AN ABSTRACT OF THE THESIS OF

Nora Boylan for the degree of Master of Science in Water Resources Science presented on August 13, 2019.

Title: Assessing the Link Between Large Wood Restoration and Groundwater Storage and Recharge: An Investigation of Indian Creek in Washington State

Abstract approved: ____

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With decreasing snowpacks and changing precipitation patterns, Washington State seeks ways to conserve, protect, and enhance its water supply. Stream restoration has been viewed as a means to utilize alluvial aquifers for groundwater storage and augment late-season streamflow. However, the relationship between stream restoration and groundwater dynamics is still under investigation. Starting in 2014, several partners including the Washington Department of Ecology (Ecology), Washington Department of Fish and Wildlife (WDFW), the Department of Natural Resources (DNR), the Yakama Nation (YN) and the Kittitas Conservation Trust (KCT) began work to restore Indian Creek, a small tributary of the Teanaway River in central Washington. These partners utilized the method of large wood restoration, or the placement of logs within the stream and across the floodplain, to form pools to enhance fish spawning, promote stream velocity heterogeneity, establish riparian vegetation, and increase groundwater storage and late-season baseflow. However, since wood installation little work has been done to investigate if these restoration goals have been reached.

This study sought to better characterize the Indian Creek alluvial aquifer and discern if any measurable changes in the groundwater dynamics have occurred since stream restoration. Ongoing monitoring occurred on a 1.2-mile reach of Indian Creek equipped with seven piezometers, four of which have been collecting data since 2014 and three of which were installed in October 2018. The newly installed piezometers, as well as slug tests, were used to better characterize aquifer properties. Water level data from the piezometers determined if there were any notable temporal and spatial patterns in the groundwater system that could be associated with stream restoration. The resulting analysis showed little change in water table elevation and groundwater baseflow. There was some increase in groundwater storage volume, but this is likely attributable to other processes and the geologic characteristics of the aquifer. Although the results provide minimal evidence that there are any measurable impacts from stream restoration on groundwater dynamics at Indian Creek, this study provides a strong foundation for continued investigation. Additional monitoring and further analyses are needed to draw a stronger conclusion about the impacts of stream restoration on this particular alluvial aquifer.

Assessing the Link Between Large Wood Restoration and Groundwater Storage and Recharge: An Investigation of Indian Creek in Washington State

by
Nora Boylan

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Director of the Water Resources Graduate Program

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Nora Boylan, Author

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1. Introduction

1.1 Overview and Problem Statement

Land use, including railroads, logging activities and over-grazing, within the Indian Creek Watershed has resulted in an incised stream and disconnected floodplain. These conditions have affected fish and wildlife, groundwater recharge, and downstream water users. Starting in 2014, several partners including the Washington Department of Ecology (Ecology), Washington Department of Fish and Wildlife (WDFW), the Department of Natural Resources (DNR), the Yakama Nation (YN) and the Kittitas Conservation Trust (KCT) began work on restoring Indian Creek. The goals of their restoration efforts were to improve fish habitat for bull trout and summer steelhead, flood the adjacent floodplain meadows, and increase groundwater storage throughout the treated area (S. Nicolai, Personal Communication, August 1, 2018). The partners, led by the YN, decided to use the method of large wood restoration, or the placement of logs within the stream and across the floodplain, to emulate the natural conditions of wood historically found in streams (Roni et al., 2014). The wood placement was anticipated to help form pools for fish spawning, promote stream velocity heterogeneity, increase overhead stream cover, and provide substrate for macroinvertebrates (Roni et al., 2014). The partners hoped that these benefits would improve the overall health and function of Indian Creek. Since 2014, 80 acres of floodplain within the Indian Creek Watershed have been treated with large wood (S. Nicolai, Personal Communication, December 21, 2018). The partners worked together to install four piezometers and three stream gages across a 1.2-mile section of Indian Creek. This launched an anticipated five- to ten-year investigation into the reaction of the stream and its surrounding aquifer. Data collection and monitoring have been ongoing since then, however, little analysis has been done with the historical data.

One of the original goals behind the large wood restoration at Indian Creek was to increase groundwater storage. Large wood is hypothesized to help flood the adjacent meadows and deposit sediments to ultimately raise both the streambed elevation and the water table (Ramstead et al., 2012). Since Indian Creek is surrounded by an alluvial aquifer, a higher water table would allow for more subsurface water storage. With increased subsurface storage, flow is hypothesized to increase during low-flow periods because the surrounding alluvial aquifer will discharge groundwater to the stream, therefore preventing current consequences of late season low-flows (Hammersmark et al., 2008). Due to the presence of historical data, the location of the site, and the many partners involved, Indian Creek Watershed provides an opportunity to investigate the potential impacts stream restoration has on groundwater dynamics. The overall goals of this project are to better characterize the Indian Creek alluvial aquifer, to observe any recent changes across the groundwater system since large wood restoration, and to establish a strong baseline study for future work at Indian Creek.

1.2 Study Area

Indian Creek Watershed spans 6 square miles and is located within the Upper Yakima Basin in Upper Kittitas County, Washington (Figure 1). Upper Kittitas County encompasses a vast area of wilderness within the Cascade Range, with elevations ranging from 1,730 to 7,960 feet (Gendaszek et al., 2014). Indian Creek Watershed is underlain by late Eocene Roslyn Formation, composed of feldspathic sandstone and carbonaceous shales. Younger, unconsolidated materials sit atop the bedrock, consisting of both glacial and non-glacial sediments (Gendaszek et al., 2014). No well logs within Indian Creek Watershed exist to provide a more robust estimate of the hydrogeologic units of the area.

Temperatures vary with topography across the area but have an average of 20 degrees Fahrenheit in the winter and 80 degrees Fahrenheit in the summer. The area experiences an average of 80 inches of precipitation a year, with most of that occurring as snow, and even higher precipitation amounts occurring in high elevations (Gendaszek et al., 2014).

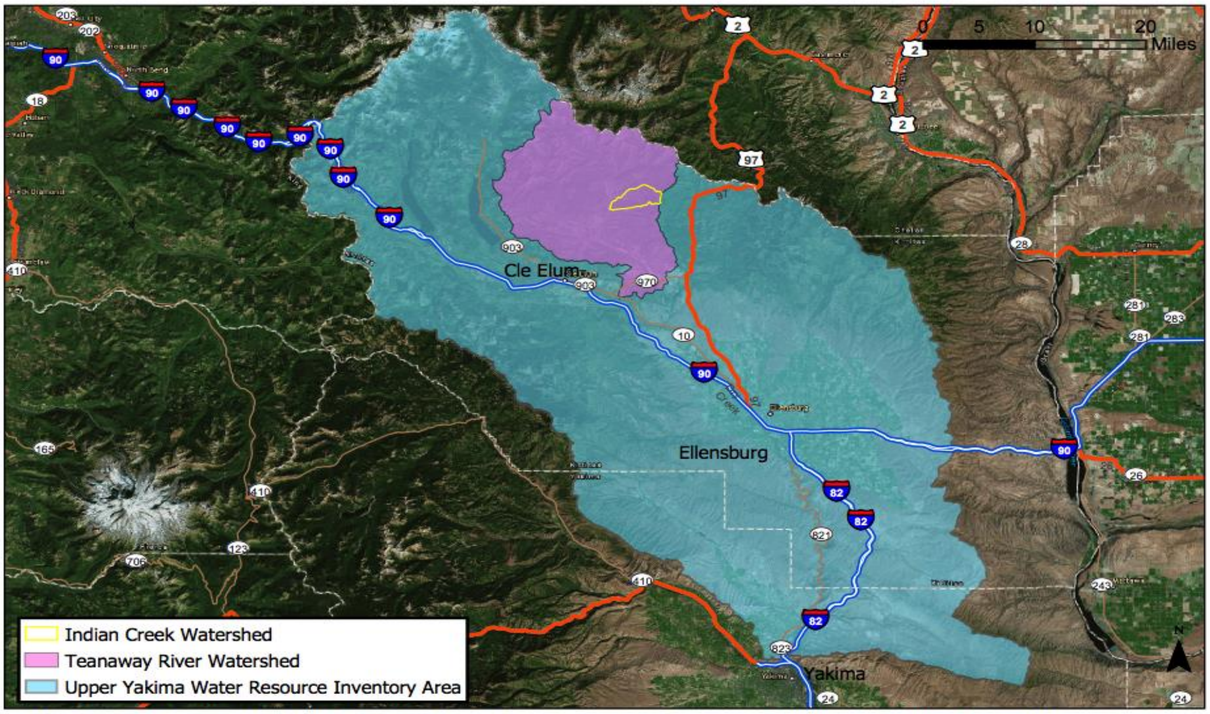

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Figure 1: Location of Indian Creek Watershed in relation to the Teanaway River Watershed, the Upper Yakima Water Resource Inventory Area (WRIA), population centers and highways.

On a smaller scale, the Indian Creek watershed is within the Teanaway Community Forest. The community forest encompasses most of the Teanaway River, a major tributary of the Yakima River. Both rivers are imperative sources of water for the Yakima Basin, an area that has historically battled water supply issues.

The Teanaway Community Forest is Washington State's first state-owned community forest and encompasses 50,241 acres, including nearly 400 miles of free-flowing streams (DNR and WDFW, 2015). The formation of the Teanaway Community Forest was one of the initiatives of the Yakima Basin Integrated Plan (YBIP). The YBIP is a collaborative and comprehensive plan to approach the Yakima Basin's water resource problems to ensure that people, farms, and fish have sustainable access to water throughout the basin (Sleeper and Perkins, 2018). In 2013, the YBIP began focusing on seven key elements of water resources: (1) structural and operational changes; (2) reservoir fish passage; (3) surface water storage; (4) groundwater storage; (5) market reallocation; (6) habitat/watershed protection and enhancement; and (7) enhanced water conservation. The formation of the Teanaway, and the subsequent Teanaway

Community Forest Management plan published in 2015, support the YBIP. Specifically, one of the goals of the Teanaway Community Forest Management plan is to protect and enhance the watersheds throughout the forest (DNR and WDFW, 2015) and therefore greatly align with the aforementioned goals of the YBIP.

Both the YBIP and the Teanaway Community Forest Management Plan emphasize the importance of groundwater storage and watershed protection. Streams like Indian Creek, which require restoration work to return to natural conditions, are excellent candidates for projects aligned with these goals. Therefore, beginning in 2014, large wood restoration and ongoing monitoring began on a 1.2-mile stretch of Indian Creek.

The section of Indian Creek where ongoing monitoring has taken place is composed of eight investigation transects from river mile (RM) 00.2- to RM 01.4. Four piezometers (MP-1 through MP-4) were previously installed near Transect 2 (T2) and Transect 8 (T8) and have been collecting water level data since 2014. Three additional piezometers (MP-5 through MP-7) were installed in October 2018 by Nora Boylan and have been collecting water levels since then. Figure 2 outlines the location of the piezometers, as well as two stream gages previously installed by WDFW.

1.3 Background and Significance

Alluvial aquifers have long been an important area of study in hydrology due to their unique geologic characteristics and how they interact with surface water. However, with a changing climate there has been renewed interest in alluvial aquifers as a means of water storage in a catchment (Kaser and Hunkeler, 2016). Their normally high hydraulic conductivity and porosity, coupled with their hydraulic connection to streams, has made alluvial aquifers a strong candidate for the emerging concept of managed aquifer recharge. Water resource managers

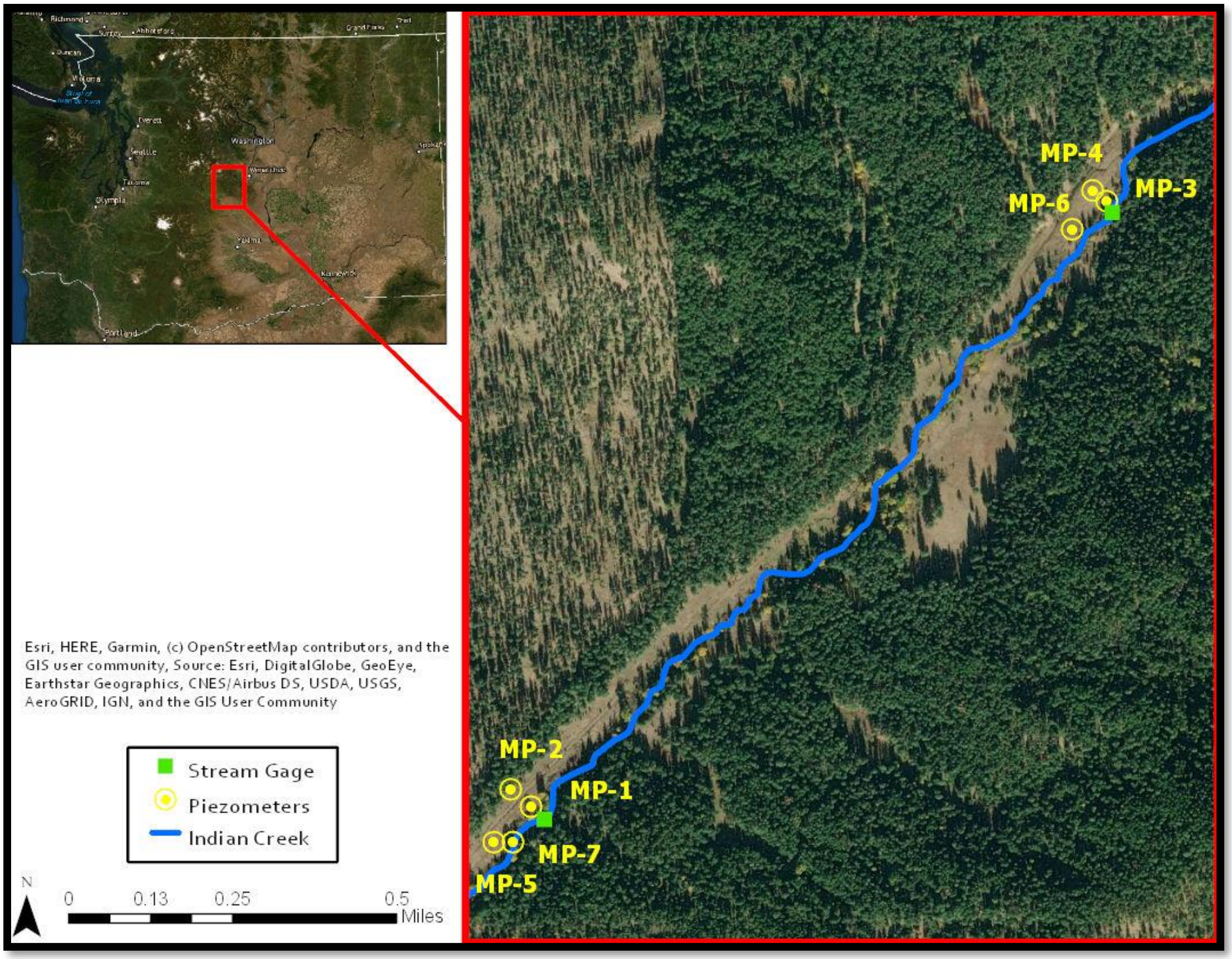

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Figure 2: Indian Creek study area location with piezometers and stream gages.

are turning to alluvial aquifer storage as a potential way to increase baseflow, store water during times of high-flow, and even contribute to late season flows to ensure both ecological and biological function of stream systems (Kaser and Hunkeler, 2016; Larkin and Sharp, 1992; Ciruzzi and Lowry, 2017). However, Kaser and Hunkeler (2016) raise the important question as to whether alluvial aquifers can actually be considered a storage unit or if they are merely a transition zone between floodplain and streams. In other words, can these systems store enough water during times of high-flow to contribute significantly to total outflow?

This question has led many to focus specifically on alluvial aquifers across montane meadows. These meadows are generally groundwater-dependent ecosystems that are low-gradient with shallow depths to water (Nash et al., 2018; Ciruzzi and Lowry, 2017). They provide groundwater to important ecologic communities and can potentially contribute significantly to baseflows (Fryoff-Hung and Viers, 2013). Recharge across these meadows is generally snow-melt dominated and transported via a network of small streams to downstream users (Ciruzzi and Lowry, 2017; Nash et al., 2018). This natural process of alluvial aquifers within montane meadows recharging and then releasing water to streams to enhance late-season flows (see Figure 3) has sparked an interest in scientists and land managers alike, hoping to use this process to better manage local water resources.

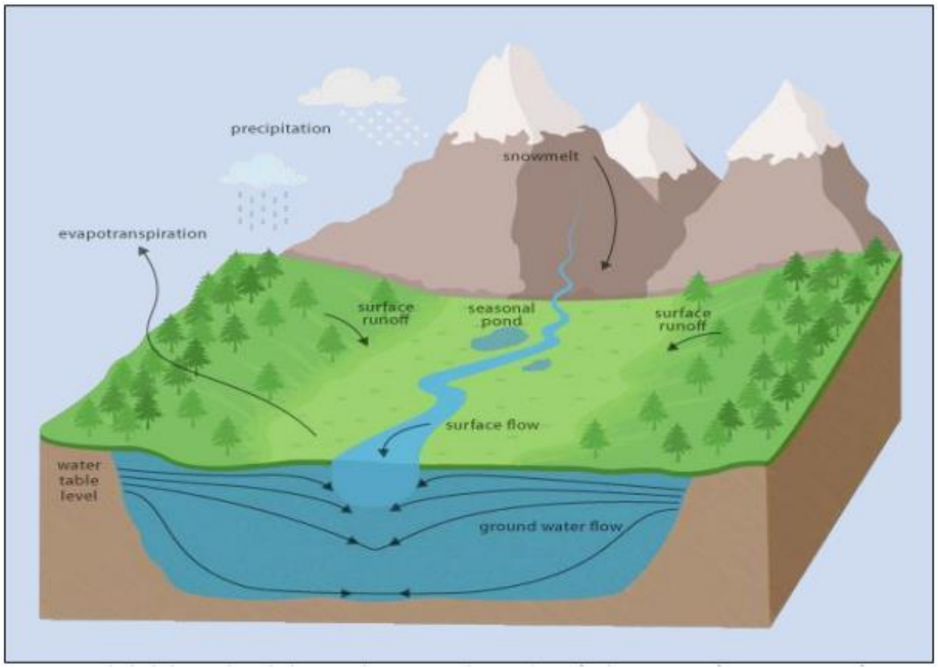


Figure 3: Hydrologic processes within a montane meadow from Viers et al. (2013)

Most of the work surrounding these unique environments has been done in the meadows of the Sierra Nevada in Northern California. This includes research surrounding montane meadow vegetation (Loheide and Gorelick, 2007), erosion patterns (Fryoff-Hung and Views, 2013), and vulnerability to climate change (Viers et al, 2013). Additionally, in the past decade there has been an increase in studies surrounding wet meadow restoration. Land use in these areas has led many montane meadows to become degraded, losing much of their ecological and hydrological benefits. Anthropogenic factors, such as grazing or the construction of roads and railways, have caused stream incision and therefore decreased hydrologic connectivity of the meadows. This can lead to decreasing groundwater levels, extreme erosion, and a loss of riparian vegetation (Viers et al, 2013). Therefore, attention has turned towards restoring these montane meadows to improve overall biologic and ecologic function of the system.

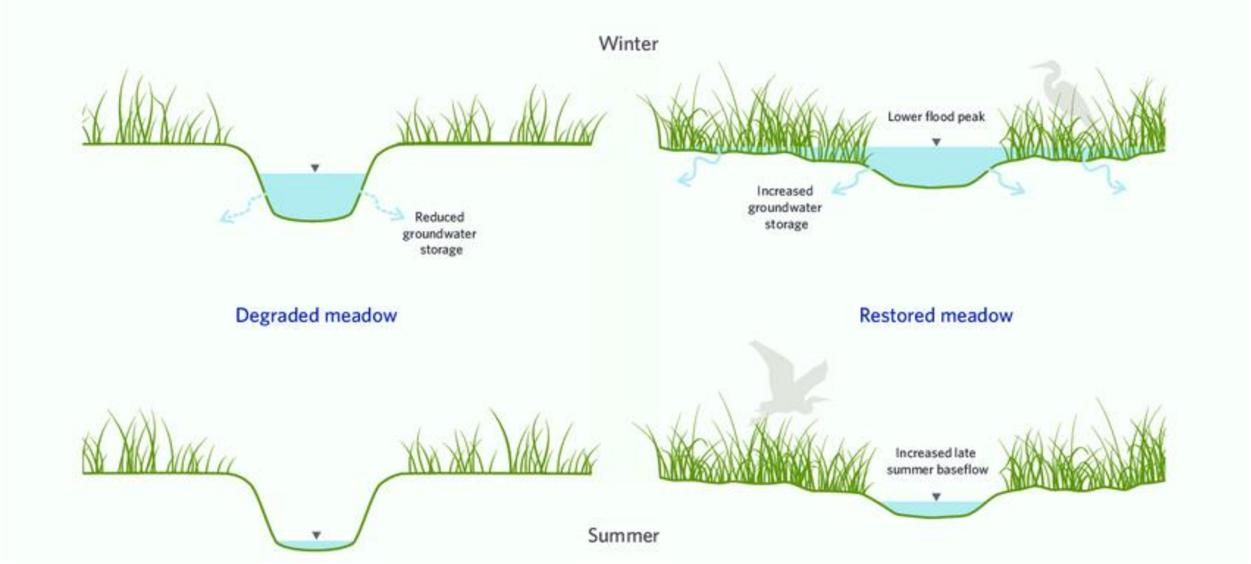


Figure 4: Diagram of wet meadow restoration and its potential impact on hydrologic interactions (Podolak et al., 2015).

Specifically, a common goal behind many of these restoration projects is to restore hydrological processes that may contribute to enhanced groundwater storage across the meadow. The idea driving these projects is that as restoration, specifically stream restoration, raises the channel bed, the depth to groundwater will decrease resulting in a larger volume of water stored in the surrounding aquifer (Nash et al., 2018; Hammersmark et al., 2008). This will occur during times of high-flow in the stream after snowmelt. Then as the stream enters times of low-flow, this volume of stored water will be released into the stream leading to augmented late-season flows that have ecological and biological benefits (Figure 4) (Loheide and Gorelick, 2007; Tague et al., 2008; Hammersmark et al., 2008). This underlying concept, however, has been debated in the literature with many arguing that there is not enough scientific evidence to link these groundwater processes to stream restoration. Below are several studies that have focused on this question but has shown varying results.

Tague et al. (2007) is one of the few studies that relies on pre- and post-restoration measurements to draw a concrete conclusion. They used a series of monitoring wells and stream gages to investigate the pre-restoration and post-restoration hydrology of a creek near Lake Tahoe. Their results showed that although there was a conclusive increase in groundwater elevation after stream restoration, there was no specific relationship between increased groundwater elevation and streamflow (Tague et al., 2007). They conclude that although an increased groundwater elevation may have other ecological and hydrological benefits, the overall argument that stream restoration allows for alluvial aquifers to act as storage units to increase late-season flows is flawed (Tague et al., 2007).

Another study compared a restored and a degraded reach along a creek in Northwest Montana. Data from piezometers and stream gages, along with isotope sampling, concluded that the restored reach had increased early-season storage, therefore allowing for higher volumetric flows during the low-flow season (Brissette, 2017). Brissette (2017) used ^{222}Radon to model baseflow discharge and compared these results to lateral groundwater gradients. This analysis showed that in the degraded part of the creek, groundwater moved quickly into the stream and little water was stored throughout the aquifer. However, in the restored reach, Brissette (2017) found lower early-season inflows from groundwater coupled with a more gradual decline in the surrounding aquifer's discharge during baseflow recession (Brissette, 2017). Despite these results, Brissette (2017) also emphasizes the importance of outside factors, such as precipitation, topography and lithology, and their impact on aquifer storage and inflows to streams. This is an important distinction, urging for more studies on varied landscapes and in different climates to determine whether this process of increased storage and late-season flows is a definitive benefit of stream restoration (Brissette, 2017).

Different from the above studies, Nash et al. (2018) argued that although stream restoration can increase total water storage it does not ultimately result in increased late-season flows. Nash et al. (2018) used a water budget analysis coupled with a physically based model of three different incision-depth scenarios. The less incised streams showed larger volumes of total aquifer storage, however, lateral drainage to the stream was less compared to the more incised scenarios (Nash et al., 2018). It was argued that this is because the hydraulic gradient decreases with restored channels, therefore decreasing the amount and rate of groundwater flowing into the stream. Additionally, the authors noted that increasing the elevation of the water table can increase both riparian vegetation and evapotranspiration rates, therefore resulting in less water being available for baseflow (Nash et al., 2018). Although they conclude that stream restoration should not be expected to increase late-season flows, they too push for additional studies in varying climates and geographic locations (Nash et al., 2018).

Even with the varying results many states throughout the United States have invested large amounts of money into stream restoration hoping they may see some of the positive hydrologic benefits. One of the most commonly deployed methods of stream restoration is that of large wood restoration. For decades, humans worked to remove wood from streams only to discover that this likely disrupted their natural hydrologic complexity. Therefore, beginning as far back as the 1890s, people started replacing wood in streams to restore this complexity and ultimately improve fish habitat (Roni et al., 2014). The hope was that wood in streams would encourage sediment buildup, the formation of side channels and even the formation deep pools suitable for fish spawning (Montgomery et al., 1996; Beechie and Sibley, 1997). Large wood restoration can range from simply placing riparian woody vegetation into the stream, to building highly engineered structures in pre-determined locations. The specific location and goals behind individual restoration projects help dictate the best method of large wood restoration (Roni et al., 2014). However, despite the popularity of this restoration method, there is some debate about its measurable impacts, specifically those surrounding the aforementioned idea of groundwater storage.

Partners of the YBIP have invested a significant amount of time and money into large wood restoration projects, and Indian Creek is an excellent opportunity to study the success of these projects on a microscale. Specifically, there is an opportunity to investigate the groundwater dynamics, and whether the restoration efforts in this specific montane meadow are seeing the anticipated improvements in groundwater storage. Clearly, the literature is vast, and conclusions contradict one another. This study aims to use pre-existing and newly collected field data to contribute to these existing case studies with the hopes of improving conclusions surrounding these types of projects and ultimately aid Washington State in future restoration and storage efforts.

1.4 Project Objectives

The primary objects if the Indian Creek Groundwater Dynamics Investigation are as follows:

1. Determine aquifer properties between RM 00.2 to RM 01.4 on Indian Creek
2. Assess changes in groundwater levels and groundwater gradients since stream restoration in Indian Creek from RM 00.2 to RM 01.4.
3. Calculate total potential storage of the alluvial aquifer from RM 00.2 to RM 01.4 and determine how it is changing with time since restoration

Together, these objectives will lead to an understanding of how groundwater reacts to wood placement within the area, and possibly provide insight into the potential reaction of stream restoration in other aquifers in the Yakima Basin. This study will aid the YBIP in water resource and ecosystem protection.

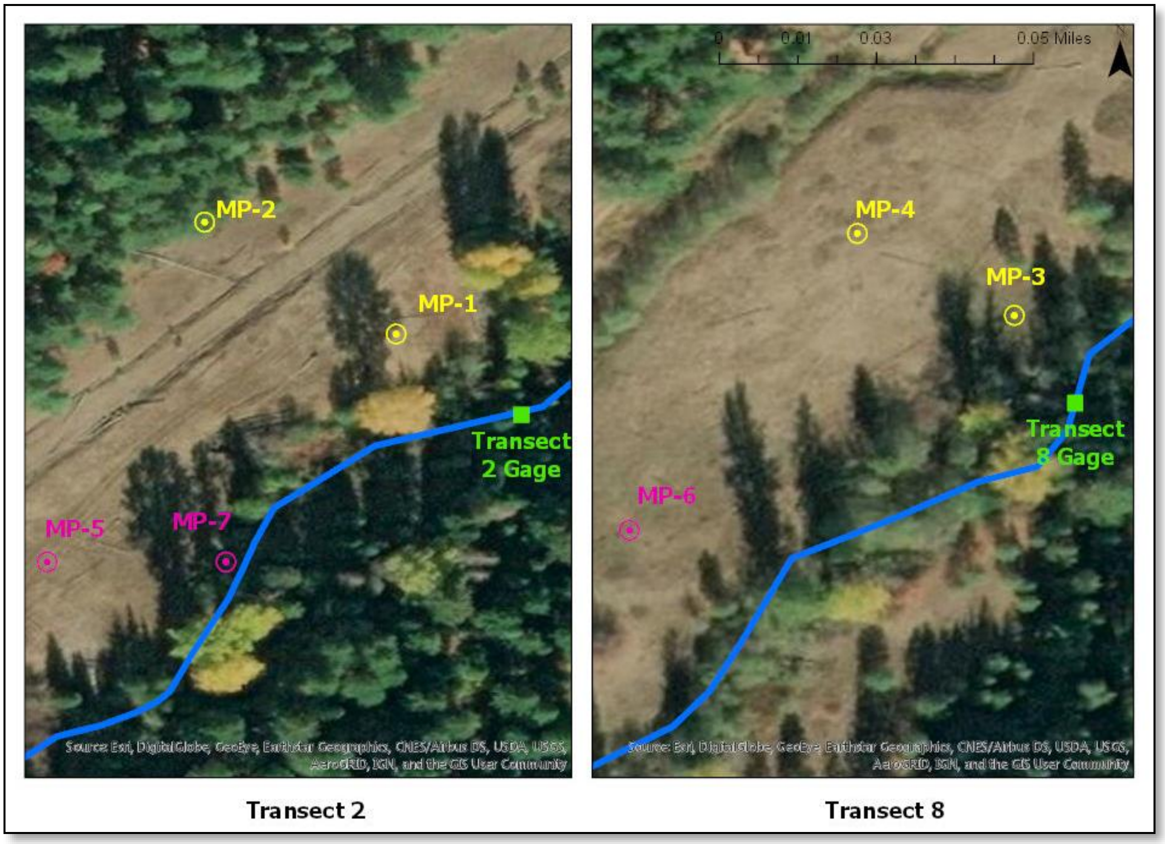
2. Methods

2.1 Field Methods

2.1.1 Piezometer Installation

The Indian Creek site was previously equipped with four monitoring piezometers that have been recording water level data since 2014. These piezometers were installed on two separate transects, Transect 8 (T8), an upstream transect, and Transect 2 (T2), a downstream transect. Two piezometers were installed on each transect in line with one another and perpendicular to the stream (see Figure 5). These piezometers are MP-1, MP-2, MP-3 and MP-4. The installation was done by Ecology, WDFW and KCT.

To better determine the groundwater flow direction, three additional piezometers were installed in October 2018. The installation locations for the three new piezometers were determined specifically to use a three-point triangulation method to determine the flow direction. Therefore, the additional piezometers were installed downstream and midway between the two existing piezometers. On T8 one additional piezometer, MP-6, was installed 245 feet downstream from the original piezometers (MP-3 and MP-4) and midway between the two. The same was done on T2, with a piezometer, MP-5, installed 280 feet downstream from MP-1 and MP-2. An additional piezometer, MP-7, was installed on T2 in line with MP-5 to aid in future storage calculations along that part of the stream. All piezometer locations are shown in Figure 5.



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Transect 2

Transect 8

Figure 5: Piezometer locations at T2 and T8. Piezometers installed by KCT, Ecology and WDFW are in yellow and the new piezometers installed in October 2018 are in pink.

The new piezometers (MP-5, MP-6 and MP-7) were installed by augering a hole and placing PVC pipe within the hole. The holes were dug using a 2 ¾” Signature Regular Auger by AMS Inc. If resistance was met within 3 feet below ground surface (bgs), then the hole was side-stepped and augering began again from the surface at the new location. This occurred occasionally due to boulders within the alluvial substrate. Past 4 feet bgs the holes were augered until once again met with resistance at which point the hole was considered complete. General soil composition notes were taken during this process.

Next, the PVC was installed. Prior to field work, 5-feet long sections of 1 ½” OD Schedule 40 PVC were measured. For three of these sections, ⅛” diameter holes were drilled in the bottom one foot of the PVC. This was to mimic a well screen and allow water to flow freely through the PVC pipe. The bottom of each piece of PVC was capped.

Once a hole was at maximum depth the PVC was placed in the hole. If the hole was deeper than 5 feet additional pieces of PVC were attached so that there were at least 6 inches of PVC extending above ground surface. Then, using a fence post-driver, the PVC was pounded farther into the ground until it was secured in the hole. Each hole was then backfilled if necessary and each piezometer was equipped with a Torquer locking well plug. See Figure 6 for a schematic of the piezometers installed in October 2018.

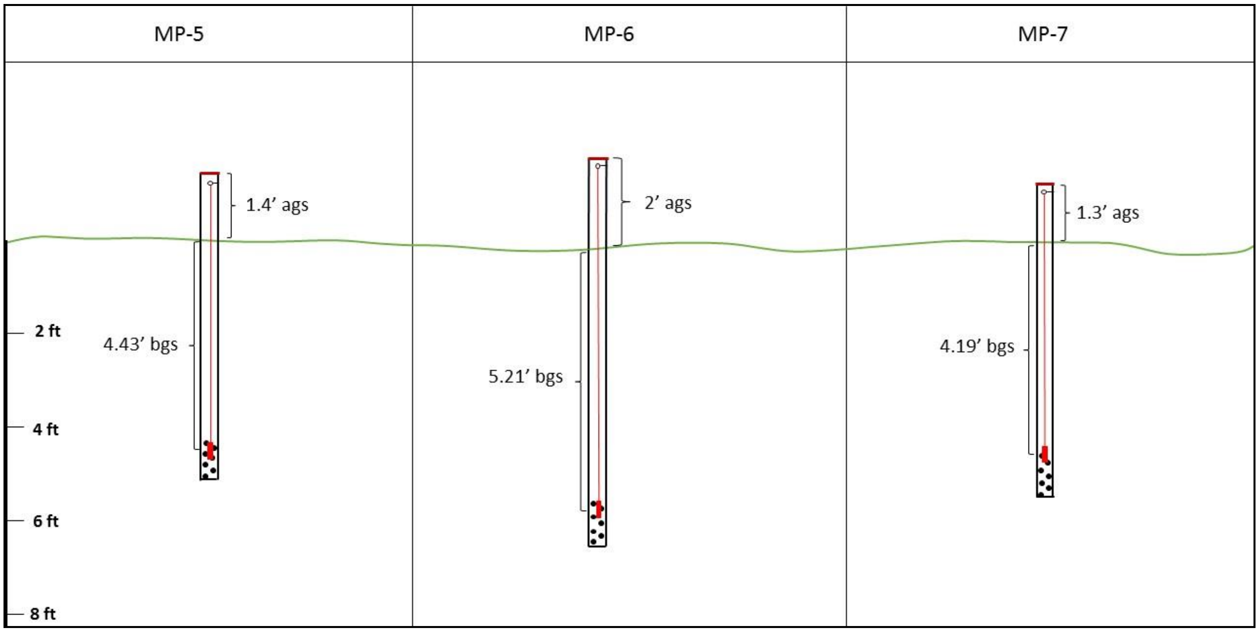


Figure 6: Schematic of piezometers installed in fall 2018. Depths of transducers shown bgs and height of piezometer shown above ground surface (ags).

2.1.2 Piezometer Development

All 7 of the piezometers on the study reach were developed to ensure that they were clear of sediment buildup and that water was freely flowing through the screen. There are several different methods of well development, but here a simple "surge and purge" method was used. First, each piezometer was surged using a wooden rod smaller than the inner diameter (½" used for the MP-1 through MP-4 and 1" used for MP-5 through MP-7). The wooden rod was pulled up and pushed down several times in order to stir up any sediment. A peristaltic pump was then used to pump out the water and sediment in the piezometer. Each piezometer was pumped until the water coming up ran clear, or until the piezometer was dry. On most of the wells, water returned to its original depth and the process was repeated several times until the water purged clear, indicating that water was flowing through the piezometer screen.

2.1.3 Slug Tests

Slug tests were performed in each piezometer to determine the hydraulic conductivity of the surrounding aquifer. Generally, in a slug test, the water level in a well is changed rapidly and then its response is monitored against time. In this study, to change the water level rapidly, additional water was poured into the piezometer until it reached the top of the casing. A water level meter (Solinst 102 E-Tape) was then used to record the rate at which the water level dropped back to its original depth. Once back to its original water level the slug test was repeated to ensure accuracy of measurements.

A series of successful slug tests were performed at MP-2, MP-4 and MP-5 (see Appendix A for slug test data). MP-1 and MP-7 were both dry during the time of slug tests and therefore were unable to be tested. Both MP-3 and MP-6 failed to return to their original water level after the first slug test and therefore only one slug test was performed at each.

2.1.4 Transducer Data Collection

All seven piezometers were equipped with pressure transducers that automatically collected data whilst deployed. MP-1, MP-2, MP-3 and MP-4 were equipped with vanEssen Micro-Divers in 2014 by KCT and Ecology. These transducers were secured to the top of the well caps via a steel cable and installed at a depth within the screen for each piezometer. The depths of installation can be seen in Table 1. Each transducer recorded pressure measurements at fifteen-minute intervals. Data from these transducers were retrieved annually by an individual from KCT. Throughout the five years of collection there were some data quality issues. At times the transducer cables were moved and therefore the transducers were not collecting accurate data. Therefore, when looking at the data from these transducers, any water levels deeper than the depth of the well or shallower than ground surface were removed from the data set. Additional review of the data deleted any remaining outliers from the data set.

KCT and Ecology also deployed a barometer on T8 to record atmospheric pressure. This was used to compensate the pressure measurements in the piezometers and produce water level measurements in feet.

MP-5, MP-6 and MP-7 were all originally outfitted with MadgeTech Level1000s on October 26, 2018. These transducers were secured with eye bolts installed on the side of each piezometer 1" down from the top. Transducers were then attached to the eye bolts with braided nylon rope. The depths of installation can be seen in Table 1. Each transducer recorded pressure measurements at a fifteen-minute interval and pressure data were compensated with the previously deployed barometer. Data were retrieved from these transducers by Nora Boylan in November 2018, April 2019, May 2019, and June 2019. Data were not retrieved during the winter months due to snow accumulation limiting access to the piezometers.

Upon data retrieval in April 2019 it became apparent that the Level1000 in MP-6 had stopped working. Therefore, upon the next site visit (May 2019), a new transducer was installed using the same installation methodology and data collection intervals as previously stated. This transducer is a HOBO U20 Water Level Logger. This logger was used for the remaining data collection period.

2.1.5 Manual Water Level Measurements

Manual water levels were measured during each site visit. Water levels were taken using a Solinst 102 E-Tape. Measurements were taken in reference to a designated measuring point on each piezometer to ensure accuracy.

Piezometer ID	Type	Latitude	Longitude	Piezometer Depth (ft bgs)	Transducer Depth (ft bgs)
MP-1	¾” OD Steel	47.30491 N	120.84885 W	5.52	5.42
MP-2	¾” OD Steel	47.30517 N	120.84930 W	8.38	8.02
MP-3	¾” OD Steel	47.31395 N	120.83617 W	6.63	5.92
MP-4	1.25” OD Sch. 40 PVC	47.31411 N	120.83648 W	9.10	8.88
MP-5	1.25” OD Sch. 40 PVC	47.30438 N	120.84967 W	4.97	4.43
MP-6	1.25” OD Sch. 40 PVC	47.31353 N	120.83693 W	6.29	5.21
MP-7	1.25” OD Sch. 40 PVC	47.30438 N	120.84925 W	5.04	4.19

Table 1: Piezometer specifications

2.2 Analytical Methods

2.2.1 Water Levels

Water levels were calculated for each piezometer with the pressure data collected from the transducers and the barometer. For MP-1 through MP-4 (those equipped with the MicroDiver), barometric compensation was performed by the associated software, DiverOffice. It was then spot-checked against compensations done by hand for accuracy. For MP-5, MP-6 and MP-7 barometric compensation was done in Microsoft® Excel.

Water levels for MP-1, MP-3 and MP-4 were calculated for May 2014 through June of 2019. Water levels for MP-2 were calculated for May of 2014 through May 2018. Due to a malfunction with the MP-2 transducer data collected after May 2018 was not included in the calculations. All calculated water levels were graphed in Microsoft® Excel.

Water levels from October 2018 to June 2019 were also graphed for MP-5 and MP-7. As mentioned, there were issues with the MP-6 transducer and therefore only limited data are graphed.

Precipitation data for Cle Elum, WA (approximately 20 miles from the Indian Creek site) were added to the water level graphs. This data came from Climate Data Online (CDO), a free resource produced by the National Ocean and Atmospheric Administration (NOAA).

2.2.2 Groundwater Flow Direction

One of the main reasons the newer piezometers were installed was to better determine the groundwater flow directions along both T2 and T8. The technique used for this study was a "three-point" technique, or triangulation of the groundwater flow direction. This method uses the hydraulic head from three wells spaced in a triangle and the distance between them to geometrically calculate the groundwater flow direction.

The groundwater flow direction was first calculated by hand using the steps outlined in Heath (1983). Manual water levels collected in October of 2018 were used in conjunction with elevation data collected by WDFW in October 2018 to calculate the hydraulic head of wells at both T2 and T8. At T2, the three-point triangle was made up of MP-1, MP-2 and MP-5. At T8, the triangle was made up of MP-3, MP-4 and MP-6.

In order to get a more comprehensive understanding of the groundwater flow direction it was determined that calculations should be done for each season considering the water levels at Indian Creek vary with season. To accomplish this more efficiently compared to calculations by hand, a program called "3PE: A tool for Estimating Groundwater Flow Vectors" was used. The program, hereafter referred to as 3PE, was built by the Environmental Protection Agency (EPA) and is free for public use. As described by the EPA, "3PE is an interactive spreadsheet developed in Microsoft® Excel for estimation of horizontal hydraulic gradients and groundwater velocities," (Beljin et al., 2014). 3PE uses the same formulas as outlined in Heath (1983) but uses pre-defined Excel functions to do so. The user enters location data for the wells of interest, as well as various water level data and 3PE produces a graph showing the groundwater flow direction vector. This allows for a quick, but accurate, calculation of groundwater flow direction for various dates.

Manual water level measurements at both T2 and T8 taken during each different season were put into 3PE. However, since manual measurements were not collected during winter, transducer data were used for the T2 calculations for January 2019. Unfortunately, since the MP-6 transducers stopped collecting data after November 2018 a groundwater flow direction for the winter at T8 was unable to be calculated.

2.2.3 Groundwater Gradients

Groundwater gradients, or the change in hydraulic head over distance, were calculated for both T2 and T8. This was accomplished through the use of stream gage data provided by WDFW. There was a seasonal stream gage installed by WDFW at both T2 and T8 for 2014 through 2018.

At both T2 and T8, the older piezometers (MP-1 through MP-4) were used to calculate groundwater gradients. For each individual piezometer the daily average hydraulic head was calculated using transducer data and the WDFW survey data. The daily average hydraulic head was also calculated for the two stream gages. The calculated head values from a specific stream gage were then subtracted from the calculated head values of each piezometer along the same transect. This number was then divided by the distance between the specified piezometer and the stream gage. For each piezometer to gage reach, the hydraulic gradient for each year was graphed on the same plot in order to analyze temporal changes.

2.2.5 Aquifer Properties

The next step in the analytical methods was to better characterize the aquifer properties along the designated reach of Indian Creek. Little work had been done previously to understand how the aquifer was functioning, preventing any real analysis to be done on the groundwater dynamics and how they might be changing with restoration.

Slug tests were performed to determine the hydraulic conductivity (K) of the aquifer surrounding the reach. Data from the slug tests were analyzed via the Bouwer-Rice 1976 method. This empirical model calculates the hydraulic conductivity of an unconfined aquifer near a well using the recovery time to the original water level in a well after a sudden change in volume (Bouwer and Rice, 1976). Their model is based on the Thiem equation of steady state flow to a well. This calculates the rate of groundwater flow from a well:

$$Q = \frac{2\pi K(l-d)H_w}{\ln\left(\frac{R}{r_w}\right)} \qquad \text{Equation 1}$$

where Q is the volumetric flow rate, d and l are the screen interval depths, H_w is the water level at a specified time, K is the hydraulic conductivity, R is the radius of influence of the well in which the volume is displaced and r_w is the effective radius of the well (Theim, 1906).

From this, Bouwer and Rice then relate the rate of change in the water level to the flow rate and the well's cross-sectional area:

$$\frac{dH_w}{dt} = -\frac{Q}{\pi r_w^2} \qquad \text{Equation 2}$$

where t is time. Combining Equations 1 and 2 provides the governing equation for the Bouwer-Rice method:

$$\frac{dH_w}{H_w} = -\frac{2K(l-d)}{r_w^2 \ln\left(\frac{R}{r_w}\right)} dt \qquad \text{Equation 3}$$

The above governing equation was used to analyze the slug test data collected at Indian Creek in October 2018. The data from MP-2, MP-3, MP-4, MP-5 and MP-6 were put into Microsoft® Excel and graphed. A trendline was determined from the data points, and this, in combination with the individual piezometer specifications, was used to calculate the hydraulic conductivity using Equation 3 and the assumptions associated with the Bouwer-Rice method (see Appendix A).

Results from the Bouwer-Rice method were then checked via a graphing method derived from Hvorslev (1951). This involved determining a time at which the head equaled 0.37 (the natural logarithm of which is -1) and using this time to calculate the slope of the line of best fit. For this particular graphing method, on the same plot used for the Bouwer-Rice method, a straight line was plotted at 0.37 for the head value. The time lag from the Bouwer-Rice method was then graphed as a vertical line. If these two lines intersected with the line of best fit at the same place it was determined that the results from the Bouwer-Rice method were accurate.

The next aquifer property investigated was saturated thickness. Bedrock is assumed to be between ten and fifteen feet bgs based on well logs from the surrounding area available from the

“Well Report Map” by Ecology. In order to calculate the saturated thickness across the designated reach of Indian Creek, an average depth to the water table for each season per year was calculated for T2 and T8 separately. The average depth to the water table for T2 was calculated using data from MP-1 and MP-2, and the average depth to the water table for T8 was calculated using data from MP-3 and MP-4. These values were then subtracted from an average depth to bedrock of 12.5 feet below ground surface. This produced a range of saturated thickness for both transects. It should be recognized that this is likely an overestimate since in some areas the depth to bedrock is likely shallower than 12.5 feet.

This calculated saturated thickness was then used to calculate the transmissivity of the aquifer surrounding the study reach of Indian Creek. The equation below was used to calculate an average transmissivity based on the average saturated thickness and average hydraulic conductivity for each transect:

$$T = Kb \qquad \text{Equation 4}$$

where K is hydraulic conductivity and b is aquifer thickness.

Values for the remaining important aquifer properties were gathered from the literature. Notes on the soil composition collected during piezometer installation allowed for the conclusion that the alluvial aquifer below the designated reach of Indian Creek is mainly composed of sandy gravel with some clay. With this information, values were assigned to porosity, specific yield and specific retention in accordance with the values in *Basic Ground-Water Hydrology* by Ralph Heath (1983).

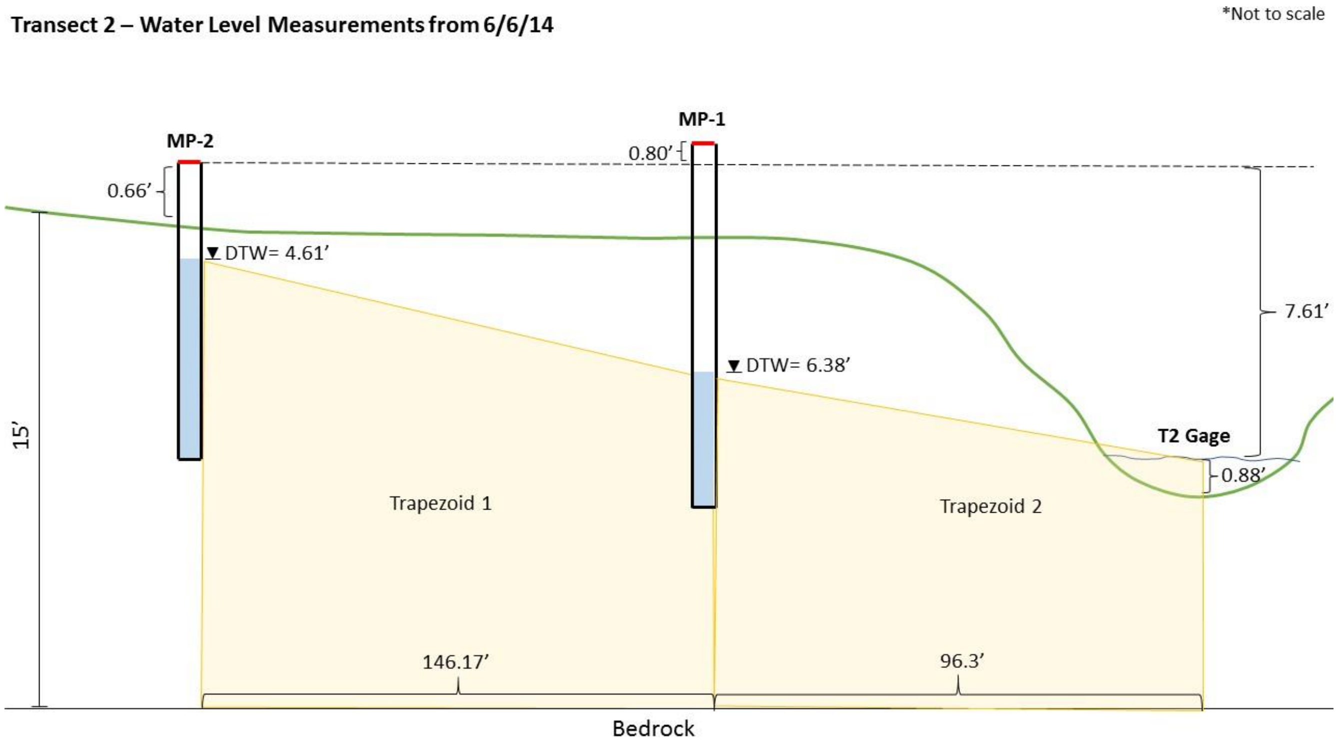
2.2.6 Groundwater Storage

A main objective of this project was to discern if the volume of water being stored in the alluvial aquifer surrounding the designated reach of Indian Creek is changing over time since stream restoration. To investigate this, simple geometric calculations were performed for both T2 and T8.

Each transect was broken into two trapezoids: one defined by the distance between the two piezometers at the transect and the other by the distance between the WDFW stream gage and the piezometer closest to the stream. The area of these trapezoids was calculated using the water levels in the piezometers and an established depth to bedrock. Since the exact depth to bedrock is unknown, calculations were done with the bedrock at two different depths (10 feet and 15 feet bgs). The areas of the two trapezoids were summed and the result was multiplied by 1 to produce a volume of storage per foot width. A first round of calculations was then done by multiplying this volume by porosity to obtain the available volume for groundwater storage in the alluvial aquifer. A second set of calculations was then done multiplying the previous volume by the specific storage to determine how much of that stored water could be available for release. In order to investigate any temporal changes, this series of calculations was repeated using the daily average water levels for 2014 through 2018 at each piezometer.

Figure 7 details these calculations.

The final step in the storage calculations was to determine the total increase in the volume of groundwater stored across the 1.2-mile reach over the study period. This was done for each transect individually by calculating the difference between the maximum storage of the first and last year of data and then multiplying it time over the study period. This number was then used to estimate the contribution of stored groundwater to Indian Creek. Since specific yield provides information about how much water is available for the stream, the storage analyses using a specific yield of 0.15 and a depth to bedrock of 15 feet bgs were used for the above calculation.



1. Calculate area of Trapezoid 1 DTW from surface level at MP-2: MP-2 = 4.61- 0.66 = 3.95' MP-1 = 6.38- (0.66+0.80) = 4.92' Depth from water level to bedrock: MP-2 = 15-3.95 = 11.05' MP-1 = 15-4.92 = 10.08' Area = [(11.05+10.08)/2]*146.17 = 1,544 ft^2	2. Calculate area of Trapezoid 2 DTW from surface level at MP-2 MP-1 = 6.38- (0.66+0.80) = 4.92' T2 Gage = (7.61+0.88) = 8.49' Depth from water level to bedrock: MP-1 = 15-4.92 = 10.08' T2 Gage = 15-8.49 = 6.51' Area = [(10.08+6.51)/2]*96.3 = 798.8 ft^2
3. Add areas together 1,544.3 ft^2 + 798.8 ft^2= 2,343.1 ft^2 Multiply by 1 ft to get volume per foot width 2,343.1 ft^2 * 1 ft = 2,343.1 cubic ft/ft	4. Multiply by porosity 2,343.1 ft^3 * 0.3 = 702.93 ft^3 **700 cubic ft/ft of storage per unit width at T2 on 6/4/14**

Figure 7: Example groundwater storage calculation using data from 6/4/2014

3. Results

3.1 Water Levels

Pressure transducer data were used to calculate water levels for all seven piezometers. Water levels were graphed to observe any notable changes since installation. Manual measurements were also graphed to ensure accuracy of transducer data.

MP-1 through MP-4 collected data from mid-2014 through January 2019. Since these four piezometers collected almost five years of data, they were useful in identifying trends in the water table depth since stream restoration occurred; Figure 8 shows their water level graphs.

As expected, some of the piezometers experience shallower depths to the water table during the spring, possibly indicating that the aquifer is recharging during times of high-flow. This is especially notable in MP-1 and MP-4. These shallow depths to water also appear to follow high precipitation events. Additionally, there are some clear changes with water level over time (shown in the red trendlines in Figure 8). If the stream restoration is increasing alluvial aquifer storage one would expect to see a pattern of decreasing depths to the water table over time. MP-2 and MP-3 may exhibit this decreasing depth to the water table, but MP-1 and MP-4 show the opposite, with an increasing depth to the water table.

For the remaining piezometers, MP-5 through MP-7, there are insufficient data to draw any conclusions regarding temporal changes. Despite this, they do exhibit a similar pattern of shallow depths to water during the one spring for which data are available, as well as shallower depths to water after precipitation events. Water level data for these piezometers can be found in Appendix B.

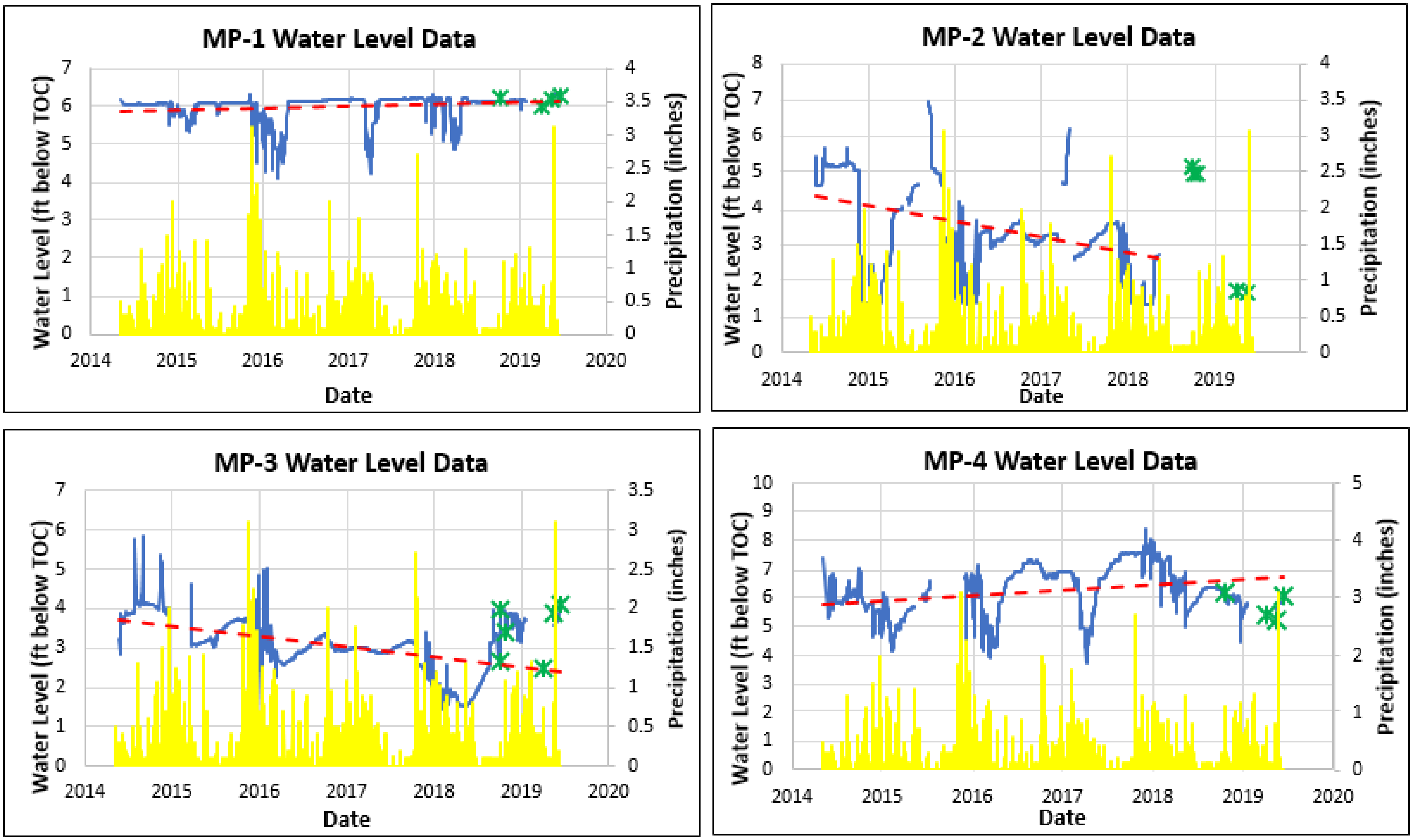


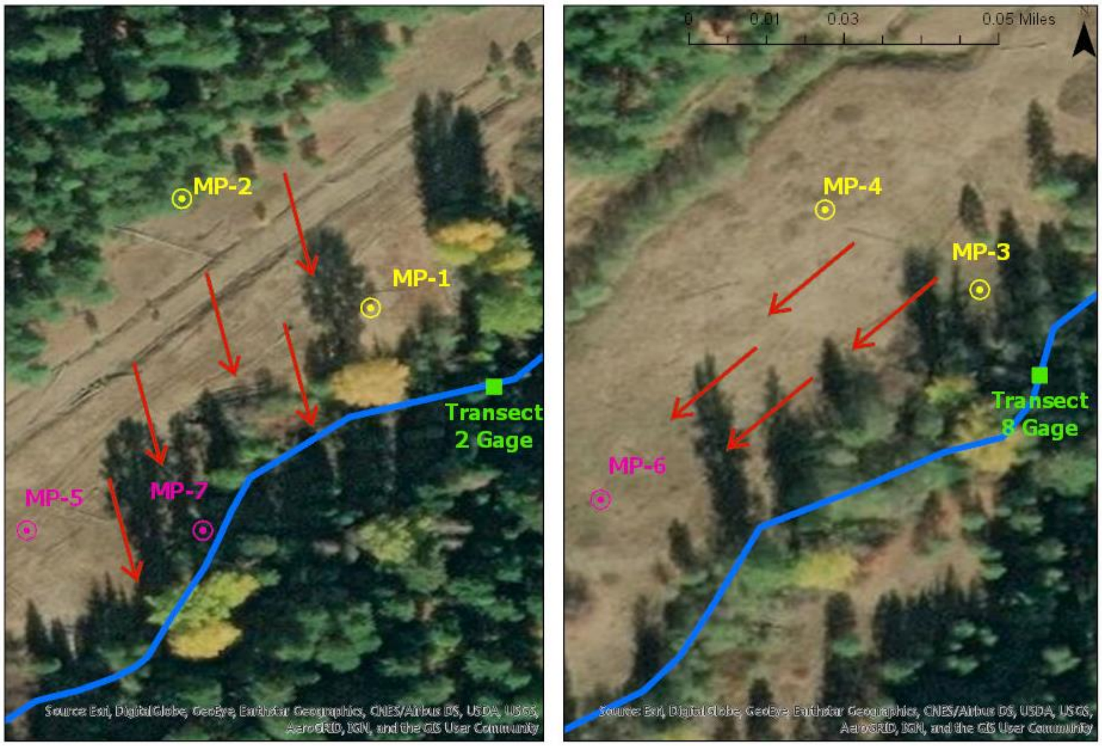
Figure 8: Water level measurements from transducers (blue) for MP-1, MP-2, MP-4 and MP-4 graphed alongside precipitation data (yellow). Red dashed lines show trendline for water level change over measurement period. Manual water levels intermittently measured are shown in green.

3.2 Groundwater Flow Direction and Gradients

Determining the groundwater flow directions for both T2 and T8 was a crucial step in understanding the overall function of the alluvial aquifer. Calculations done by hand using a triangulation method produce somewhat surprising results. These calculations used manual water level measurements taken in April 2019 to determine the groundwater flow direction at each transect. As seen in Figure 8, the results showed that groundwater was flowing towards the stream at T2 and somewhat parallel to the stream at T8. Previously, it was assumed that groundwater was flowing directly into the stream at both transects, but based on these calculations the groundwater at T8 was not flowing directly into the stream during April 2019.

These findings were supported by the results of the 3PE program analysis. The 3PE analysis separated flow directions for each season, providing a more comprehensive understanding of groundwater movement. For T2, the results from 3PE aligned with the results from the hand calculation, and overall, there was little variation in flow direction amongst the different seasons. At T2 water flows towards the stream in a downstream direction (southeast).

The T8 results from 3PE varied slightly from the hand-calculated flow directions. In general, groundwater flows in a downstream direction somewhat parallel to the stream (southwest); however, according to the analysis done with 3PE the flow direction veers slightly away from the stream during summer and flows to the northwest. The groundwater flow direction for winter at T8 was unable to be calculated due to a malfunction with the transducer. Figure 10 shows results from the 3PE analysis and additional information on the 3PE spreadsheet tool is in Appendix C.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Transect 2

Transect 8

Figure 9: Groundwater flow direction hand calculation results. Original piezometers seen in yellow and piezometers installed in 2018 seen in pink.

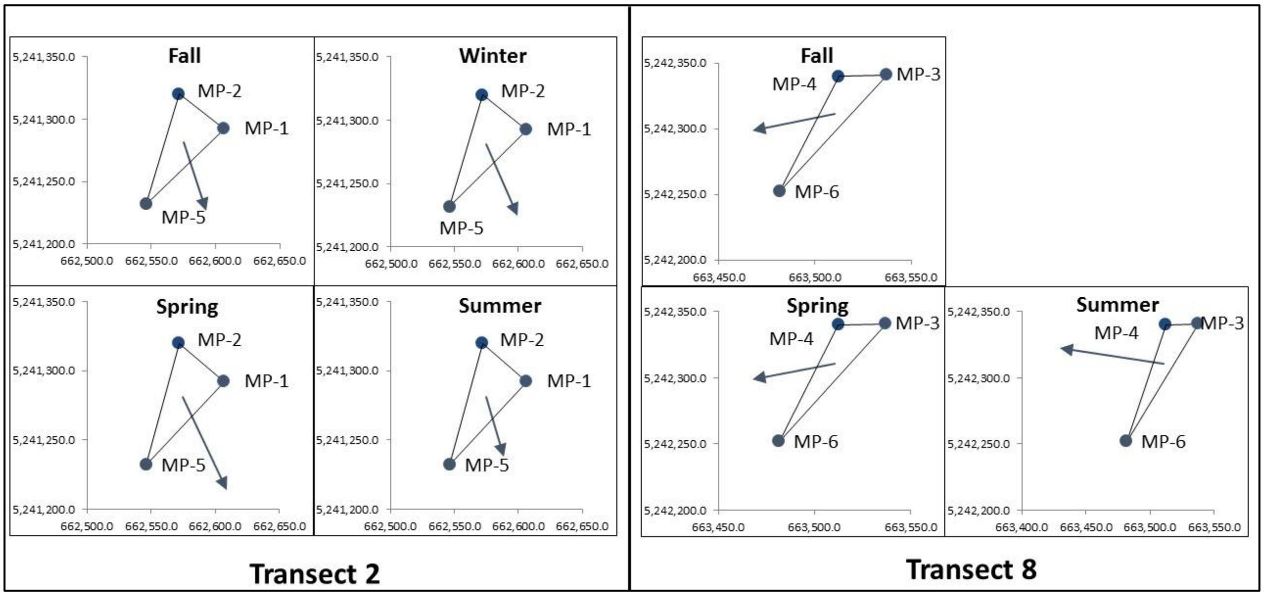


Figure 10: Results from 3PE analysis of groundwater flow direction for T2 and T8 divided seasonally. Axes represent location in U.S. State Plane coordinate system. Blue arrows show groundwater flow direction.

Annual groundwater gradients were calculated for both T2 and T8 using piezometer and stream gage data. MP-1 and MP-2 were used in conjunction with the T2 stream gage and MP-3 and MP-4 were used in conjunction with the T8 stream gage.

As seen in the groundwater flow direction analysis, water at T2 is generally flowing towards the stream. The hydraulic gradients between MP-1 and the T2 gage remain relatively stable over the five-year period. There is comparatively little fluctuation in the MP-1 water levels over time and therefore the gradient would not vary as much. The gradient between MP-1 and the T2 gage is the largest in 2017, while 2014 and 2015 (the earliest years post wood placement) have slightly smaller groundwater gradients (see Figure 11).

The hydraulic gradient between MP-2 and the T2 stream gage shows more variability over time. The early years post-wood placement (2014-2015) depict smaller groundwater gradients than the later years, which exhibit larger groundwater gradients. There is even an order of magnitude difference between the gradient in 2014 and in 2016. Unfortunately, there are minimal data available for 2017 and no data for 2018.

T8 also shows more temporal variability in the groundwater gradients over time. The groundwater gradients at this transect are negative as groundwater is generally moving parallel to or away from the stream. Between MP-3 and the T8 gage the magnitude of the groundwater gradient generally decreases over time. There is an order of magnitude difference between the gradient in 2014 compared to the gradient in 2018, meaning that the flow direction is slowly moving more towards the stream then away from the stream. However, the 2018 groundwater gradient between MP-3 and the T8 gage ranges greatly throughout the year, with the spring exhibiting a small gradient and the later months experiencing larger, or steeper, gradients indicating groundwater flow away from the stream.

There are few clear temporal trends in the gradients between MP-4 and the T8 stream gage. Here, 2014 seems to exhibit a small negative hydraulic gradient, while 2017 exhibits the largest negative gradient, but the other years lie within the middle of the two.

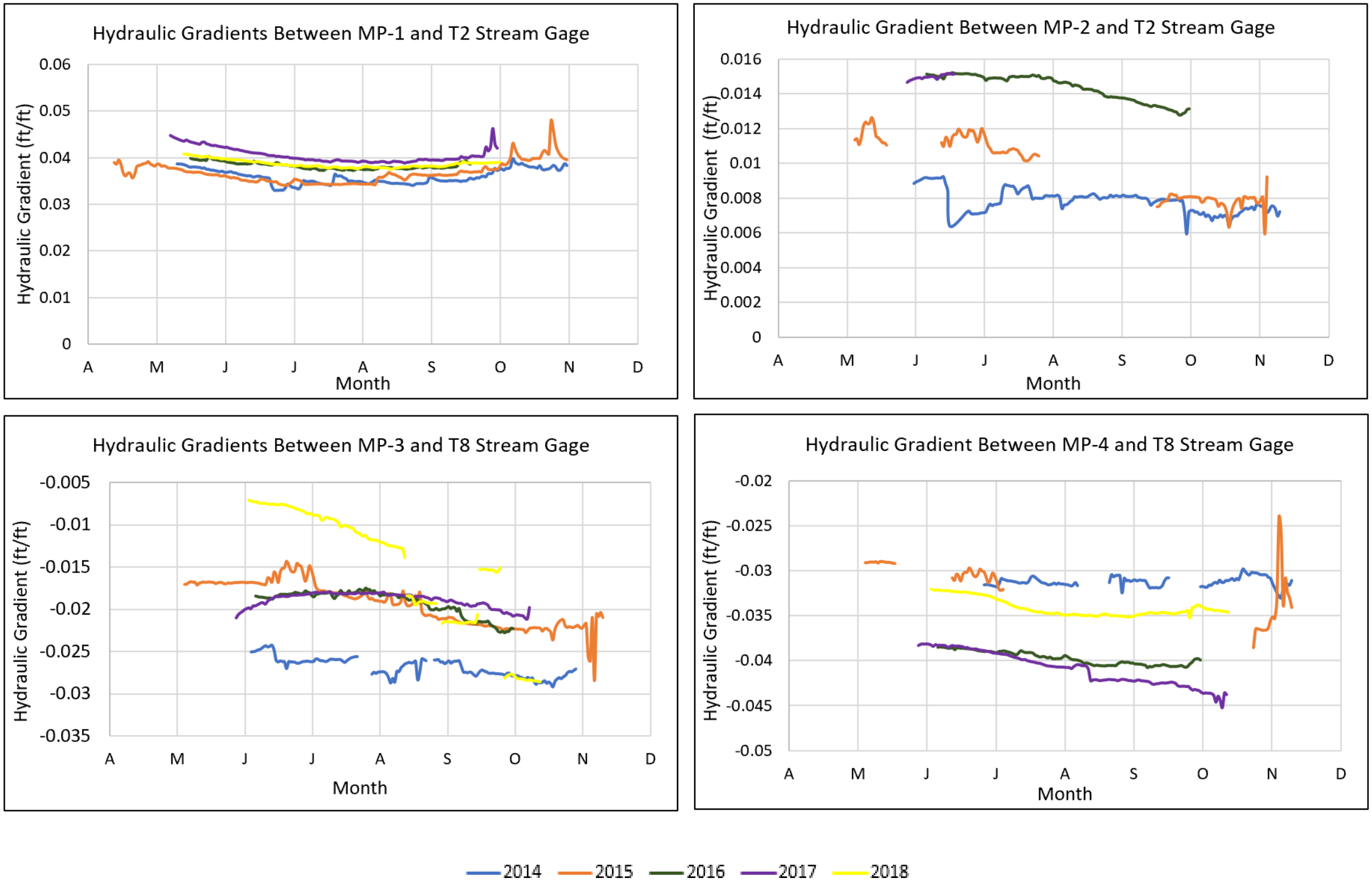


Figure 11: Annual groundwater gradients shown for both T2 and T8.

3.4 Aquifer Properties

Using the Bouwer-Rice method, data from the slug tests were analyzed to produce estimates of hydraulic conductivity for the aquifer surrounding T2 and T8. Slug test data were analyzed for MP-2, MP-3, MP-4, MP-5 and MP-6. There was a wide range of hydraulic conductivities, ranging from 0.2 ft/day to 12 ft/day likely due to the very localized, unique stratigraphic characteristics. There was, however, a minimal range amongst the hydraulic conductivity values for each piezometer, indicating a high level of precision amongst the various trials. Values from the various trials were averaged and compared to piezometer depth, however there was minimal correlation between the two. See Table 2 for all hydraulic conductivity values.

	Hydraulic Conductivity (ft/day)			
Well	**Trial 1**	**Trial 2**	**Trial 3**	**Average**
MP-2	0.2	0.2	0.2	0.2
MP-3	0.3	-	-	0.3
MP-4	2.0	2.5	3.7	2.7
MP-5	8.2	9.9	11.5	10
MP-6	0.3	-	-	0.3

Table 2: Results from slug test data analyzed via Bouwer-Rice Method. For both MP-3 and MP-6 only one trial was successful.

Average water levels were calculated for each season at MP-1, MP-2, MP-3 and MP-4 to determine seasonal variations in the water table elevation. For MP-3 and MP-4 the spring showed the shallowest depth to water (DTW), indicating seasonal recharge of the water table during the wet season. This, however, was not true in MP-1 and MP-2, where the minimum DTW for both wells occurred during the winter. Below are the averaged depths to water.

	Average DTW (ft bgs)			
Season	**MP-1**	**MP-2**	**MP-3**	**MP-4**
Spring	4.81	3.23	1.14	5.40
Summer	5.05	3.82	1.42	6.36
Fall	4.82	3.11	1.66	5.82
Winter	4.79	2.55	1.38	6.07
Average	**4.87**	**3.18**	**1.40**	**5.91**

Table 3: Average DTW for the four piezometers along T2 and T8 shown in feet bgs.

Separating the individual wells by transect allowed for estimates of the saturated thickness along both T2 and T8. Seasonal average water levels for MP-1 and MP-2 were used for T2 and seasonal average water levels for MP-3 and MP-4 were used for T8. As mentioned, bedrock is assumed to be between ten and fifteen feet bgs. Table 4 shows the aquifer's saturated thickness surrounding the investigation transects using a depth to bedrock of 12.5 feet bgs, a median value. This resulted in an average saturated thickness of 8.5 feet at T2 and an average saturated thickness at T8 of 8.9. The maximum saturated thickness for each transect occurred during the summer.

Since a bedrock depth of 12.5 feet bgs is a median value, additional calculations were done using both the maximum (15 feet bgs) and minimum (10 ft bgs) depths for each transect. T2 exhibited a 20% change in saturated thickness between the maximum and minimum depth, whereas T8 exhibited a 50% change. This indicates that the depth to bedrock has a relatively large impact on the saturated thickness of the surrounding aquifer, especially at T8 where the average DTW is smaller and the saturated thickness is therefore heavily influenced by the depth to bedrock.

The average saturated thickness for each transect was used with averaged hydraulic conductivity to calculate the aquifer transmissivity. The resulting transmissivities for the two transects were notably different. T8 exhibited a much higher transmissivity, most likely due to the relatively large hydraulic conductivity value found via slug tests in MP-4.

The remaining aquifer characteristics from *Basic Ground-Water Hydrology* by Ralph Heath (1983) and are in Table 5.

A

Season	T2 Average DTW (ft bgs)	Depth to Bedrock (ft bgs)	Saturated Thickness (ft)
Spring	4.02	12.5	8.5
Summer	4.43	12.5	8.1
Fall	3.96	12.5	8.5
Winter	3.67	12.5	8.8

B

Season	T8 Average DTW (ft bgs)	Depth to Bedrock (ft bgs)	Saturated Thickness (ft)
Spring	3.27	12.5	9.2
Summer	3.89	12.5	8.6
Fall	3.74	12.5	8.8
Winter	3.66	12.5	8.9

C

Transect	Saturated Thickness (ft)	Hydraulic Conductivity (ft/day)	Transmissivity (ft^2/day)
T2	8.5	0.2	1.7
T8	8.9	1.5	13.35

Table 4: Depth to water and saturated thickness calculations

(A) T2 averaged DTW calculated from water levels at MP-1 and MP-2 and then multiplied by average depth to bedrock to get saturated thickness per season, (B) T8 averaged DTW calculated from water levels at MP-3 and MP-4 and then multiplied by average depth to bedrock to get saturated thickness per season, (C) saturated thicknesses from A and B and hydraulic conductivities from Table 2 used to calculate transmissivity of each transect.

Aquifer Property	Literature Value
Porosity	0.30
Specific Yield	0.15
Specific Retention	0.15

Table 5: Values assigned to Indian Creek aquifer surrounding T2 and T8 based on soil composition notes and Heath (1983).

3.5 Groundwater Storage

Calculations were done to determine the potential volume of water that can be stored in the alluvial aquifer surrounding the investigation transects and how it might be changing with time. A range of calculations were performed to determine how both aquifer properties and the depth to bedrock may impact the storage volume.

Figure 12 shows storage calculations for T2 at both 10 feet bgs and 15 feet bgs. This calculation also incorporates a porosity of 0.3 to determine the actual amount of available storage in the aquifer. Over the four years graphed, T2 exhibits an average storage volume of 300 cubic feet per foot width when the depth to bedrock is assumed to be 10 feet bgs. When bedrock is assumed to be 15 feet bgs it exhibits an average storage volume of 600 cubic feet per foot width, almost double that of the storage with bedrock at 10 feet bgs. Figure 12 depicts the same analysis, except instead of incorporating porosity it incorporates a specific yield value of 0.15 to determine how much of that volume could be released from storage. This results in storage volumes almost half of those calculated using porosity.

For both calculations, T2 is generally showing an increase in storage volume over the years. This can be seen through the separate year segments (seen in green in Figure 12 and blue in Figure 13) generally trending upwards. A line of best fit was also calculated for each annual segment. This is of interest because it helps provide insight into how quickly stored water is draining out of the alluvial aquifer and presumably into the stream. For both the porosity and the specific yield volume calculations all of the lines of best fit have a negative slope. Since the annual segments generally span from June to October these negative slopes may indicate that the aquifer is losing stored water during the drier months. As seen in both Figure 11 and 12, the slope of the trendlines are generally increasing, or becoming steeper, over the years. The slope of the trendline for 2014 is -0.04, where was the slope of the trendline for 2017 is -0.15. This indicates that water may be releasing at a faster rate from the aquifer overtime.

Similar to the hydraulic gradient analysis, T8 does not depict as clear a temporal trend as T2. Over the five years graphed, T8 had an average storage volume of 300 cubic feet per foot width when considering bedrock at 10 feet bgs and a porosity of 0.3 (Figure 14), and an average storage volume of 600 cubic feet per foot width when considering bedrock at 15 feet bgs and a porosity of 0.3. The volume of storage almost doubles when bedrock is just five feet deeper.

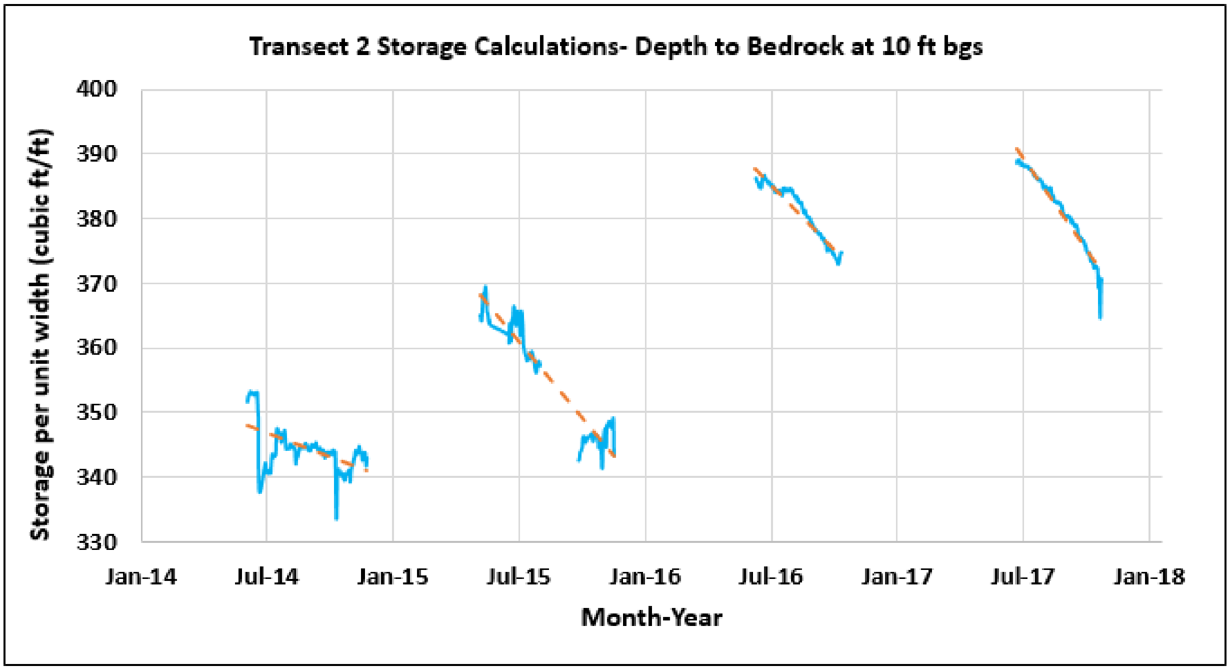
Similar to T2, when considering a specific yield of 0.15 instead of a porosity of 0.3, the storage volumes decrease by about half (Figure 15).

Although there is not as clear an increase in storage volume per year at T8, the largest storage does occur during 2018. Despite this, storage appears to fluctuate greatly during this year and therefore it is difficult to draw a conclusion that storage is increasing. Additionally, the storage volumes appear almost equivalent during 2016 and 2017, again possibly disputing an increase in storage over time. However, similar to T2, the slope of the trendline for each year increases, with a slope in 2014 of -0.02 and -0.47 in 2019. This indicates that water may be releasing from the aquifer at a quicker rate over the five years.

Additional calculations were done to determine the change in the volume of water stored across the 1.2-mile reach of Indian Creek. As seen in Table 6, the total volume of storage over the four-year study period for T2 was 114,000 ft^3 and the total volume of storage over the five-year study period for T8 was 158,000 ft^3. These volumes indicate that overall, there was measurable increase in the groundwater storage across the investigation reach. The calculated volumes were then divided by the data collection time period for each year (140 days) to discern a streamflow contribution from this stored groundwater. The results for both T2 and T8 are the same at 0.01 ft^3/sec.

	Transect 2	**Transect 8**
Volume of water stored over study period	114,000 ft^3	158,000 ft^3
Streamflow contribution over study period	0.01 ft^3/sec	0.01 ft^3/sec

Table 6: Results for storage calculations and streamflow contributions across the entire 1.2-mile study reach



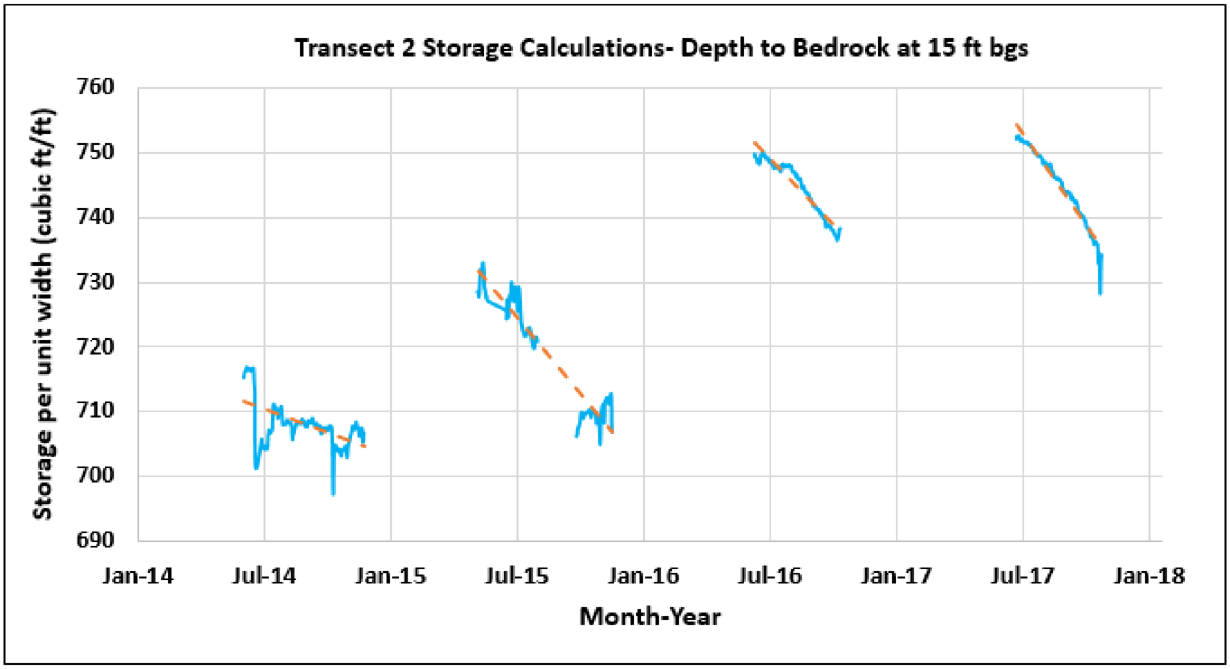
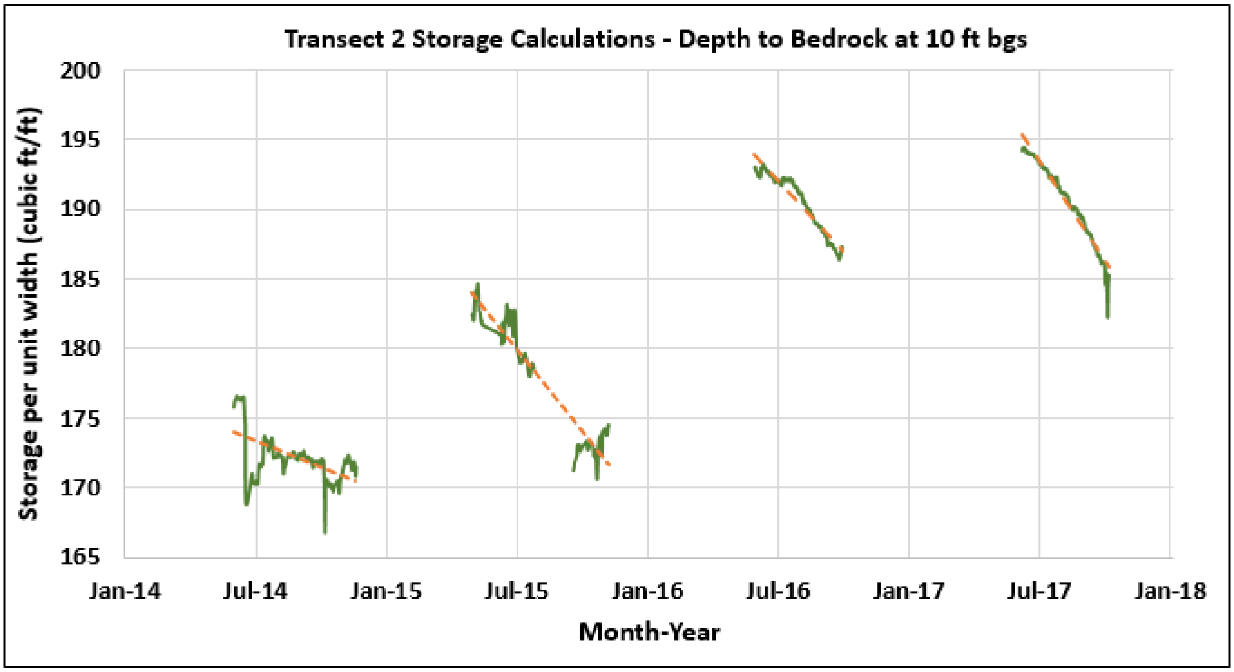


Figure 12: Storage calculations for T2 from 2014-2018 incorporating a porosity of 0.3. Orange dashed segments represents trendline for each year.



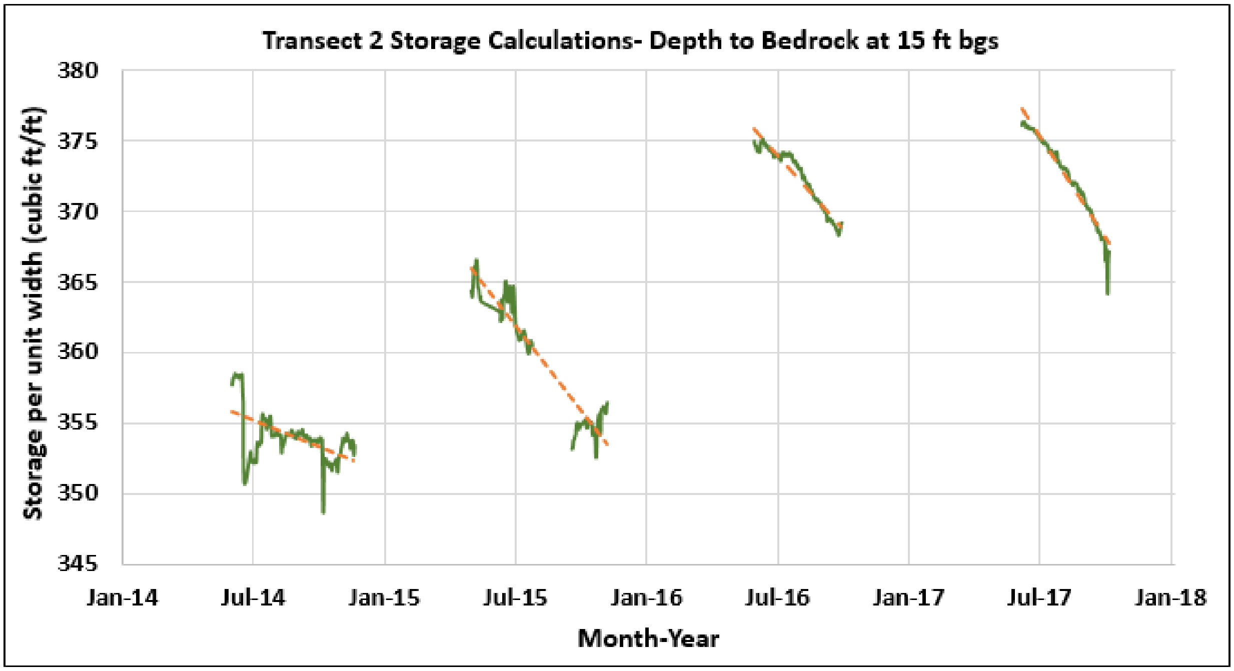
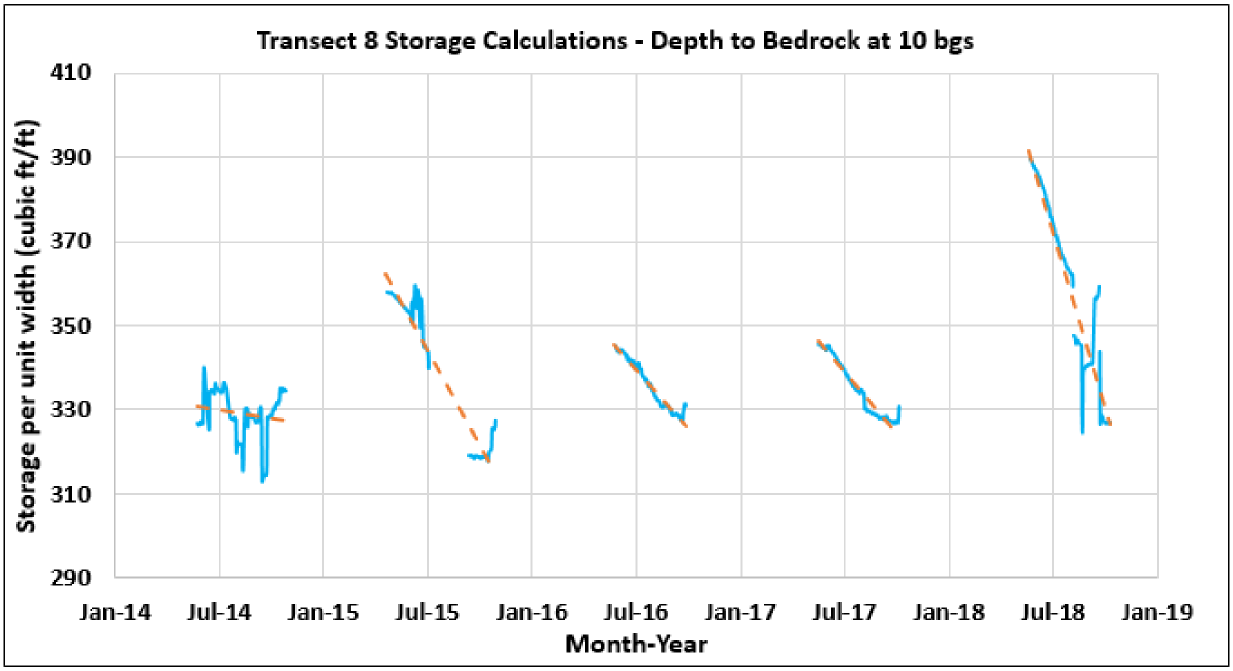


Figure 13: Storage calculations for T2 from 2014-2018 incorporating a specific yield of 0.15. Orange dashed segments represent trendline for each year.



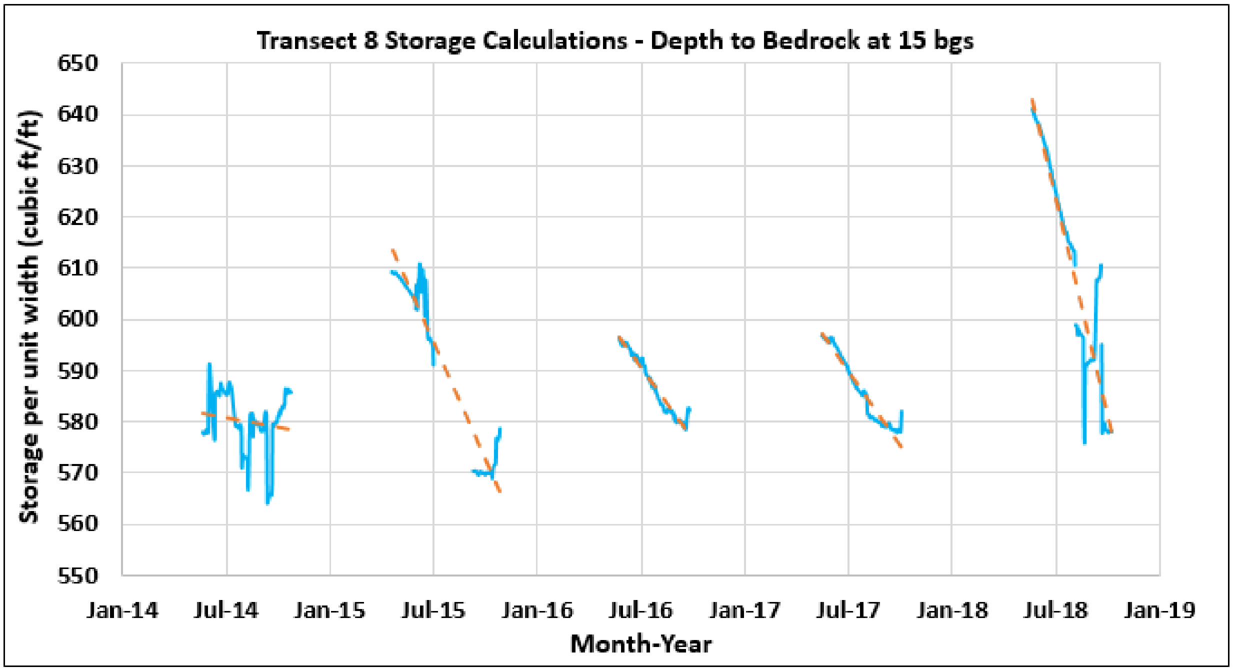
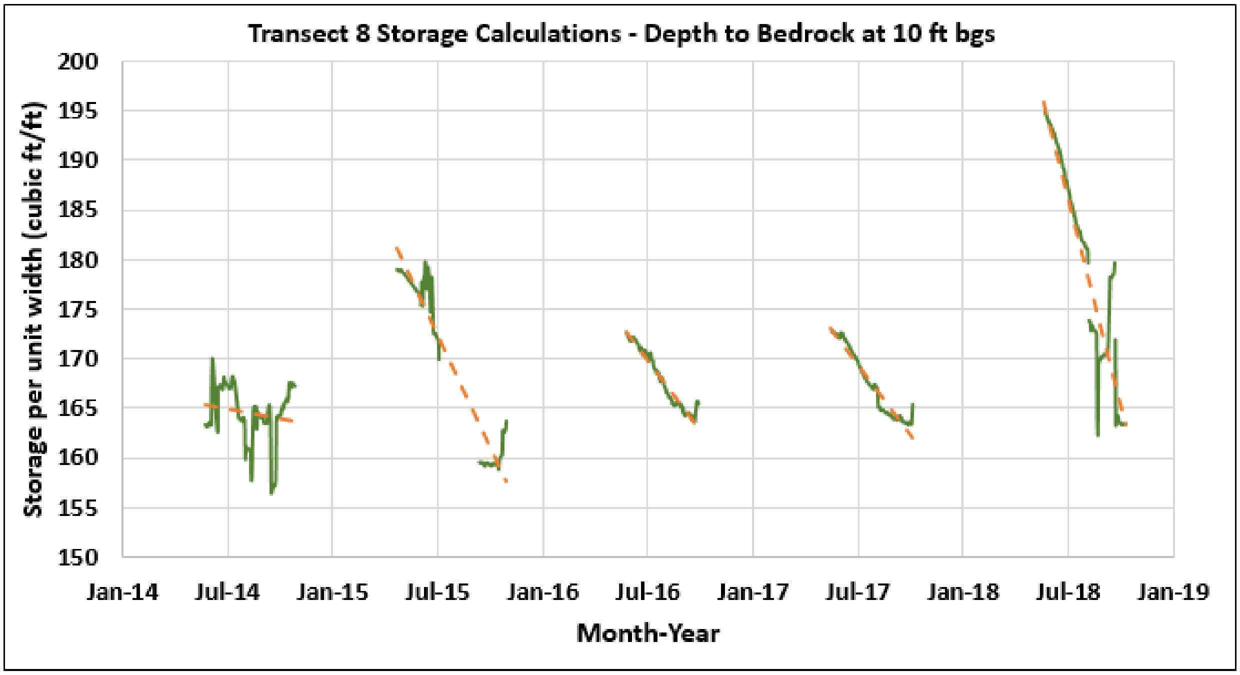


Figure 14: Storage calculations for T8 from 2014-2019 incorporating a porosity of 0.3. Orange dashed segments represent trendline for each year.



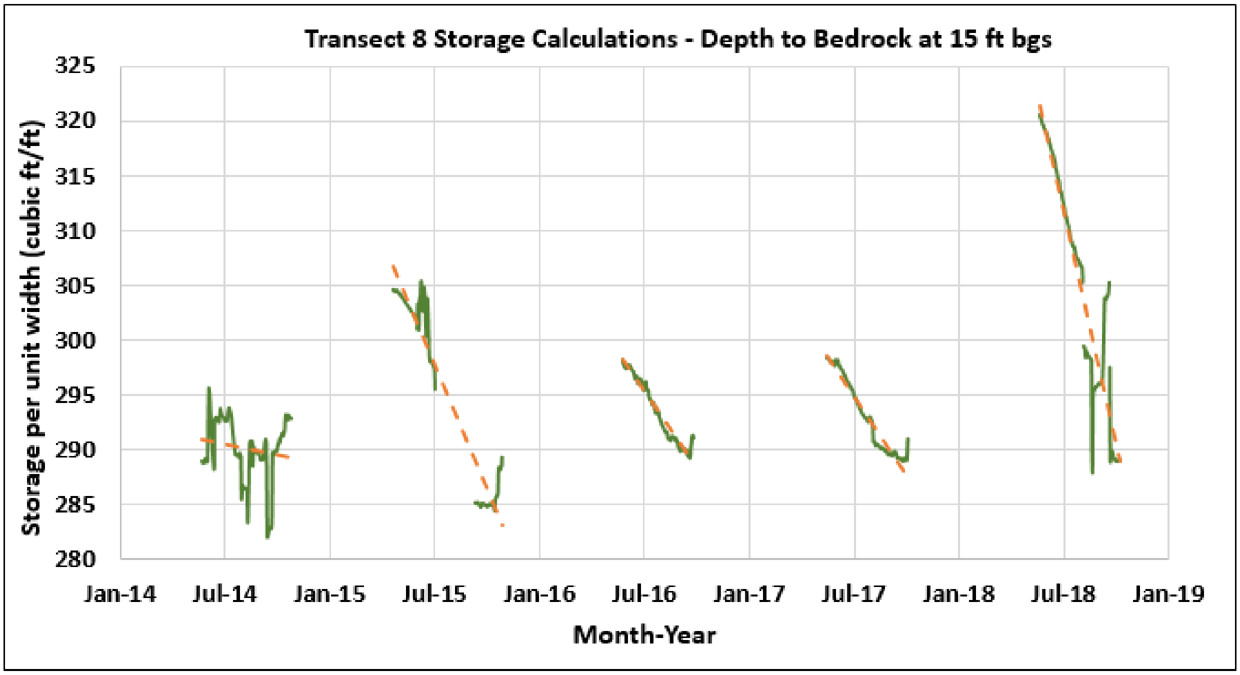


Figure 15: Storage calculations for T8 from 2014-2019 incorporating a specific yield of 0.15. Orange dashed segments represent trendline for each year.

4. Discussion

4.1 Water Levels

It is useful to investigate the water levels of each piezometer in terms of annual trends to discern how the aquifer may be reacting to wood placement. If stream restoration is successfully raising the elevation of the streambed over time, then the water levels surrounding this restored reach would likely begin to increase as well. As the floodplain and the stream become reconnected due to restoration, water easily moves into the alluvial aquifer during times of high-flow and raises the elevation of the water table. This pattern is only seen at some of the piezometers at Indian Creek.

The graphs in Figure 8 help interpret what has happened with the water levels in the individual piezometers over time. If the water table elevation was increasing since restoration one would expect to see the red trendlines generally sloping downward. This is clearly not the case at MP-1, where there even seems to be a slight increase in the DTW over time. However, there trendline for the MP-2 water levels is sloping downward, indicating an increase in the water table elevation. This is surprising considering there is only 150 feet distance between the two and one would assume the water table elevation would be reacting the same way along the same transect. One possible explanation for this could be varying vegetation density at the two locations. MP-1 is much closer to the stream then MP-2 and could therefore be experiencing denser riparian vegetation and subsequent higher evapotranspiration rates. Another possible explanation could be the localized geology, allowing for one part of the transect to store more water and therefore elevate its water table elevation compared to another. Unfortunately, since there is no vegetation data and no geologic investigation at Indian Creek it is impossible to say which, if any, of these explanations hold true.

A similar conclusion can be drawn surrounding T8 and its corresponding groundwater levels. According to Figure 8, MP-4 has experienced a similar response to MP-1, with the trendline sloping upwards and indicating a decrease in the water table elevation. MP-3 water levels show slightly different results, with a trendline sloping gently downward with time. As the shallowest DTW occurs during spring 2018, the most recent year of data, the water table elevation at this piezometer may be increasing over time. Therefore, continued monitoring of the water levels at

MP-3 is important, especially if a continued trend of increasing water table elevations is observed in the future.

Even with MP-2 and MP-3 exhibiting a slight increase in water table elevations, the cumulative water levels of the four piezometers along T2 and T8 do not indicate a significant temporal trend of increasing water table elevations in the first five years post stream restoration. This is contrary to other studies, both model-based and field-based, that have noted increased water table elevations within just a short time post-restoration. For example, through their hydrologic model based off Bear Creek in California, Hammersmark et al. (2008) note significant increases in water table elevation just two years post pond-and-plug stream restoration, a response they relate to the raised channel bed of the stream (Hammersmark et al., 2008). Alternatively, a field-based study near Lake Tahoe in California also notes significant increases in groundwater levels over four years of observation, especially during the spring time indicating possible enhanced storage during times of high flow (Tague et al., 2008).

The graphs in Figure 8 are also useful for understanding any seasonal patterns in water levels across both transects. If stream restoration was achieving the goal of enhancing groundwater storage and contributing to late season flows, then one would expect to see high water table elevations during the spring and early summer as the aquifer is recharging, and lower water table elevations during the late summer and fall as it is releasing water back to the stream. At Indian Creek, only MP-3 and MP-4 support this hypothesis, with their shallowest depths to the water table occurring during the spring and their deeper depths to the water table occurring in the late summer and fall.

Seasonal trends in water table elevations post-restoration have also been linked to increased evapotranspiration as riparian vegetation often increases with restoration activities (Nash et al., 2018 and Brown, 2013). For example, a comparative study of a restored versus unrestored reach of a montane meadow in California concluded that there was more variation in the water table elevation between the wet and dry season on the restored reach of meadow compared to the unrestored reach. The author explains that this is likely because the shallower depths to water make water more available for plants to use for evapotranspiration, subsequently causing more variation in DTW between seasons (Brown, 2013). Again, only the water levels at MP-3 and MP-4 are potentially exhibiting this.

The seasonal water levels at MP-1 and MP-2 do not display the same pattern. At these piezometers, the shallowest depth to the water table occurs during the winter. As this montane meadow is greatly influenced by snow and snowmelt, it is possible that these wells are experiencing higher water levels during this time due to heavy snowmelt and some infiltration of the snow into the aquifer. Another explanation for this could be due to the groundwater flow direction. At T2 groundwater is flowing towards the stream. This may limit the maximum water table elevation that the aquifer reaches at T2 because the groundwater naturally wants to flow back into the stream. Therefore, even when there is high-flow in the stream (like during the spring) the water table elevation at T2 may not be influenced as much as it is at T8, making a seasonal trend of high water levels in the spring unlikely. On the other hand, water is flowing somewhat away from the stream at T8 and it is therefore easier for the surrounding aquifer to recharge during high-flow, exhibiting higher water table elevations during that time.

Successful stream restoration is often associated with obvious and quick responses in the water table elevation. This brings to question whether the restoration at Indian Creek is considered successful by this metric as there no clear increase in the water table elevation over the years and minimal seasonal trends. However, it is important to note that many of these stream restoration studies can be considered microcosms; extremely site-specific studies on relatively small scales. Therefore, it can be difficult to conclude that water table elevations should react within a certain timeframe at each individual restored stream. Different systems, based on their unique geology, precipitation, or ecology, are likely to react differently to different methods of restoration. This supports the idea that just because clear changes in water table elevation have not yet been seen at Indian Creek does not mean they will not eventually emerge. Again, this emphasizes the need for more a more long-term investigation of this unique system.

4.2 Groundwater Flow Direction and Gradients

As mentioned, it was previously assumed that groundwater flowed into the stream at both transects. This was found to be untrue at T8, where water is flowing parallel, and even at times away from, the stream. The question then emerges if this part of Indian Creek is naturally a losing reach of stream, or if the degradation of Indian Creek has caused this part of the stream to transition to a losing reach. It is possible that low groundwater levels as a result of degradation and floodplain disconnection caused the water to transition from flowing into the stream to flowing out of the stream.

The groundwater flow direction observed at T8 provides insight into the concept of enhanced late-season flows from stored groundwater at Indian Creek. Both the water table elevations and the groundwater flow direction away from the stream may indicate that T8 is able to store groundwater during times of high-flow. However, from the 3PE analysis it is known that at no point during the year does water at T8 flow back into the stream. However, since the water table elevations return to lower levels during later summer and fall, the question emerges as to the fate of this excess stored water.

One possible explanation for the dynamics occurring at T8 could be underflow. As opposed to baseflow (water that flows normal to the stream), underflow is the concept of groundwater moving downstream in the same direction as the stream, but at a much slower rate (Larkin and Sharp, 1992). Underflow is common in alluvial aquifers and is generally transient, transitioning back and forth between underflow and baseflow (Larkin and Sharp, 1992). The groundwater flow direction parallel to the stream at T8 aligns with the concept of underflow, and therefore, groundwater could be moving slowly downstream through the alluvial aquifer and then contributing to baseflow somewhere further downstream from T8. If this section of the aquifer is experiencing underflow then it is possible that T8 is gaining groundwater during times of high flow (as seen in seasonal water levels), transitioning it downstream, and then releasing it to baseflow. However, at this point there is no way to confirm that this process is occurring at T8. To investigate this hypothesis, additional stream gages and piezometers are needed downstream of T8, along with stream discharge and seepage test data discern which parts of the stream may be losing or gaining.

Additional analysis was done to investigate the hydraulic gradients across the two investigation transects. The hydraulic gradients along T2 exhibit a very modest temporal trend across the five years of investigation. The graph seen in Figure 11 shows a slight increase in the hydraulic gradient between MP-1 and the T2 stream gage. The gradient between MP-2 and the T2 gage shows a similar increase, however holes in the data make it more difficult to draw a conclusion regarding any temporal trend.

One common explanation for increases in hydraulic gradients after stream restoration is that the water table is rising and therefore creating a steeper path for groundwater to flow into the stream. However, from the water level analysis, it is clear that the water table is not rising over time and therefore this cannot explain the increasing gradient. Since there are no obvious changes in the water table elevation, a more likely explanation for the slight increase in the hydraulic gradient observed at T2 is that the stream bed elevation is changing with time. When considering stable water levels, the positive change in the gradient at T2 would indicate that the stream bed is decreasing in elevation post restoration. As seen through other studies (Hammersmark et al., 2008; Brown, 2013; Tague et al., 2008) stream restoration normally causes an increase in streambed elevation. Since the streambed of Indian Creek is experiencing the opposite effect, it is presumably not reacting in a way that would indicate successful stream restoration for groundwater storage.

The hydraulic gradient between MP-3 and the T8 gage show a slightly different pattern. As seen in Figure 11, the hydraulic gradient here is decreasing in magnitude over time. This scenario could indicate that as time since stream restoration progresses, the aquifer along this part of the stream is filling slightly, therefore decreasing the magnitude of the hydraulic gradient. This is further supported by the water table elevations seen in Figure 8, where there is a slight trend of increasing elevation with time. It is possible that if this trend of hydraulic gradients decreasing in magnitude over time were to continue in future years then it could even reverse the hydraulic gradient between MP-3 and the T8 gage. This would mean that eventually groundwater at this part of Indian Creek could flow towards the stream instead of away. See Figure 16 for a schematic of this.

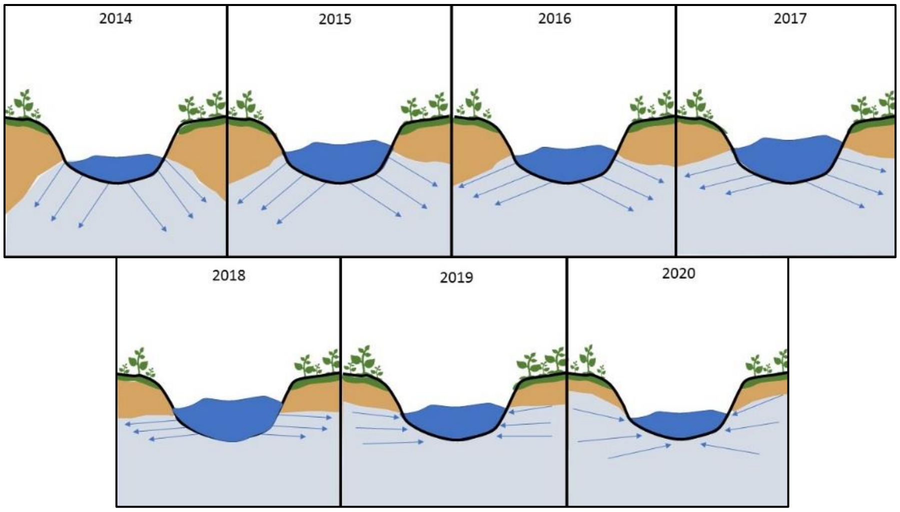


Figure 16: Groundwater gradients shown in blue arrows (not to scale) 2019-2020 are predictions of groundwater flow direction if the current trend continues.

As the 3PE analysis showed there is currently no period at T8 when groundwater is flowing towards the stream, likely preventing recharge of the stream during times of low-flow. A possible reversal in the hydraulic gradient, especially during the spring, could therefore enhance late season flows at T8. Although the years recorded at MP-3 so far show this pattern, further monitoring is necessary to discern if this gradient change is actually occurring at T8, and if so, how this may impact the process of alluvial storage and enhanced late season flows.

It is difficult to discern any clear temporal patterns occuring with the hydraulic gradient between MP-4 and the T8 stream gage. Excluding the 2018 data, it would appear that the gradients observed immediately after wood placement are smaller in magnitude as compared to those later on. This would be an opposite trend to the previously discussed gradient between MP-3 and the T8 gage. One possible explanation for these decreased gradients is that the streambed is rising due to restoration and therefore decreasing the elevation different between the streambed and the water table. However, as discussed previously, this is likely not happening based on the behavior of the gradients between MP-3 and the T8 gage. Another explanation for the decreased gradients could be that we water table is dropping in elevation at MP-4, but again, that explanation is not consistent with the water level graph for MP-4.

Overall, the hydraulic gradients at both T2 and T8 are not reacting as one would expect with successful stream restoration and subsequent enhanced alluvial aquifer storage. As presented by Nash et al. (2018), if a stream bed is reacting to restoration by sediment aggradation and a raised streambed then the hydraulic gradient would be decreasing. Even if the alluvial aquifer was gaining more groundwater, successful stream restoration would result in a less-incised channel and therefore a generally low incline gradient (Nash et al., 2018). Nash et al. (2018) go even further to argue that this lower hydraulic gradient may negate some of the assumed benefits of stream restoration, enhanced groundwater storage and subsequent late-season flows. Since these decreased gradients are not observed at either investigation transect at Indian Creek it is not possible to investigate if this concept holds true here. However, it would be interesting to see if further data collection leads to observable gradient changes and if these low gradients limit the amount of stored water being released into the stream.

Similar to water levels, seasonal variation of the Indian Creek gradients is lacking. Although there are some peaks and dips in Figure 11, there is no notable seasonal pattern between most of the wells and the two gages. If the large wood placement was indeed leading to alluvial aquifer storage and then high late season flows, one might expect to see gradients flowing away from the stream during times of high flow, and then back towards the stream during times of low flow. This is a well documented process, especially in snowmelt dominated watersheds, where bank storage occurs when the stream stage is above the water table and the stream recharges the alluvial aquifer. This is then followed by a time of lower stream stage and a reversed hydraulic gradient that allowes the stored groundwater to supplement late-season low flows (Brissette, 2017). The only place this seasonal variation is notable is in 2018 between MP-3 and the T8 gage where there is a rapid decrease in the hydraulic gradient between spring and fall. This could be indicating some storage and release, but since it is only one year of data it is difficult to determine the actual cause.

4.4 Aquifer Properties

The overall goals of the slug tests were to better characterize the aquifer surrounding Indian Creek and to understand how the system is functioning to aid in future investigations. However, slug tests in these piezometers sample a very small aquifer volume and cannot be considered representative of the entire Indian Creek alluvial aquifer. Therefore, more comprehensive aquifer testing is required to determine hydraulic conductivity values more representative of the larger area. Despite this, the tests done here do provide some insight into the specific hydraulic properties surrounding T2 and T8.

Slug test results at Indian Creek revealed relatively low hydraulic conductivities compared to those typical of unconsolidated materials in the surrounding area. An investigation of the unconsolidated sediment throughout the Yakima River Basin in Kittitas County found hydraulic conductivities ranging from 4 to 190 ft/day, much larger than those found at Indian Creek (Gendaszek et al., 2014). Although the Yakima River Basin covers a much larger and more diverse area than the Indian Creek aquifer, it is still surprising that these lower hydraulic conductivities were found at Indian Creek.

The stratigraphy surrounding the Indian Creek transects, more specifically the highly localized clay layers throughout the subsurface, is a possible explanation for these low hydraulic conductivities. Soil notes taken during the installations of MP-5, MP-6 and MP-7 outline several dense, gray-green clay layers throughout each soil column. The depths of these clay layers varied throughout the three locations, so it is difficult to pinpoint at what depths these clay layers exist throughout the Indian Creek aquifer and thus, how they impact the hydraulic conductivities in the vicinity of different piezometers. Still, it can be argued that these localized clay units, at whichever depths they may occur, limit the rate at which water is flowing in to and out of the piezometers and possibly lead to a comparatively lower hydraulic conductivity of the aquifer surrounding Indian Creek as compared to the Yakima River Basin in Kittitas County.

The higher hydraulic conductivity values at MP-5 are also supported by the soil composition notes. The notes indicate that the substrate surrounding this piezometer was mostly gravelly sand and only had one small clay layer. The fact that the MP-5 location displayed different stratigraphic properties and subsequently different hydraulic conductivities further supports the idea that the very localized stratigraphy throughout the Indian Creek aquifer has a large impact on water movement. Therefore, a more detailed stratigraphic investigation, including soil sampling, is needed to further explain the hydraulic conductivities and other aquifer properties.

Despite the lack of detailed stratigraphic data, the range of hydraulic conductivities found through the slug tests does provide some insight in to how water is moving through the aquifer and the aquifer’s potential to store and release groundwater. There is an order of magnitude difference between some of the hydraulic conductivities found at different piezometers, suggesting that some areas of the aquifer may be able to store and release water faster and more efficiently compared to others. For example, the area surrounding MP-5, where the hydraulic conductivity is high, may be more conducive to the storage process. However, if a goal behind a stream restoration project is to increase late season flows, it is also important that the surrounding aquifer does not have an exceedingly high hydraulic conductivity as this may lead to poorly-timed releases. Therefore, determining the hydraulic conductivity of stream restoration sites should be considered an important first step. If slug tests were performed at Indian Creek prior to restoration, partners may have been able to see which areas would best suited for groundwater storage and well-timed releases and then use this information to pinpoint the location of their restoration efforts. Even without this being done prior to restoration, information gathered through the slug tests performed in October 2018 can still provide insight into why or why not there may be signs of successful restoration in the Indian Creek aquifer, especially when looked at in conjunction with other aquifer properties and water table elevation data.

Similar to hydraulic conductivities, transmissivity for the two transects was calculated in order to better characterize the aquifer surrounding T2 and T8, particularly for future research. A higher transmissivity was found at T8. This is not surprising, as transmissivity incorporates hydraulic conductivity and a higher average hydraulic conductivity was found at T8. This higher transmissivity at T8 could indicate that this transect has more potential to successfully store groundwater. However, this is contradictory to the results of the saturated thickness calculations. T2 displays a slightly larger saturated thickness than T8, therefore indicating that it may have the potential to store more groundwater if the bedrock is considered to be at the same depth. With these results, it is difficult to conclude if one transect is more suitable for alluvial aquifer storage compared to the other, again emphasizing the need for further study to best characterize these transects and any future transects established along Indian Creek.

4.5 Groundwater Storage

Similar stream restoration studies (Hammersmark et al., 2008; Brown, 2013) concluded that stream restoration can have a measureable impact on the amount of groundwater stored in an alluvial aquifer and is dependent on many factors; saturated thickness, hydraulic conductivity, slope and water table elevation. A simplified analysis was done for Indian Creek to investigate if the amount of water being stored in the surrounding aquifer has increased since large wood placement.

As mentioned, the area of water between the stream and the piezometers was multiplied by either porosity (Figure 12 and Figure 14) or specific yield (Figure 13 and Figure 15) to obtain a possible storage volume for the alluvial aquifer surrounding T2 and T8. Multipling the area by the porosity provided insight into how much water the aquifer could hold in total, while multiplying the area by the specific yield provided insight into how much water might be available to drain back into the stream. The results for both showed the same pattern, just with a different magnitude. The calculations done using porosity were almost double than those done with specific yield because a porosity of 0.3 was used and a specific yield of 0.15 was used. This makes sense since even if the aquifer was completely saturated not all of that water would be considered available. Additional calculations were done with varying depths to bedrock to incorporate a sensitivity analysis to that unccertainty.

When looking at the storage results for T2, a clear pattern of increasing storage over time is apparent. The storage calculations along T8 show less of a clear pattern, but still have the maximum storage volume occuring in 2018. The total volume of water stored over the study period is estimated to be between 100,000 ft^3 and 200,000 ft^3 (see Table 6). Although these numbers may appear large, it is difficult to discern if this is actually a notable increase in storage without historic data. Despite that, one can assume that any increase in the amount of groundwater stored has some ecological, biological or hydrologic benefit for the system as a whole.

The change in storage volume over the four years is closely linked to the changes in the groundwater elevations. As noted, both MP-2 and MP-3 are experiencing a rise in the water table elevation over the five years. This would therefore translate to an increase in the water stored in the alluvial aquifer. Additionally, these calculations incorporate the thickness of the aquifer, which is likely more influential to the amount of water being stored along the two transects. Therefore, when incorporating saturated thickness into calculations it is easier to see a trend in stored volume compared to calculations of just water levels alone.

The calculations done here consider a uniform thickness of unconsolidated sediments, similar to other studies (Hammersmark et al., 2008; Loheide and Gorelick, 2007; Lowry et al. 2011). However, a recent study by Ciruzzi and Lowry (2017) concluded that montane meadows like Indian Creek are far more hydrologically complex then previously assumed and that most of that is because of bedrock geology. Through the use of ground penetrating radar (GPR) and in-depth bedrock morphology analyses, Ciruzzi and Lowry (2017) conclude that uniform thickness models often overestimate groundwater storage potential for the meadow edges and underestimate storage potential for the middle of the valley (Ciruzzi and Lowry, 2017). Although the analysis done here for Indian Creek does incorporate a range of aquifer thicknesses, it does not consider variable thickness throughout different locations of the meadow. Therefore, the storage estimates found through this analysis, although useful for understanding how the system in generally functioning, are likely not providing the most accurate interpretation of storage potential. This emphasizes the need for more detailed information regarding the geology below Indian Creek. Understanding the thickness of the aquifer, and therefore making the calculations outlined in Figure 7 more specific, would allow for more accurate calculations of storage that may explain the upward trends seem at both T2 and T8.

Another aspect of the debate behind stream restoration for groundwater storage is the timing of the release of stored water back into the stream. Some argue that water is released once the stream is experiencing the dry season in order to supplement late-season flows (Tague et al., 2008; Brissette, 2017; Hammersmark et al., 2008; Brown, 2013). Therefore, for this investigation, trendlines were fitted to each annual storage calculation (each of which spanned from June to October). The slope of the trendlines is assumed to be representative of the rate at which the storage volume as decreasing. Therefore, the original goal behind the slope calculations was to determine how quickly groundwater may be releasing back into the stream.

Based on this theory, it could be assumed that both T2 and T8 experience a more rapid release of storage in the later years post restoration since the slopes of the trendline are increasing in negativty annully for both transects. This could indicate that the water within the aquifer is becoming more and more readily available for the stream during times of lowflow and therefore the restoration could be potentially successful at contributing to late season flows. However, since there were only minimal seasonal changes oberserved in the groundwater gradients this seems unlikely.

This rapid release of water from storage could possibly be due to the unique geology of the aquifer surround Indian Creek. Since there is minimal information available regarding the bedrock geology there is no way of knowing if there are geologic features that are causing drainage of water from the alluvial aquifer. For example, there may be bedrock fractures across the meadow there groundwater will naturally flow into from the alluvial aquifer.

Another explanation for the increasing rates of release could be the restoration's influence on vegetation. As mentioned, increased riparian vegetation is a well-documented result of many stream restoration projects, and therefore it can be argued that with stream restoration comes increased rates of evapotranspiration. It is possible that these investigation transects are experiencing this annual increase in riparian vegetation as a result of restoration and therefore quickly lose most of their stored water to the plants during their peak growing season. This phenomenon has previously been observed in other restored meadows (Lowry and Gorelick, 2006; Hammsermark et al., 2008). Therefore, any water potentially being stored in the alluvial aquifer during peak flows is quickly lost to evapotranspiration. This not only explains the steep slopes of the trendlines in the storage calculations, but may also explain why increased water levels are not easily observed at any of the piezometers over a larger temporal investigation. Further analysis could be done to see if there are dirunal flucuations in groundwater levels and how these may be reacting over time to see if evapotransipiration is having a large impact on groundwater levels and subsequent storage.

Regardless of the reasoning behind the increasing rate of groundwater release, it is important to investigate the potential volume of water that could be leaving the alluvial aquifer and entering the stream. Using storage volumes for both transects, an average flow rate of 0.01 ft^3/sec was estimated as the maximum possible contribution of groundwater to streamflow. In other words, this estimates the flow rate into the stream if all of the stored groundwater was flowing into the stream. This is unlikely actually occuring at Indian Creek, but it does provide some insight into how the large wood restoration could possibly be influencing the streamflow. Unfortunately, since there is no streamflow data prior to restoration, one cannot discern if this is an increase or decrease in streamflow.

4.6 Future Work

There are several areas for future work surrounding the Indian Creek stream restoration and its connection to groundwater dynamics.

1.) Water level data from piezometers and stream gages should continue to be collected. Each of the aforementioned restored montane meadow streams are unique and it is difficult to place a timeframe onto when the impacts of restoration may become noteable. Continued monitoring may shed light on on whether large wood restoration can enhance groundwater storage and late season flows.
2.) More piezometers should be installed downstream of both T2 and T8 to see if downstream areas are influenced by restoration. Most studies that observe no measureable impact in late season flows are focused on a very small area directly along restoration activities and may be missing some of the downstream effects.
3.) Stream discharge data should be collected and analyzed to determine when and where water is entering or leaving the stream.
4.) More detailed geologic information is needed to understand the aquifer below Indian Creek. This study provided some information into general aquifer properties, but more aquifer testing and stratigraphic investigations are needed.
5.) Additional investigation is needed into the vegetation dynamics surrounding Indian Creek. As argued by Nash et al. (2018), evapotransipiration often increases in restored meadows, and therefore impacts the overall water budget of the system. Unfortunately, pre-restoration and even shortly after restoration records of vegetation do not exist. Therefore, although understanding the temporal change in vegetation density along the reach may be difficult, vegetation transects and quadrats performed in the future could shed light into how much vegetation is influencing the water budget of Indian Creek and if it could possibly be influencing groundwater storage and releases.

The Indian Creek investigation should serve as an example to stakeholders, especially those involved in the YBIP, that stream restoration is does not gaurentee groundwater storage and late season streamflows. Many parties throughout Washington and the Pacific Northwest, are spending both time and money on large wood restoration projects that may not be reap the promised benefits. Indian Creek is a perfect example that site specificity can largely influence reactions to stream restoration and just because a method works for one location at improving groundwater dynamics, does not mean it is always the best way to allocate resources.

5. Conclusion

The investigation into the groundwater dynamics surrounding the restored reach of Indian Creek provide further evidence that the concept of stream restoration for groundwater storage and subsequent late season flows is more complicated then previously assumed. Although there is an increasing amount of literature available concerning alluvial aquifer storage in montane meadows, different studies are coming to different conclusions based on the hydrological complexity of these systems.

The results here provide provide some insight into how Indian Creek may be reacting to large wood restoration. Some individual piezometers show temporal trends of increasing groundwater elevations and therefore the transects exhibit increases in the water stored in the alluvial aquifer. This increased volume of storage generally indicates that restoration has been effective concerning aquifer recharge, but it is difficult to make such a conclusion without a better understand of the specific of the Indian Creek system, such as vegetation dynamics and geologic makeup. Since baseline data is missing, it is difficult to directly relate the increased groundwater storage to the large wood restoration.

Next, the groundwater gradients and groundwater flow direction analyses do not show clear evidence of increased late-season flows. Without discharge data, contribution to streamflow from aquifer storage cannot be ruled out, however, the work done here emphasizes that it is unlikey groundwater is signifcantly contributing to streamflow along these two transects.

Despite this, stream restoration at Indian Creek for enhancing groundwater storage should not be considered a failure.. There is no established timeline for observed changes due to stream restoration, and therefore it is possible that the impacts to groundwater dynamics due to wood placement at Indian Creek have simply not emerged yet. Additionally it is important to remember that groundwater dynamics are not the only measurement of stream restoration success and increased riparian vegetation, improved fish habitat, and reconnection to the floodplain are all important benefits of stream restoration. The work done through this study, specifically the data collected and the establishment of basic aquifer properties, perfectly sets the stage for continued investigation. A long-term study of Indian Creek based on this work and incorporating the above suggestions could be very beneficial.

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Appendices

Appendix A: Slug Test Data

Slug Test Data:

Hydraulic conductivities were calculated using the Bouwer-Rice method in Microsoft® Excel and check via a graphical method derived from Hvorslev (1951). Governing equations are outlined on page 17-18.

The Bouwer-Rice method incorporates the following assumptions:

- The aquifer is bounded below by an aquiclude.
- All layers are horizontal and extend infinitely in the radial direction.
- The initial water table (before injection) is horizontal and extends infinitely in the radial direction.
- The aquifer is homogeneous and isotropic.
- Groundwater density and viscosity are constant.
- Groundwater flow can be described by Darcy's Law.
- A volume of water, V, is injected instantaneously at time t = 0.
- Head losses through the well screen, filter material, and developed zone (if present) are negligible.
- The aquifer is incompressible.
- Build-up of the water table is small compared to the aquifer saturated thickness.

MP-2 Slug Test Data														
Trial 1					Trial 2					Trial 3				
Time (min)	**DTW (ft)**	**H_o (ft)**	**H_w (ft)**	**H_w/H_o**	**Time (min)**	**DTW (ft)**	**H_o (ft)**	**H_w (ft)**	**H_w/H_o**	**Time (min)**	**DTW (ft)**	**H_o (ft)**	**H_w (ft)**	**H_w/H_o**
0.98	0.5	5.15	4.65	0.90	1.08	0.5	5.15	4.65	0.90	0.52	0.5	6.39	5.89	0.92
1.50	0.7	5.15	4.45	0.86	1.55	0.7	5.15	4.45	0.86	1.15	0.7	6.39	5.69	0.89
2.10	0.9	5.15	4.25	0.83	2.10	0.9	5.15	4.25	0.83	2.27	0.9	6.39	5.49	0.86
2.72	1.1	5.15	4.05	0.79	2.60	1.1	5.15	4.05	0.79	3.27	1.1	6.39	5.29	0.83
3.32	1.3	5.15	3.85	0.75	3.17	1.3	5.15	3.85	0.75	4.83	1.3	6.39	5.09	0.80
4.20	1.5	5.15	3.65	0.71	3.78	1.5	5.15	3.65	0.71	6.15	1.5	6.39	4.89	0.77
4.97	1.7	5.15	3.45	0.67	4.40	1.7	5.15	3.45	0.67	7.60	1.7	6.39	4.69	0.73
5.78	1.9	5.15	3.25	0.63	5.07	1.9	5.15	3.25	0.63	9.82	1.9	6.39	4.49	0.70
6.72	2.1	5.15	3.05	0.59	5.80	2.1	5.15	3.05	0.59	12.5	2.1	6.39	4.29	0.67
7.65	2.3	5.15	2.85	0.55	6.57	2.3	5.15	2.85	0.55	23.7	2.3	6.39	4.09	0.64
8.68	2.5	5.15	2.65	0.51	7.40	2.7	5.15	2.45	0.48	30.5	2.5	6.39	3.89	0.61
9.73	2.7	5.15	2.45	0.48	9.30	3.1	5.15	2.05	0.40	36.4	2.7	6.39	3.69	0.58
10.9	2.9	5.15	2.25	0.44	10.5	3.3	5.15	1.85	0.36	41.2	2.9	6.39	3.49	0.55
12.2	3.1	5.15	2.05	0.40	11.6	3.5	5.15	1.65	0.32	52.5	3.1	6.39	3.29	0.51s
13.5	3.3	5.15	1.85	0.36	12.9	3.7	5.15	1.45	0.28	58.7	3.3	6.39	3.09	0.48
15.1	3.5	5.15	1.65	0.32	14.5	3.9	5.15	1.25	0.24	60.1	3.5	6.39	2.89	0.45
16.8	3.7	5.15	1.45	0.28	16.1	4.1	5.15	1.05	0.20	60.4	3.7	6.39	2.69	0.42
18.6	3.9	5.15	1.25	0.24	18.2	4.3	5.15	0.85	0.17					
20.7	4.1	5.15	1.05	0.20	20.5	4.5	5.15	0.65	0.13					
23.2	4.3	5.15	0.85	0.17	23.3	4.7	5.15	0.45	0.09					
26.0	4.5	5.15	0.65	0.13	26.7	4.9	5.15	0.25	0.05					
29.4	4.7	5.15	0.45	0.09										
32.7	4.9	5.15	0.25	0.05										
39.3	5.1	5.15	0.05	0.01										

Table A- 1: MP-2 slug test data

MP-3 Slug Test Data				
Trial 1				
Time (min)	**DTW (ft)**	**H_o (ft)**	**H_w (ft)**	**H_w/H_o**
1.6	0.50	2.50	2	0.80
4.5	0.73	2.50	1.77	0.71
7.0	0.93	2.50	1.57	0.63
10.3	1.13	2.50	1.37	0.55
17.8	1.53	2.50	0.97	0.39
31.0	2.09	2.50	0.41	0.16
43.3	2.49	2.50	0.01	0.00

Table A- 2: MP-3 slug test data

MP-4 Slug Test Data														
Trial 1					Trial 2					Trial 3				
Time (min)	**DTW (ft)**	**H_o (ft)**	**H_w (ft)**	**H_w/H_o**	**Time (min)**	**DTW (ft)**	**H_o (ft)**	**H_w (ft)**	**H_w/H_o**	**Time (min)**	**DTW (ft)**	**H_o (ft)**	**H_w (ft)**	**H_w/H_o**
0.73	5.30	7.9	2.59	0.33	0.15	3.0	7.91	4.91	0.62	0.13	3.1	7.9	4.8	0.61
0.93	6.00	7.9	1.89	0.24	0.33	3.5	7.91	4.41	0.56	0.30	5.2	7.9	2.7	0.34
1.10	6.40	7.9	1.49	0.19	0.45	5.3	7.91	2.61	0.33	0.42	5.9	7.9	2	0.25
1.25	6.70	7.9	1.19	0.15	0.60	6.0	7.91	1.91	0.24	0.52	6	7.9	1.9	0.24
1.42	7.00	7.9	0.89	0.11	0.78	6.7	7.91	1.21	0.15	0.65	6.9	7.9	1	0.13
1.67	7.30	7.9	0.59	0.08	0.90	6.9	7.91	1.01	0.13	0.78	7.2	7.9	0.7	0.09
2.23	7.70	7.9	0.19	0.02	1.07	7.2	7.91	0.71	0.09	0.93	7.4	7.9	0.5	0.06
					1.22	7.4	7.91	0.51	0.06	1.17	7.6	7.9	0.3	0.04
					1.40	7.6	7.91	0.31	0.04	1.7	7.8	7.9	0.1	0.01
					1.73	7.8	7.91	0.11	0.01	2.0	7.85	7.9	0.05	0.01
					2.67	7.9	7.91	0.01	0.00					

Table A- 3: MP-4 slug test data

MP-5 Slug Test Data														
Trial 1					Trial 2					Trial 3				
Time (min)	**DTW (ft)**	**H_o (ft)**	**H_w (ft)**	**H_w/H_o**	**Time (min)**	**DTW (ft)**	**H_o (ft)**	**H_w (ft)**	**H_w/H_o**	**Time (min)**	**DTW (ft)**	**H_o (ft)**	**H_w (ft)**	**H_w/H_o**
0.32	3.1	5.39	2.29	0.42	0.03	4.50	5.91	1.41	0.24	0.03	4.40	5.91	1.51	0.26
0.70	4.0	5.39	1.39	0.26	0.28	4.90	5.91	1.01	0.17	0.31	4.80	5.91	1.11	0.19
1.68	5.0	5.39	0.39	0.07	0.38	5.00	5.91	0.91	0.15	0.39	5.00	5.91	0.91	0.15
4.18	5.3	5.39	0.09	0.02	0.58	5.20	5.91	0.71	0.12	0.57	5.20	5.91	0.71	0.12
					1.47	5.50	5.91	0.41	0.07	1.84	5.50	5.91	0.41	0.07
					2.18	5.60	5.91	0.31	0.05	2.11	5.60	5.91	0.31	0.05
					11.8	5.75	5.91	0.16	0.03	11.8	5.80	5.91	0.11	0.02

Table A- 4: MP-5 slug test data

MP-6 Slug Test Data				
Trial 1				
Time (min)	**DTW (ft)**	**H_o (ft)**	**H_w (ft)**	**H_w/H_o**
0.27	0.62	6.44	5.82	0.90
0.53	0.80	6.44	5.64	0.88
0.82	1.00	6.44	5.44	0.84
1.23	1.30	6.44	5.14	0.80
1.60	1.60	6.44	4.84	0.75
2.13	2.00	6.44	4.44	0.69
3.13	2.50	6.44	3.94	0.61
4.30	3.00	6.44	3.44	0.53
7.10	3.60	6.44	2.84	0.44
8.80	4.00	6.44	2.44	0.38
11.4	4.50	6.44	1.94	0.30
24.1	5.00	6.44	1.44	0.22
39.0	5.06	6.44	1.38	0.21

Table A- 5: MP-6 slug test data

Appendix B- Water Level Data

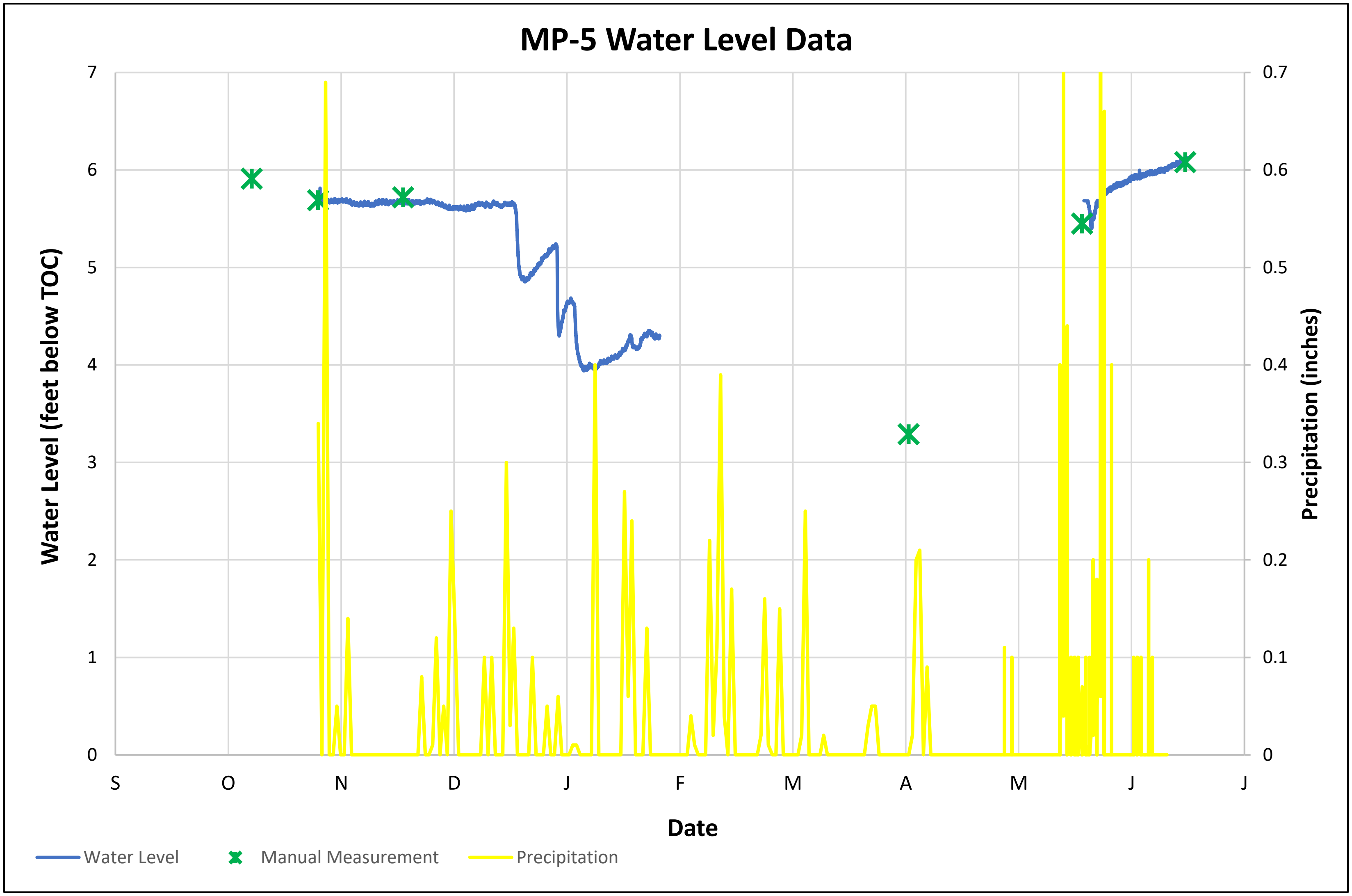


Figure B- 1: MP-5 water level data

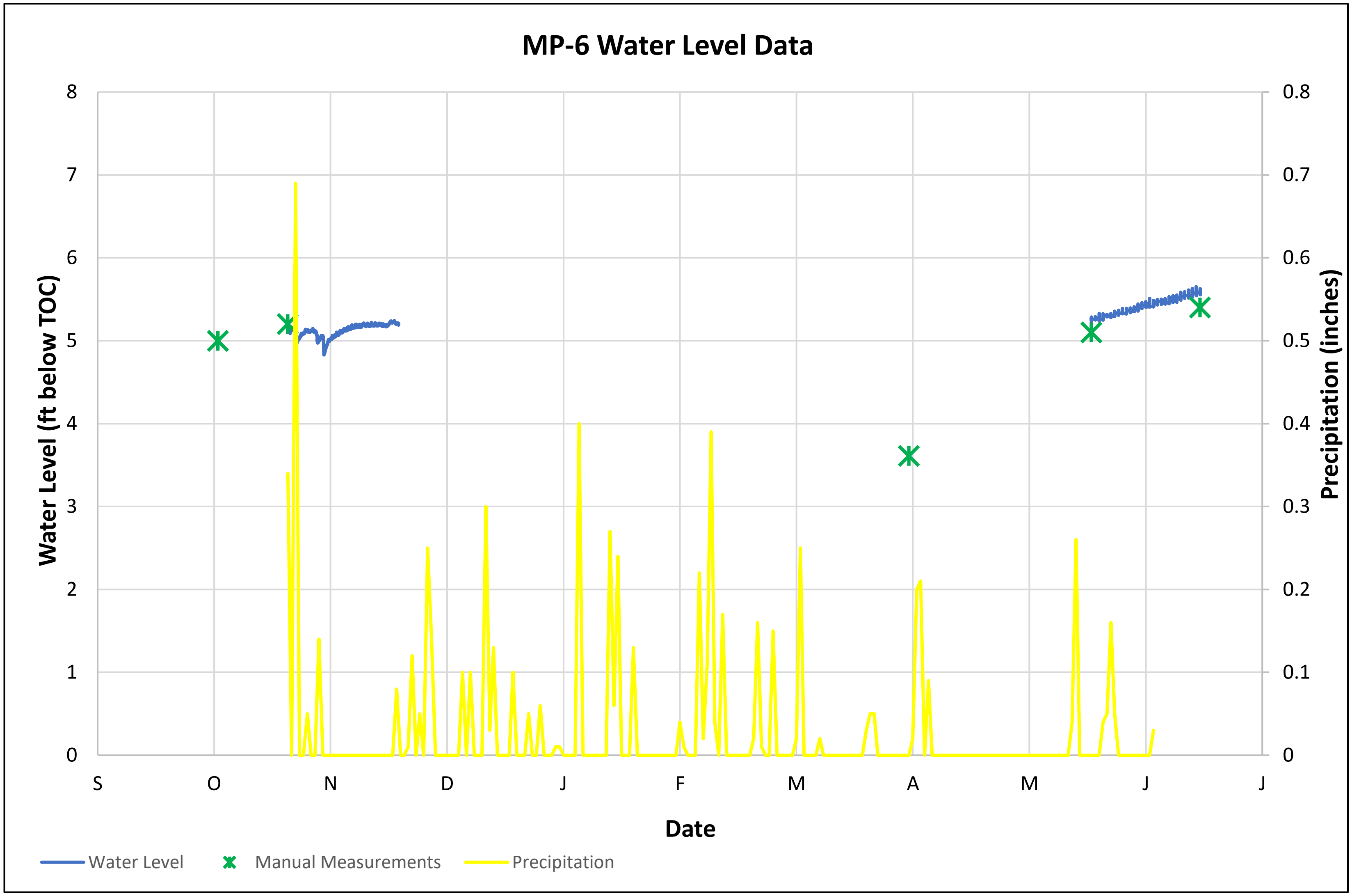


Figure B- 2: MP-6 water level data

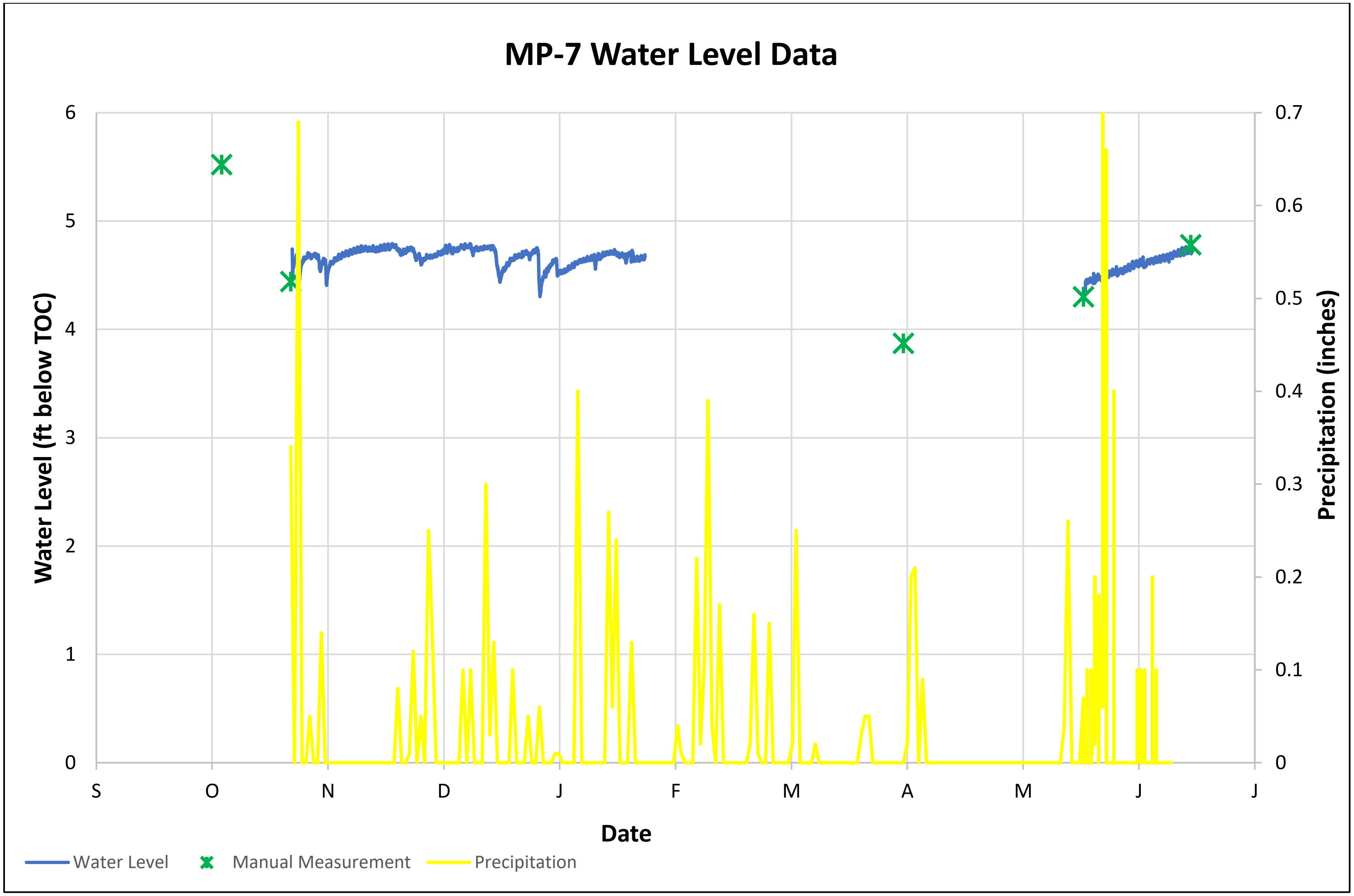


Figure B- 3: MP-7 water level data

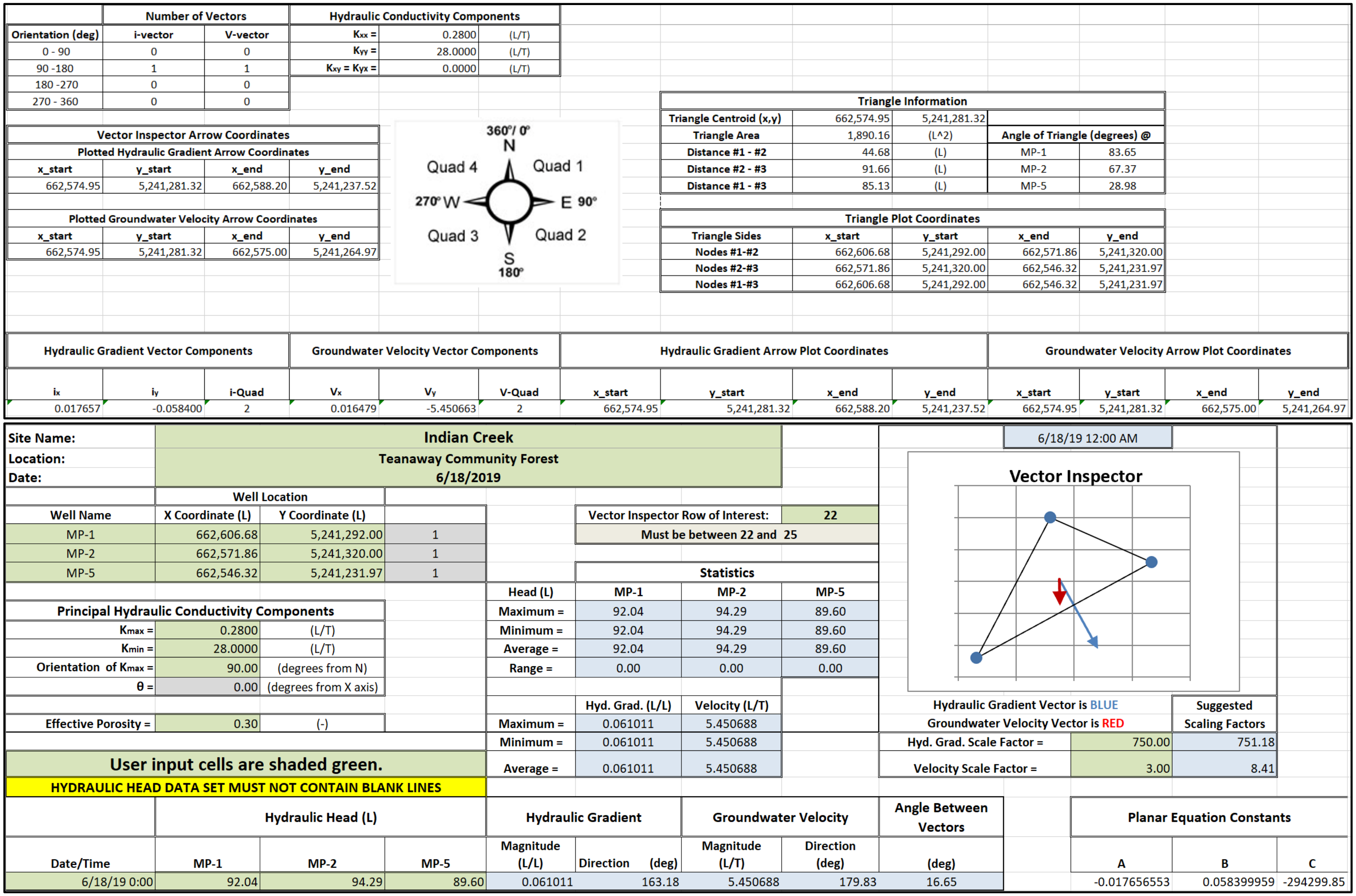
Appendix C- 3PE Procedure

3PE: A Tool for Estimating Groundwater Flow Vectors:

The EPA’s 3PE program was used to estimate groundwater flow directions at T2 and T8. 3PE uses the three-point triangulation method to estimate horizontal hydraulic gradients. It allows for more rapid calculations compared to the hand-drawn triangulation method. A full description of the tool and the required steps can be found in *3PE: A Tool for Estimating Groundwater Flow Vectors* (2014) published by the Environmental Protection Agency. However, a summary of the steps used for this analysis are listed below:

1.) After adding the necessary header information input the US State Plane coordinates of three wells.
2.) Add aquifer properties (hydraulic conductivity and porosity).
3.) Input hydraulic head data for each of the three wells for the specified date and time.
4.) Adjust the scale factors for the vector plots so that they are similar to suggested values and the arrows are visible.

An example of a 3PE spreadsheet used in this investigation is seen in Table C-1.



	Number of Vectors	
Orientation (deg)	i-vector	V-vector
0 - 90	0	0
90 -180	1	1
180 -270	0	0
270 - 360	0	0

Hydraulic Conductivity Components		
K_{xx} =	0.2800	(L/T)
K_{yy} =	28.0000	(L/T)
K_{xy} = K_{yx} =	0.0000	(L/T)

Vector Inspector Arrow Coordinates

Plotted Hydraulic Gradient Arrow Coordinates			
x_start	y_start	x_end	y_end
662,574.95	5,241,281.32	662,588.20	5,241,237.52

Plotted Groundwater Velocity Arrow Coordinates			
x_start	y_start	x_end	y_end
662,574.95	5,241,281.32	662,575.00	5,241,264.97

Triangle Information				
Triangle Centroid (x,y)	662,574.95	5,241,281.32		
Triangle Area	1,890.16	(L^2)	Angle of Triangle (degrees) @	
Distance #1 - #2	44.68	(L)	MP-1	83.65
Distance #2 - #3	91.66	(L)	MP-2	67.37
Distance #1 - #3	85.13	(L)	MP-5	28.98

Triangle Plot Coordinates				
Triangle Sides	x_start	y_start	x_end	y_end
Nodes #1-#2	662,606.68	5,241,292.00	662,571.86	5,241,320.00
Nodes #2-#3	662,571.86	5,241,320.00	662,546.32	5,241,231.97
Nodes #1-#3	662,606.68	5,241,292.00	662,546.32	5,241,231.97

Hydraulic Gradient Vector Components			Groundwater Velocity Vector Components			Hydraulic Gradient Arrow Plot Coordinates				Groundwater Velocity Arrow Plot Coordinates			
i_x	i_y	i-Quad	V_x	V_y	V-Quad	x_start	y_start	x_end	y_end	x_start	y_start	x_end	y_end
0.017657	-0.058400	2	0.016479	-5.450663	2	662,574.95	5,241,281.32	662,588.20	5,241,237.52	662,574.95	5,241,281.32	662,575.00	5,241,264.97

Site Name:	**Indian Creek**
Location:	**Teanaway Community Forest**
Date:	**6/18/2019**

	Well Location		
Well Name	X Coordinate (L)	Y Coordinate (L)	
MP-1	662,606.68	5,241,292.00	1
MP-2	662,571.86	5,241,320.00	1
MP-5	662,546.32	5,241,231.97	1

Principal Hydraulic Conductivity Components		
K_{max} =	0.2800	(L/T)
K_{min} =	28.0000	(L/T)
Orientation of K_{max} =	90.00	(degrees from N)
θ =	0.00	(degrees from X axis)

Effective Porosity =	0.30	(-)

User input cells are shaded green.

HYDRAULIC HEAD DATA SET MUST NOT CONTAIN BLANK LINES

Vector Inspector Row of Interest:	22
Must be between 22 and 25	

Statistics			
Head (L)	MP-1	MP-2	MP-5
Maximum =	92.04	94.29	89.60
Minimum =	92.04	94.29	89.60
Average =	92.04	94.29	89.60
Range =	0.00	0.00	0.00

	Hyd. Grad. (L/L)	Velocity (L/T)
Maximum =	0.061011	5.450688
Minimum =	0.061011	5.450688
Average =	0.061011	5.450688

6/18/19 12:00 AM

Vector Inspector

Hydraulic Gradient Vector is BLUE
Groundwater Velocity Vector is RED

		Suggested Scaling Factors
Hyd. Grad. Scale Factor =	750.00	751.18
Velocity Scale Factor =	3.00	8.41

	Hydraulic Head (L)			Hydraulic Gradient		Groundwater Velocity		Angle Between Vectors
Date/Time	MP-1	MP-2	MP-5	Magnitude (L/L)	Direction (deg)	Magnitude (L/T)	Direction (deg)	(deg)
6/18/19 0:00	92.04	94.29	89.60	0.061011	163.18	5.450688	179.83	16.65

Planar Equation Constants		
A	B	C
-0.017656553	0.058399959	-294299.85

Table C- 1: Example 3PE groundwater flow direction spreadsheet for T2 on June 18, 2018

Appendix D - Photos

Photo D- 1: Wood in floodplain. Photo taken in October 2018

Photo D- 2: Stream incision and wood placement. Photo taken in June 2018

Photo D- 3: Wood in stream. Photo taken in June 2018.

Photo D- 4: Piezometer installed in 2014 by Ecology, WDFW and KCT. Photo taken in June 2018.

Photo D- 5: MP-2 stream gage. Photo taken in October 2018.

Photo D- 6: Example of slug test setup at MP-2. Photo taken in October 2018.

Photo D- 7: Example of soil cores taken during piezometer installation in October 2018.

Photo D- 8: Piezometer installed by Nora Boylan in October 2018.

Photo D- 9: Location of MP-7 close to creek's edge. Photo taken in April 2019.

Photo D- 10: Large wood in floodplain. Photo taken in May 2019.

Photo D- 11: PVC pipe holding barometer used for water level compensation. Photo taken in June 2019.