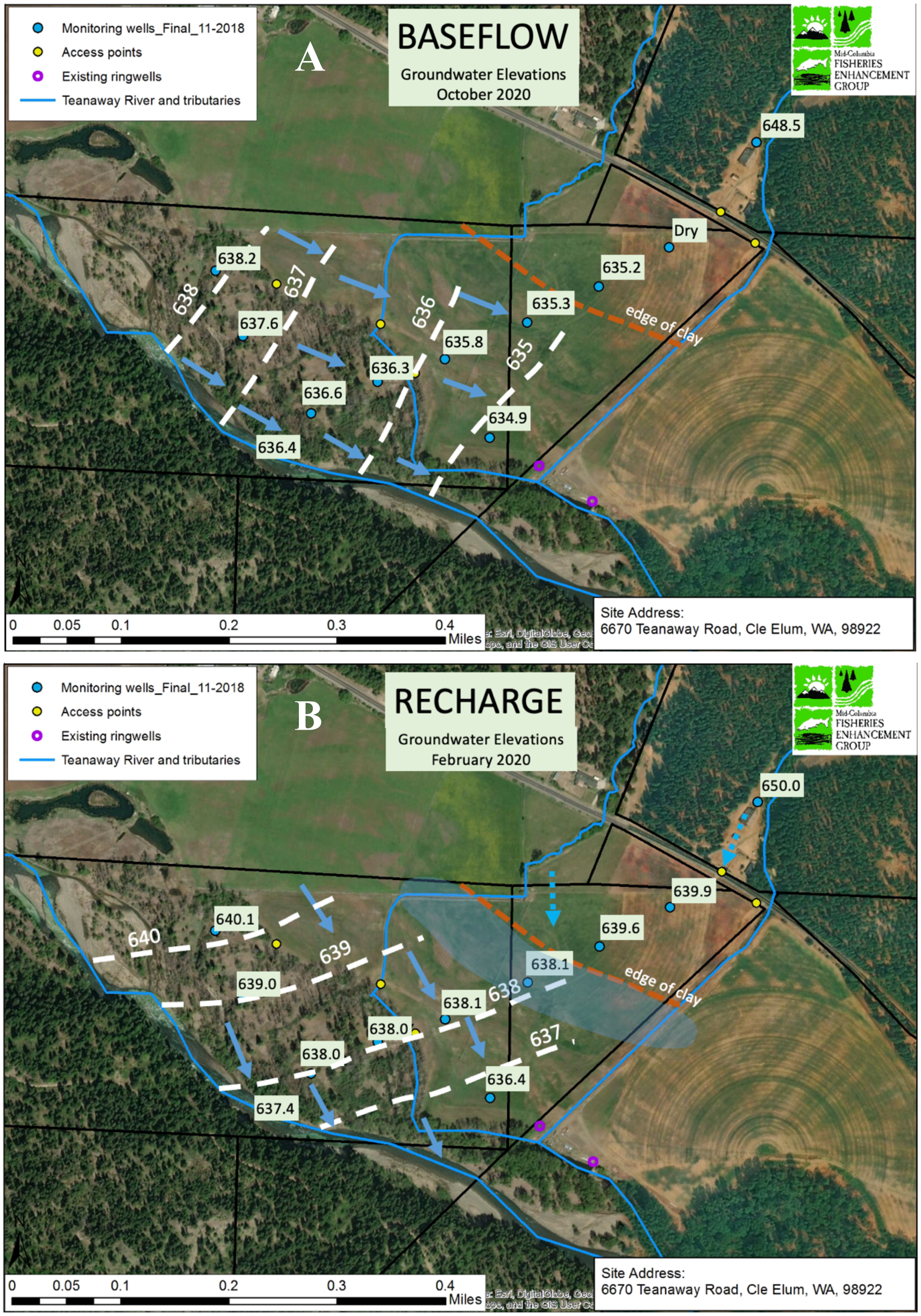

Figure 13. Contour maps of the water table at TVFF A) during baseflow season, and B) during the recharge season. Elevations are from manual measurements made on October 3, 2020 (Baseflow) and February 5, 2020 (Recharge). White dashed lines are 1-m contours of the water table for the alluvial aquifer. Blue arrows show the direction of groundwater flow. The shaded blue area in the Figure 30 B is the area where groundwater from the hillslopes initially collects during recharge.

Figure 31 presents cross sections for the same two dates as the contour maps of Figures 30. The increased recharge near the clay contact can be seen in Figure 31B. The potentiometric surfaces for the two confined aquifers of Well 1 (John Creek valley) and Wells 2 and 3 (upper floodplain) are also shown in these two figures. During the baseflow period, Well 2 is dry and the groundwater level in Well 3 is not substantially above the alluvial aquifer water table. During recharge, the pressure in this confined aquifer has increased to the point that the head is well above the alluvial aquifer water table. The shape of the hydrograph of Well 4 suggests that this pressure is transmitted to the alluvial aquifer and is likely responsible in part for the collection of groundwater on the north side of the aquifer. This increased hydraulic head in the confined floodplain aquifer likely represents local input, largely snowmelt, from the hillslopes and flow in the ephemeral streams. The groundwater elevation for Well 1 reflects a second confined aquifer that is not strongly connected hydraulically to the aquifer of Wells 2 and 3. The potentiometric surface of this aquifer is 10 to 13 meters above that of the lower confined aquifer. Because of the location of Well 1 above the Teanaway River floodplain, this aquifer derives its water from snowmelt and streamflow in the John Creek subbasin.

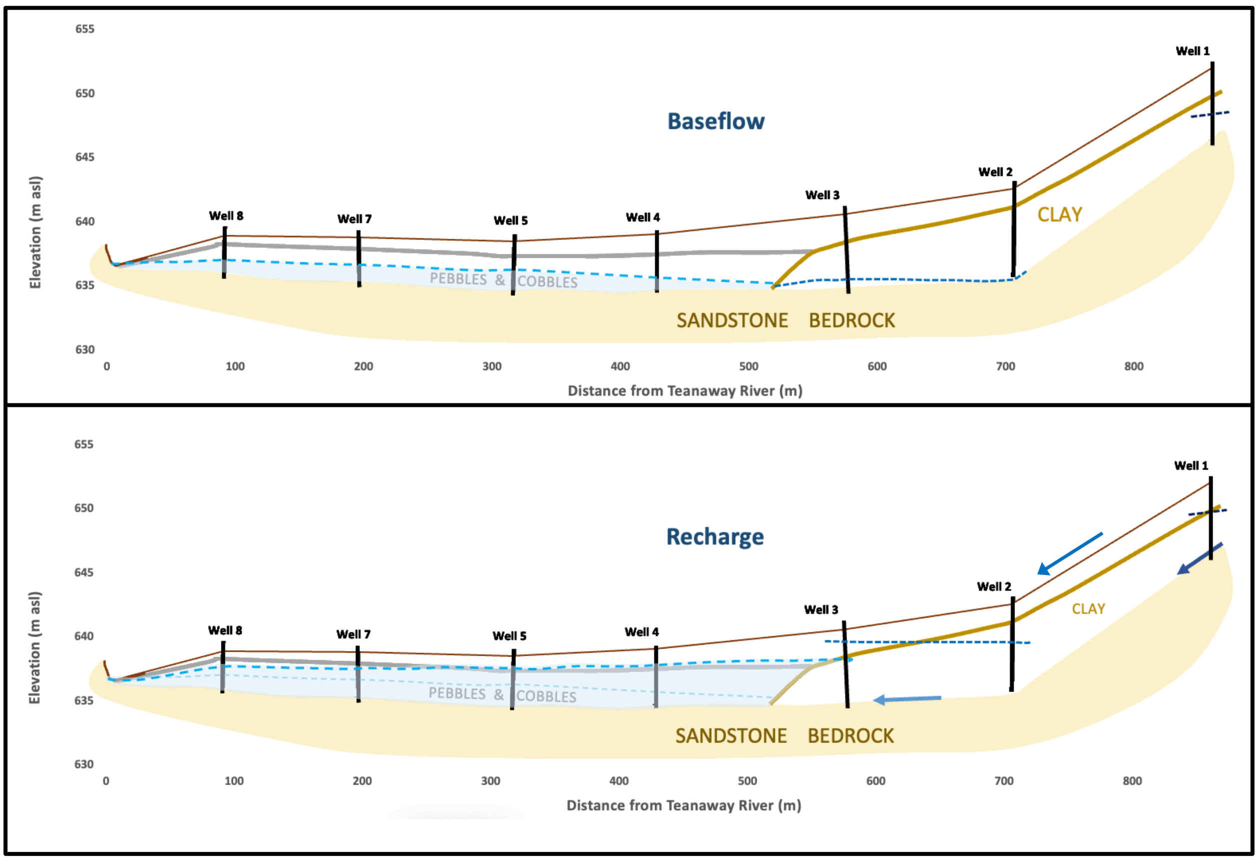

Figure 14. Cross-sectional view of groundwater levels in alluvial aquifer A) during baseflow period, and B) during groundwater recharge period. The cross section runs along line A-A' in Figure 22. Three distinct aquifers are depicted in these diagrams: an unconfined alluvial aquifer, and two hydraulically disconnected confined aquifers beneath a thick clay layer.

Response to Precipitation Input and Preferential Flow

Response of the groundwater system to a pulse of precipitation in October 2019 can be seen through 15-minute transducer data following the pulse. Figure 32 shows the details of elevation changes (in m) for wells 4 through 10 and the Teanaway River in the week following 10/20/19. Elevations for each water level is shown relative to the elevation on 10/1/19 at 12 a.m. so that the changes in groundwater elevation can be observed on the same scale. A significant rain event occurred on 10/20/19, as shown in Figure 33, historical weather data for a nearby station Wenatchee for the month of October 2019 (Weather Underground, 2023).

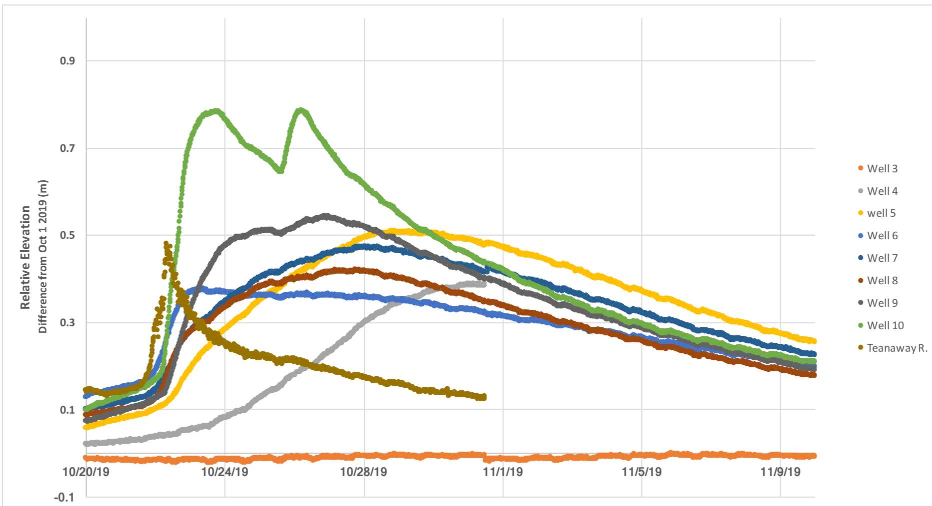

Figure 15. Response of Teanaway River and groundwater to a precipitation event on October, 2019. Relative elevations in meters, zero for each well is set at the elevation on October 1, 2019 12 a.m.

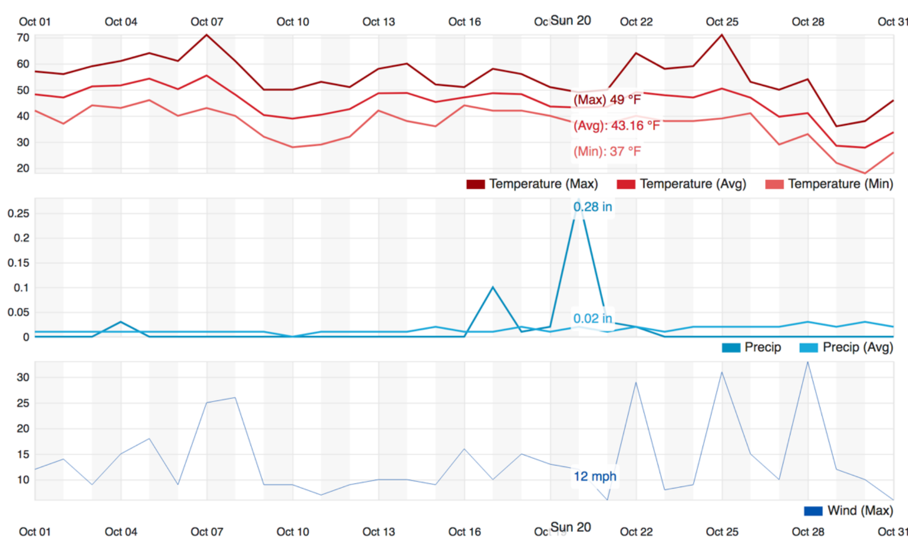

Figure 16. Weather history for Wenatchee, WA for the month of October 2019. Data and figures from Weather Underground, 2023.

The hydrologic pulse from the precipitation can be seen travelling from the river to each of the wells. The Teanaway River shows a sharp response to the precipitation event, peaking on the morning of October 22 at 0.46 meters above the October 1 level. The first two wells to respond are Well 10 and Well 6. Although these are not the closest wells to the river, the hydrologic pulse appears to have a more permeable pathway to those wells. Well 10 and Well 9 show a distinctive second pulse, likely related to the same precipitation event. Attenuation of the signal in Wells 5, 7, and 8 may represent input from this second hydrologic pulse. The location of Wells 10 and 9 suggest that the second pulse originates upgradient from Well 10. A series of ponds in the upstream (Figure 34) property likely represents an abandoned channel that provides a preferential flow path that transmits a delayed pulse of pressure to the downstream wells. The hydrologic pulse from the precipitation event reached Well 4 last, approximately 12 days after the precipitation event and did not influence that water level in Well 1-3 at all. Hydraulic pressure from Fred and John Creek and the thick clay layer on the northeast side of the valley control the elevations in these three wells.

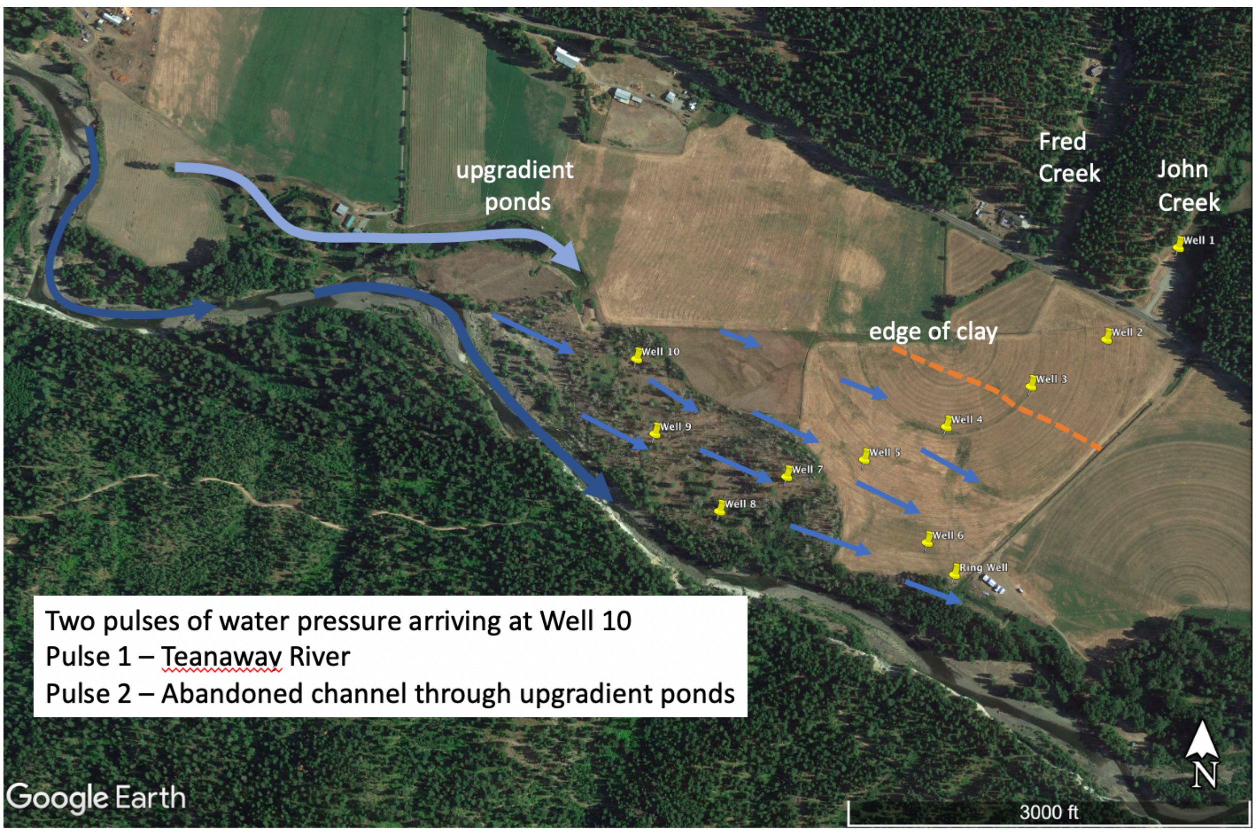

Figure 17. Hydrologic flow directions and major flow paths at TVFF. Teanaway River flow is shown by the large, dark blue arrow; groundwater flow through the alluvial aquifer is shown by the short, medium blue arrows; a preferential flow path through an abandoned channel occupied now by upgradient ponds is shown by the light blue arrow. Pulses described in text box are shown in Figure 32.

Impact of Pumping from Upgradient Ponds

Examination of historical imagery and first hand accounts indicate that the cottonwood forest on the TVFF property has been dying off over the past ≈10 years. Current observations from the field include dead and decaying logs, shattered tree branches, and dead standing cottonwoods. Not many cottonwoods remain. Only a select few cottonwoods on the TVFF property, near the ring well on the southeast corner. The only trees remaining within the area surround wells 9-10 are conifer and pine trees, which were sparse to begin with. A number of potential causes, such as disease or pest infestation have been considered to explain the die off, but no conclusive evidence has been found to support these as the main cause. The wells were emplaced on TVFF partly to determine the availability of groundwater to the cottonwood forest and explore the possibility that the die off is due to lack of sufficient water.

Cottonwood trees require shallow alluvial aquifers with water table depths consistently above approximately 2 m below ground surface to persist throughout the year (Scott et al., 1999). Without a persistent water table within the roots of the cottonwood trees, a grove of trees is unable to survive. The cottonwood trees along the banks of the Teanaway River on the TVFF property have suffered from a lack of a consistent water table. Figure 35 shows depth to groundwater from August 2019 to October 2020.

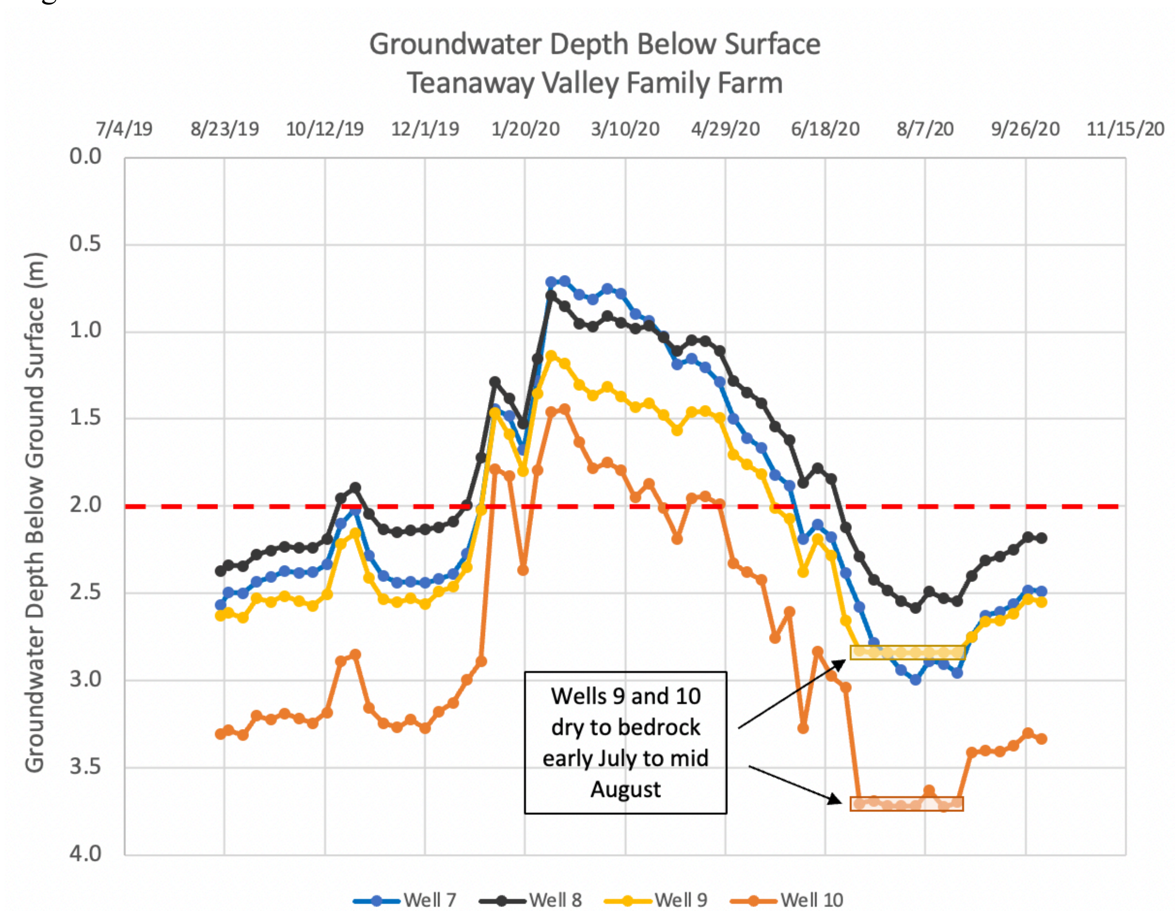

Figure 18. Groundwater levels as depth below surface for wells in the riparian zone at TVFF. The line at 2.0 meters represents the water level needed for cottonwood survival (Scott et al., 1999).

During spring recharge, the water table is above the average level of mature cottonwood roots. However, the water table does not persist at this depth for long, and by June 18, 2020 the water table has fallen to a depth below 2 m for all of the riparian zone wells.

The downward decline in water level is most pronounced for Well 10. Groundwater levels in that well also undergoes greater fluctuations with episodic downward surges throughout this period of water level decline. Some of these fluctuations are seen in Well 9, 7, and 8, but with decreasing amplitude away from Well 10. This pattern is likely the result of pumping from the upgradient pond during the summer months. The owner states that they must be careful about their pumping rate or the pond will go dry. Because of this removal of upgradient water, Wells 9 and 10 also go completely or nearly dry during the late summer. This is also the area where the cottonwood survival rate is the lowest. Overall, the cottonwood roots are absent of groundwater for 5-6 months of the year, depending on proximity to the upgradient ponds.

Isotopic Evidence of River Water/Groundwater Interaction

All of the isotope data for 285 groundwater samples and 43 surface waters are shown on a δD-$\delta^{18}O$ plot (Figure 36). Wells are grouped into 3 color groups: green = wells in the alluvial aquifer and in riparian forest near the river; blue = wells in the alluvial aquifer and in the field; yellow = wells in the confined aquifer below the clay. The Teanaway River samples, shown in red, fall along a line with equation $\delta D = 8.5\ \delta^{18}O + 17.1$. Two local meteoric water lines (LMWLs), based on measurements of Ellensburg and Cle Elum precipitation (Robertson and Gazis, 2006), are shown for reference. The groundwater samples are more similar in isotopic composition to Ellensburg precipitation than Cle Elum precipitation, but the slope of the Ellensburg LMWL is considerably lower at 5.8.

Groundwater samples at TVFF fall along a broad zone that is subparallel to the Teanaway River line. Nearly all of the groundwater samples lie below the Teanaway River line, suggesting that they have undergone some degree of evaporation, which tends to increase the $\delta^{18}O$ and δD of a water sample along a trajectory to the left (arrow on Figure 36). It is possible that some of this evaporation occurs in the well casing where groundwater is in direct contact with the atmosphere. Samples from the riparian forest are most similar isotopically to the Teanaway River, with a similar, but slightly smaller range in isotopic composition. Samples from below the clay are isotopically lightest among the groundwater samples and have the narrowest range of isotopic compositions. Samples from the field below the clay unit appear intermediate in their isotopic composition.

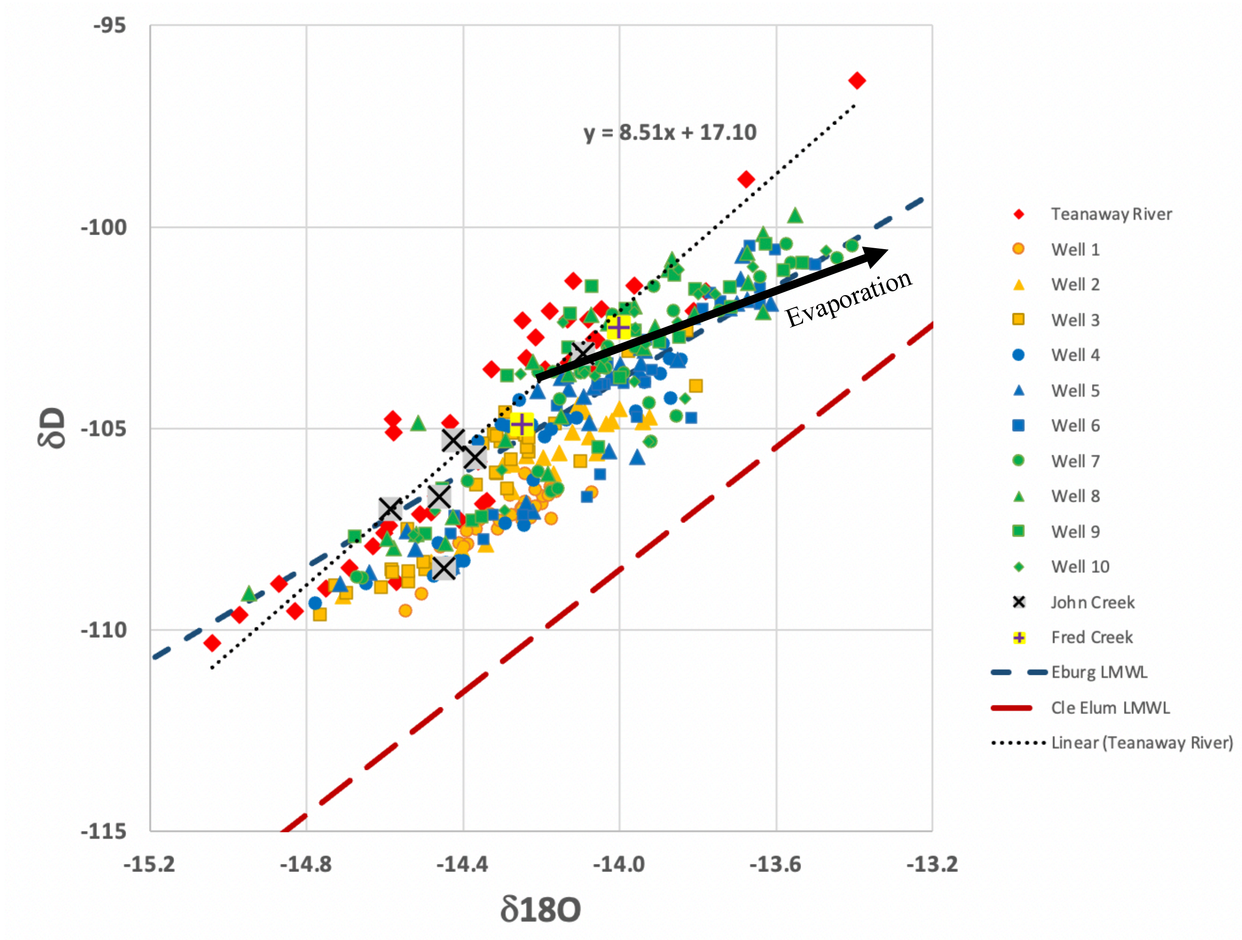

Figure 19. δD vs. δ^{18}O plot of groundwaters and Teanaway River water. Wells are divided into three groups: green = wells in riparian forest; blue = wells in cobble-rich alluvium in field; yellow = wells in clay unit. Teanaway River measurements have been fit with a line and the equation for that line is shown. Local meteoric water lines (LMWLs) are shown for Cle Elum and Ellensburg for comparison. The equations for these lines are $\delta D = 5.8\ \delta^{18}O - 22.6$ (Ellensburg) and $\delta D = 7.6\ \delta^{18}O - 2.1$ (Robertson and Gazis, 2006).

Comparison of the isotopic composition of Teanaway River water and groundwater samples through time (Figure 37) further clarify the extent of mingling between the Teanaway River water and groundwater withing the alluvial aquifer. Teanaway River water varies by more than 10 per mil with time but does not have the typical seasonal pattern of lower δD in the winter and higher δD in the summer. We interpret this to be the result of the wide range of source regions in the watershed. In particular, the West and Middle Forks of the Teanaway River drain an area that is further west than the area drained by the North Fork. Precipitation falling in the North Fork drainage is likely to be isotopically lighter than precipitation in the West and Middle Forks. Varying contributions from the different forks will lead to variability in the isotopic composition of the main stem water, which may be combined with any seasonal variation to produce the observed temporal pattern.

Figure 20. Hydrogen isotope composition of Teanaway River and TVFF groundwater with time. Teanaway River data is shown in red. A) Groundwater from wells in confined aquifers; B) Groundwater from wells in field part of alluvial aquifer; C) Groundwater from wells in riparian forest part of alluvial aquifer.

The isotopic composition of groundwater in the riparian zone aquifers closely tracks that of the Teanaway River, indicating that there is rapid exchange with the river in that area. The peaks and valleys of the trend generally occur at the same sampling time, suggesting that water exchanges in this zone over periods of days to weeks. One the other end of the spectrum, groundwater in

Wells 1 to 3 is isotopically distinct from Teanaway River water, with δD that is several per mil lower than the river water. These waters do not vary seasonally as much as the Teanaway River and their peaks and valleys do not coincide with the river trends. The water in these wells is interpreted to be a "resident" groundwater for the region, which is derived more locally from inputs from the hillslopes. Finally, Wells 4 to 6 represent a mixture of river water and resident groundwater. Comparison of timing of local maximum δD values between river water and groundwater in these wells suggests that there may be a month-long delay before the river water reaches these wells. These groundwaters mixes with river water and are influenced by pressure pulses from the river, but do not get fully replaced by river water. Mass balance calculations were used to calculate the contribution of two end members, Teanaway River water and Well 3 groundwater, to these intermediate groundwaters. They suggest that approximately 70% of the water in Well 4, 30% of the water in Well 5, and minimal water in Well 6 is derived from the hillslope (Well 3 water).

Unconfined Aquifer Volume and Potential Storage

This three-year dataset of groundwater elevation data presents a clear picture of the groundwater storage patterns and storage potential in the region. The clay on the northeastern side of the floodplain reduces that storage potential. During the three years studied, the annual patterns have been similar for all wells with some differences in the peak groundwater elevations and timing but no net increase or decrease in groundwater level during the summer baseflow period. Therefore, average flows for each day of the year were calculated for each well and for the Teanaway River. Descriptive statistics for these averaged daily groundwater elevations are given in Table 10 and the annual hydrographs themselves for Wells 1, are shown in Figures 38 and 39.

Table 10. Descriptive statistics for groundwater elevation data by well, based on daily averages from three-year period. Daily averages are derived from 15-minute data for each day.

	Groundwater Elevation - Daily Averages August 2019 to November 2022							
	mean	std dev	median	max	min	range	max date	min date
	m	m	m	m	m	m		
Well 1	649.2	0.6	649.3	650.3	648.2	2.0	4-Mar	1-Nov
Well 2	636.8	1.3	636.3	639.7	635.7	4.0	5-Mar	27-Sep
Well 3	636.7	1.5	636.2	639.8	635.2	4.6	4-Mar	12-Oct
Well 4	636.3	1.1	636.0	638.3	634.9	3.4	5-Mar	30-Aug
Well 5	636.6	0.8	636.4	638.0	635.3	2.7	5-Mar	21-Aug
Well 6	635.5	0.6	635.4	636.4	634.7	1.8	5-Mar	22-Aug
Well 7	636.9	0.7	636.7	638.0	635.8	2.2	6-Mar	22-Aug
Well 8	637.2	0.6	637.1	638.1	636.3	1.7	4-Mar	4-Aug, 21-Aug
Well 9	638.0	0.5	638.0	638.9	637.3	1.7	4-Mar	19-Aug
Well 10	638.8	0.7	638.8	640.0	637.8	2.2	4-Mar	19-Aug
Teanaway River	636.5	0.2	636.5	636.8	636.2	0.6	3-May	10-Sep

Figure 38 shows a typical hydrograph and denotes the extent of the alluvial aquifer by showing the surface elevation and the bedrock. The maximum amount of water stored in the aquifer at this location is called seasonal storage and is equivalent to the range (maximum – minimum) at that location, 2.2 meters for Well 7. If the porosity of the cobble-rich alluvium is 35%, this would equate to a 77-cm column of water at this location. If this same reasoning is applied along the transect between Well 4 and the Teanaway River and there is assumed to be a linear change between wells, a uniform thickness for the transect can be calculated with the following equation:

$$t = \frac{n * \sum(r_i * d_i)}{\sum d_i}$$

Where t is the uniform thickness over the entire transect, n is the effective porosity, r_i is the range in elevations for Well i and d is the distance between Well i and the previous well (Well i-1). The storage is assumed to end at the clay and so Well 3 is assigned a r_i of zero. This calculation results in seasonal storage equivalent to 0.76 m across the transect or 2.5 acre-ft per acre in the floodplain downgradient of the clay unit. At TVFF, approximately 50 acres of the property is in this lower floodplain, the seasonal storage for the property is approximately 125 acre-ft.

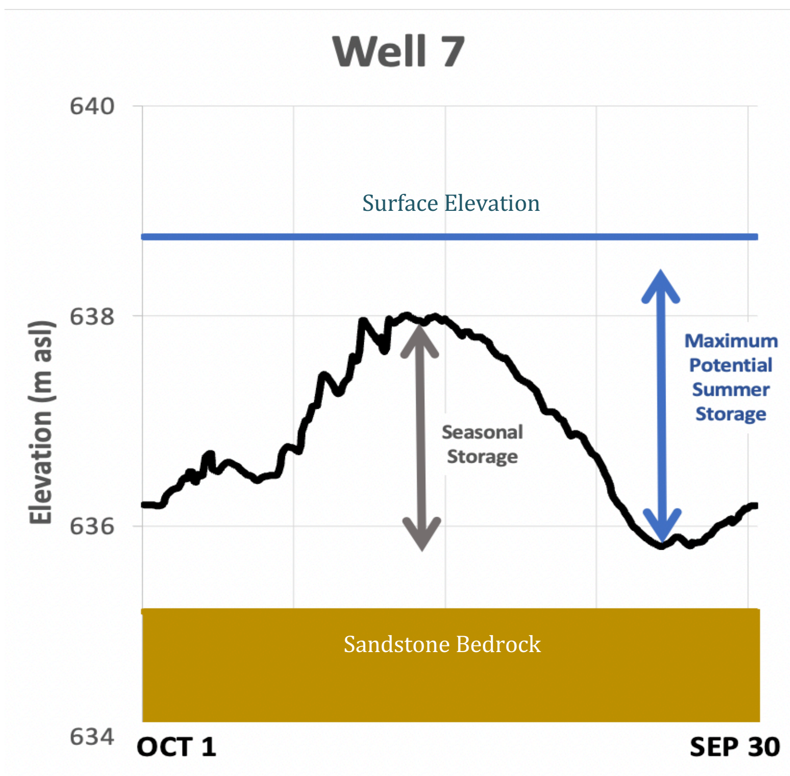

Figure 21. Typical annual hydrograph and storage regimes. The maximum saturated height of the aquifer is the distance between the surface and the sandstone bedrock. Arrows show the maximum seasonal

storage when groundwater elevations peak (grey) and the maximum potential storage that is available through unsaturated sediment at the driest time of year.

The goal of groundwater storage at TVFF would be to maintain some of this groundwater storage into the summer months and possibly even increase the storage by filling additional pore space above the maximum groundwater elevation. Figure 39 shows hydrographs for six of the wells along the transect. Well 1 is excluded because it appears to be hydraulically disconnected from the wells in the floodplain. The hydrographs in Wells 2 and 3 represent pressure changes in a confined aquifer at the base of the clay layer. Although the water level changes are large, this aquifer appears to be thin and thus does not have significant storage potential. However, the shape of the hydrograph in Well 4 suggests that there is some hydraulic connectivity between the confined aquifer and the alluvial aquifer that has shifted the hydrograph for Well 4 so that the water level declines more slowly. The time of minimum groundwater elevation for Well 4 (August 30) is approximately ten days after the minimum for most of the other alluvial aquifer wells (August 19-21).

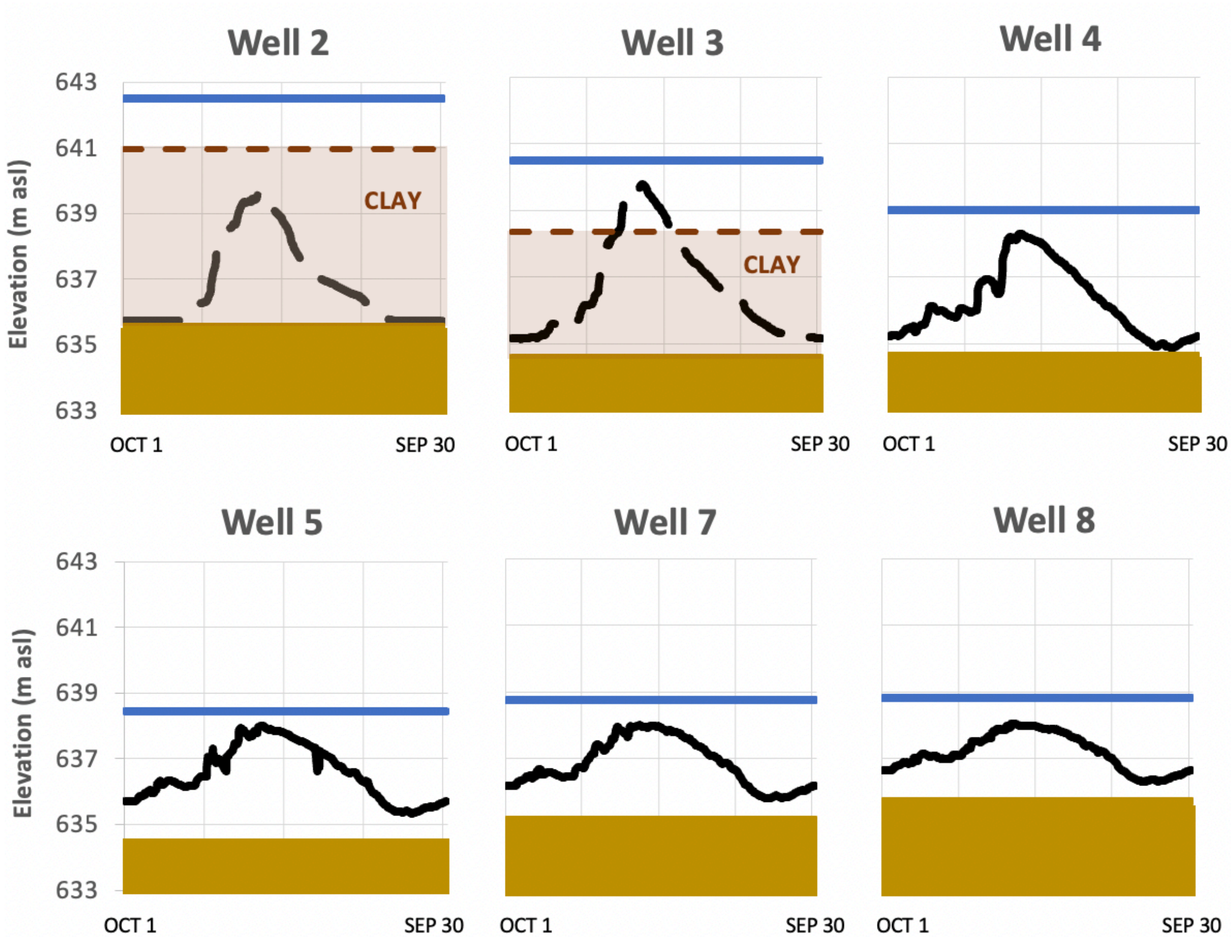

Figure 22. Hydrographs along transect from Well 1 to Teanaway River. Brown area at base of graphs is sandstone bedrock; blue line is the ground surface; black line is the average daily groundwater elevation throughout a water year. Shaded area in Well 2 and 3 graphs is are clay deposits.

The hydrographs across the transect indicate that there is ample aquifer volume that could be used for storage during the dry months. A realistic storage goal is perhaps half of the seasonal storage or about one acre-foot per acre. For the 50-acre part of the property in the lower floodplain alluvial aquifer, this amounts to an additional storage goal of 50 acre-ft. However, it is not simply a matter of putting water into the aquifer, but of preventing the rapid decrease in elevation that occurs after snowmelt inputs have ended. The permeability of the cobble-rich alluvium is extremely high. Slug tests in wells 4-10 indicate that water levels return to static level in less than 10 seconds after slug insertion or removal. This corresponds to a hydraulic conductivity of approximately 1.0×10^{-3} cm/s. The groundwater retention challenge is compounded by preferential flow paths, particularly abandoned channels and paleochannels.

CONCLUSIONS OF THE TEANAWAY VALLEY FAMILY FARM STUDY

Teanaway Valley Family Farm (TVFF) is an 87-hectare property on the floodplain on the main stem of the Teanaway River, in a reach where the river has incised into the sandstone bedrock. TVFF and the neighboring properties have been farmed for timothy hay for decades. TVFF was purchased by the Washington Department of Fish and Wildlife in 2017 and is now being restored to promote more natural function. As part of this effort, ten monitoring wells were installed at TVFF to inform the restoration process. We analyzed pressure transducer data from these monitoring well to determine groundwater storage and flow patterns. In addition, stable isotope analyses of groundwater and surface water samples were used to determine the extent to which Teanaway River water infiltrates into the floodplain.

Examination of tailings during well installation revealed that a thick and continuous clay unit dominates the northern side of the floodplain at TVFF. This unit is up to 5 meters thick, likely the remnants of a glacial lake deposit that has been eroded away by the modern river on the lower side of the floodplain. This massive unit of clay occupies a large volume that is not accessible for water storage. Although the clay is often saturated with water, it cannot transmit water at a useful rate. At TVFF, approximately 25% of the floodplain fill above the bedrock is occupied by clay, thus reducing the potential storage volume by 25%.

Groundwater elevation data from the ten monitoring wells at TVFF define three aquifers in the study area. A cobble-rich alluvial aquifer occupies the lower two-thirds of the floodplain. In the upper third of the floodplain, there is a confined aquifer below the thick clay deposit. The potentiometric surface of that aquifer is controlled by snowmelt and streamflow in the hillslopes. This floodplain confined aquifer likely provides inputs to the alluvial aquifer seasonally. Just above the floodplain, in the valley of a small tributary, John Creek, there is another confined aquifer that is recharged only by snowmelt and streamflow in the John Creek subbasin. The potentiometric surface of this John Creek aquifer is consistently over 10 m above the potentiometric surface of the confined aquifer in the upper floodplain.

Groundwater and Teanaway River elevations over a three-year period characterize an annual cycle with three hydrologic periods: 1) a period of episodic groundwater recharge in late October until early March; 2) a snowmelt period during which groundwater elevations begin to decline while river flow is sustained by snowmelt; 3) the baseflow season, when groundwater levels decline rapidly and reach their minimum as they maintain streamflow in the Teanaway River. Groundwater flow patterns at the TVFF site shift throughout these seasons. During baseflow period, flow is roughly parallel to the river. As the unconfined aquifer is recharged, groundwater collects on the northern (upper) side of the aquifer and the direction of flow is shifted towards the south and the Teanaway River. Thus, the river is more strongly gaining during and immediately after groundwater recharge.

Stable isotope data indicate that Teanaway River water dominates the alluvial aquifer closest to the river, in the area of the riparian forest. In that region, river water moves freely in and out of the aquifer on a timescale of days to weeks. Water in the upper confined aquifers is isotopically distinct from the Teanaway River water and is likely derived from local snowmelt and streamflow on the northern hillslopes. Groundwater in the alluvial aquifer closer to the hillslope, beneath the current fields, is intermediate in isotopic composition, indicating that it is likely a mixture of Teanaway River water and water from the local hillslopes and the confined aquifers.

The cobble-rich nature of the alluvial aquifer and the rapid decline of groundwater elevations at the beginning of the baseflow period indicate that this aquifer is highly transmissible and easily drained by the Teanaway River. Because it is incised, the river functionally serves as a drain during the summer months. The seasonal draining of the alluvial aquifer is further compounded by pumping from a series of ponds that are upstream of TVFF. The ponds appear to be in an abandoned channel that serves as a preferential flow path through the alluvial aquifer. Two TVFF wells downgradient of the ponds go dry in the late summer indicating that the alluvial aquifer is no longer saturated in that area. Cottonwood mortality in the riparian forest there is likely due at least in part to lack of groundwater during the late summer.

REFERENCES

Bartlett, S.P. 2022, Assessing the Effects of Instream Large Wood on Floodplain Aquifer Recharge and Storage at Indian Creek, Kittitas County, Washington, USA. M.S. Thesis, Central Washington University. https://digitalcommons.cwu.edu/etd/1735.

Boylan, N. 2019a. Assessing the Link Between Large Wood Restoration and Groundwater Storage and Recharge: An Investigation of Indian Creek in Washington State. M.S. Thesis, Oregon State Univ., 78 p. https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/5425kh699

Boylan, N. C., 2019b, Assessing the Link Between Large Wood Restoration and Groundwater Recharge and Storage: An Investigation of Indian Creek in Washington State. Report prepared for Washington Department of Ecology.

Christophersen, N., and Hooper, R. P., 1992, Multivariate analysis of stream water chemical data: The use of principal components analysis for the end-member mixing problem, *Water Resour. Res.*, 28(1), 99– 107, doi:10.1029/91WR02518.

Collins, B. D., Montgomery, D. R., Schanz, S. A., & Larsen, I. J., 2016, Rates and mechanisms of bedrock incision and strath terrace formation in a forested catchment, Cascade Range, Washington. *Bulletin of the Geological Society of America*, *128*(5–6), 926–943. https://doi.org/10.1130/B31340.1

DeKnikker, R., 2016, Teanaway Community Forest Aquatic Restoration Project 60% Design Report.

Dickerson-Lange, Susan, Abbe, Tim, 2019, Potential for Restoration of Alluvial Water Storage in the Teanaway River Watershed. The Nature Conservancy.

Eddy, M.P., Umhoefer, P.J., Miller, R.B., Donaghy, E.E., Gundersen, M., and Senes, F.I., 2017, Sedimentary, volcanic, and structural processes during triple-junction migration: Insights from the Paleogene record in central Washington: GSA Field Guides, v. 49, p. 143–173, doi:10.1130/2017.0049(07).

Emmons, J.D., 2013, Quantifying the restorable water volume of Sierran meadows: MS Thesis, University of California, Davis, 67 p. UMI Number: 1553338

Faure, G., & Mensing, T. M., 2005, *Principles and applications* (p. 897). John Wiley & Sons, Inc.

Gurnell, A.M., and Sweet, R., 1998, The distribution of large woody debris accumulations and pools in relation to woodland stream management in a small, low-gradient stream: Earth

Surface Processes and Landforms, v. 23, p. 1101–1121, doi:10.1002/(SICI)1096-9837(199812)23:12<1101::AID-ESP935>3.0.CO;2-O.

Huggenberger, P., and Aigner, T., 1999, Introduction to the special issue on aquifer-sedimentology: Problems, perspectives and modern approaches: Sedimentary Geology, v. 129, p. 179–186, doi:10.1016/S0037-0738(99)00101-3.

Jones, K.K., Anlauf-Dunn, K., Jacobsen, P.S., Strickland, M., Tennant, L., and Tippery, S.E., 2014, Effectiveness of Instream Wood Treatments to Restore Stream Complexity and Winter Rearing Habitat for Juvenile Coho Salmon: Transactions of the American Fisheries Society, v. 143, p. 334–345, doi:10.1080/00028487.2013.852623.

Nash, C.S., Grant, G.E., Selker, J.S., and Wondzell, S.M., 2020, Discussion: "Meadow Restoration Increases Baseflow and Groundwater Storage in the Sierra Nevada Mountains of California" by Luke J.H. Hunt, Julie Fair, and Maxwell Odland: Journal of the American Water Resources Association, v. 56, p. 182–185, doi:10.1111/1752-1688.12796.

Petralia, J.C., 2022, The Effects of Channel Incision and Land Use on Surface Water/Groundwater Interactions in the Teanaway River Basin, Washington, USA. M.S. Thesis, Central Washington University. https://digitalcommons.cwu.edu/etd/1780.

Richard, G., Cousin, I., Sillon, J.F., Bruand, A., and Guérif, J., 2001, Effect of compaction on the porosity of a silty soil: Influence on unsaturated hydraulic properties: European Journal of Soil Science, v. 52, p. 49–58, doi:10.1046/j.1365-2389.2001.00357.x.

Robertson J.A. and Gazis C.A., 2006, An oxygen isotope study of seasonal trends in soil water fluxes at two sites along a climate gradient in Washington state (USA). Journal of Hydrology, v. 328: p. 375-387.

Sawyer, A.H., and Cardenas, M.B., 2012, Effect of experimental wood addition on hyporheic exchange and thermal dynamics in a losing meadow stream: Water Resources Research, v. 48, p. 1–11, doi:10.1029/2011WR011776.

Schwartz, F. W., & Zhang, H., 2003, Fundamentals of Groundwater John Wiley & Sons. New York, 583.

Scott, D.N., Wohl, E., and Yochum, S.E., 2019, Wood Jam Dynamics Database and Assessment Model (WooDDAM): A framework to measure and understand wood jam characteristics and dynamics: River Research and Applications, p. 1–12, doi:10.1002/rra.3481.

Scott, M. L., Shafroth, P. B., & Auble, G. T., 1999. Responses of riparian cottonwoods to alluvial water table declines. *Environmental Management*, *23*(3), 347-358.

Schanz, S.A., Montgomery, D.R., and Collins, B.D., 2019, Anthropogenic strath terrace formation caused by reduced sediment retention: Proceedings of the National Academy of Sciences, f. 116, no. 18, p. 8734-8739. doi/10.1073/pnas.1814627116.

Sleeper, S., 2020, A Geochemical Assessment of Potential Groundwater Storage Locations within the Yakima River Basin. M.S. Thesis, Central Washington University. https://digitalcommons.cwu.edu/etd/1372/.

Spreitzer, G., Tunnicliffe, J., and Friedrich, H., 2020, Large wood (LW) 3D accumulation mapping and assessment using structure for motion photogrammetry in the laboratory: Journal of Hydrology, v. 581, p. 124430

Tabor, R.W., Frizzell, V.A., Vance, J.A., and Naeser, C.W., 1984, Ages and stratigraphy of lower and middle Tertiary sedimentary and volcanic rocks of the central Cascades, Washington: application to the tectonic history of the Straight Creek fault, USA: Geological Society of America Bulletin, v. 95, p. 26–44, doi:10.1130/0016-7606(1984)95<26:AASOLA>2.0.CO;2.

Tabor, R.W., Waitt, R.B., Frizzell, V.A., Swanson, D.A., Byerly, G.R., and Bentley, R.D., 1982, Geologic Map of the Wenatchee 1:100,000 Quadrangle, Central Washington: U.S. Geological Survey Miscellaneous Investigations Series Map 1-1311, 42 p.

Tague, C., Valentine, S., and Kotchen, M., 2008, Effect of geomorphic channel restoration on streamflow and groundwater in a snowmelt-dominated watershed: Water Resources Research, v. 44, p. 1–10, doi:10.1029/2007WR006418.

Taylor S., and Gazis C., 2014, A geochemical study of the impact of irrigation on groundwater in the Upper Yakima River Basin, Washington, USA. Environmental Geology, v. 72: p. 1569-1587.

U.S. Bureau of Reclamation., 2012, Yakima River Basin Integrated Water Resource Management Plan: Framework for Implementation Report (Issue October). https://www.usbr.gov/pn/programs/yrbwep/2011integratedplan/plan/framework.pdf

Washington Ecology, 2023, Washington State Department of Ecology Freshwater Datastream, Teanaway R. @ Red Bridge Rd. Station Data, accessed April, 2023. https://apps.ecology.wa.gov/continuousflowandwq/StationDetails?sta=39D110

Weather Underground, 2023, East Wenatchee, WA Weather History: Pangborn Memorial Airport Station, https://www.wunderground.com/history/monthly/us/wa/wenatchee/KEAT/date/2019-10, accessed March, 2023.

Wohl, E., 2014, A legacy of absence: Wood removal in US rivers: Progress in Physical Geography, v. 38, p. 637–663, doi:10.1177/0309133314548091.

Wohl, E., 2013, Floodplains and wood: Earth-Science Reviews, v. 123, p. 194–212, doi:10.1016/j.earscirev.2013.04.009.

Wohl, E., Lininger, K. B., Fox, M., Baillie, B. R., & Erskine, W. D., 2017, Instream large wood loads across bioclimatic regions. *Forest Ecology and Management*, *404*(May), 370–380. https://doi.org/10.1016/j.foreco.2017.09.013