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Evaluating Floodplain Hydrologic Connectivity, Yakima River, WA

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EVALUATING FLOODPLAIN HYDROLOGIC CONNECTIVITY,

YAKIMA RIVER, WA

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by

Cristopher Morton

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ABSTRACT

EVALUATING FLOODPLAIN HYDROLOGIC CONNECTIVITY,

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River side-channels provide habitat for threatened fish, and restoring such habitats is a goal of resource managers. Resource managers use side-channel reconnection projects to increase the quality and quantity of aquatic floodplain habitat, and evaluating the effectiveness of reconnection is a crucial and often neglected part of these projects. The purpose of this research was to collect baseline data to determine if and how floodplain connectivity affects water quality and quantity in side-channel habitat on the Yakima River. This research compared seasonal differences in habitat quality between connected and disconnected channels by evaluating bi-weekly measurements of surface water quality and water level stage, as well as seasonal changes in water table elevation measured in monitoring wells, before a floodplain reconnection project. Water quality parameters assessed included temperature, dissolved oxygen, conductivity, turbidity and pH. Isotope concentrations of ^{18}O and ^{2}H, and temperature and conductivity profiles of side-channels were used to help detect groundwater/surface water interactions. Statistical analyses, geographic information systems, and computer models were used to detect significant changes or relationships in the data. Significant seasonal variations in water quality and water table elevations were found among and between connected and disconnected side-channel sites. Water quality and quantity in the floodplain are expected to increase after the project. These

data and analyses will provide vital information to assess future floodplain restoration and management.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONTINUED)

Figure Page

CHAPTER I

INTRODUCTION

Problem

Human activities such as over-harvest and habitat destruction have decimated salmonid fish runs, reducing wild populations by over 99% in the Yakima River basin over the last 150 years and leading to the extirpation of several species of salmon (McIntosh et al. 1994; Anchor QEA 2011; YN and WDFW 2004). By the late twentieth century, fisheries managers with the Yakama Nation and Bonneville Power Administration, along with non-profit organizations and state and federal government agencies, began taking steps to reestablish anadromous (migratory) fish runs throughout the Yakima River basin (YSFWPB 2004b; YNF 2014; YCT 2016; Sampson and Fast 2016; Larimer 2016; YSFWPB 2004a; ECONorthwest 2011). Despite tens of millions of dollars spent on projects, the effectiveness of restoration efforts has been unclear. Monitoring and evaluating the effectiveness of habitat restoration strategies has been largely neglected in Washington state, with less than 20% of stream restoration projects containing some sort of monitoring in the project record as of 2004 (Bernhardt et al. 2005).

Resource managers undertake floodplain restoration projects to increase side-channel habitat and improve water quality in existing side-channels through temperature moderation, enhanced nutrient cycling, boosted biological production from hyporheic (zone of stream and groundwater mixing) flow, and increased channel disturbance and complexity (Roni et al. 2006; Hester and Gooseff 2010; Stanford and Ward 1993; Swenson, Whitener, and Eaton 2003; Boulton et al. 2010). Thus far, studies of habitat restoration in the Yakima River basin have measured changes in water quality, flow regime, number of stream miles added, and number of acres of riparian habitat protected along tributaries and reaches of the Yakima River (YNF 2013; YNF 2014; YSFWPB 2004b). However, studies assessing the changes in side-channel water quality and water movement due to side-channel reconnection on the Wapato reach of the Yakima River, and installation of a check dam on a connected side-channel of the Yakima River, have not been completed. Monitoring the effects of these types of restoration project will provide information that will be beneficial to managers regarding the effectiveness of side-channel reconnection, and will inform future restoration strategies.

Purpose

The purpose of this research is to establish baseline data to evaluate the future effects of side-channel reconnection efforts on habitat and water storage along the Wapato Reach of the Yakima River, east of Toppenish, Washington. This was done by assessing water quality, water movement, and depth to the water table before a floodplain reconnection project (ICFI and R2C 2012). In summer 2019, the Yakama Nation will reconnect a floodplain along the main-channel Yakima River that has been cut-off from Yakima River high flows, and they will divert portions of high flows to existing side-channels. These baseline data provide an opportunity to monitor the effectiveness of these specific restoration efforts on the Yakima River.

The main questions addressed in this research are:

1) Are there seasonal changes in groundwater movement through the floodplain?
2) How do surface water and groundwater movement influence each other’s water quality parameters and water levels?

3) How do surface water and groundwater contribute to water storage in the floodplain?

The research objectives to answer these questions are:

1) To collect side-channel water quality (dissolved oxygen, conductivity, pH, turbidity, and temperature) and flow (m^3/s) data to determine differences between sites and seasons.
2) To gather groundwater depth and side-channel water level data from groundwater monitoring wells and side-channel stage recorders.
3) To use statistical analyses and Geographic Information Systems (GIS) to investigate changes in water quality measures, side-channel flow, and water levels inside groundwater monitoring wells before floodplain reconnection to determine changes in and relationships between surface and subsurface flow.
4) To use findings of this research to make recommendations regarding future floodplain reconnection efforts along the Yakima River.

Significance

This research will fill a gap in understanding how these types of restoration efforts affect floodplain habitat on the Yakima River specifically, and on similar rivers, more generally. Providing data that will be used to establish how the restoration project affects water quality and the water table in the study area will help inform resource managers about the effectiveness of similar projects aimed at improving floodplain habitat and water storage (Rumps et al. 2007). Describing how the water table changes before the project is useful for understanding how shallow groundwater water moves through the floodplain, which has implications for water quality and water storage (Seedang et al. 2016).

Additionally, salmonids are an important natural resource to the area, and an invaluable cultural resource to Native Americans. The reduction of these fishes in the Yakima River has been devastating to tribes, and reestablishing self-sustaining wild runs is of utmost consequence (Yakama Nation 2016). Since the 1980s, much of the effort to rehabilitate salmon populations has focused on releasing hatchery fish to enhance runs and establish productive populations. It has become increasingly apparent that these endeavors alone are inadequate to reach those goals, and that the quality and quantity of habitat needs to be addressed (Yakama Nation Fisheries 2014; Sampson 2016). Monitoring river restoration projects is vital to building an understanding of how to reconnect floodplains in ways that effectively create new habitat and improve existing habitat for anadromous and resident fish (Palmer et al. 2007). This study contributes to the current knowledge of the effectiveness of floodplain reconnection efforts in improving the Yakima River. Modeling changes in the water table before the project will be useful for understanding how hyporheic water moves through the floodplain, which has implications for water quality and water storage, as discussed earlier (Seedang et al. 2016; Stanford and Ward 1993).

CHAPTER II

LITERATURE REVIEW

Floodplain Reconnection

Habitat for Fish

Analysis of restoration projects around the world has shown that increasing hydrologically connected side-channel habitat provides more habitat and more diverse conditions for fish to use at different life stages (Roni et al. 2002, 2008; Rosenfeld et al. 2008). Perennially flowing side-channels provide areas of gravelly stream bed that are used for spawning, while side-channels that are connected for just a few weeks of the year during times of flooding can be useful over-wintering and salmonid rearing habitat (Jeffres et al. 2008; Henning et al. 2006; Rosenfeld et al. 2008). Restoration of lateral connectivity between rivers and floodplains allows natural disturbance to return to disconnected areas, bringing habitat variability, organic matter, and nutrients needed for diverse and functional ecosystems. Studies investigating fish yields and growth rates have concluded that increased river-floodplain connectivity increases fish productivity, and juvenile salmonids grow quicker in side-channel habitats than main river channels (Bayley 1991; Henning et al. 2006; Jeffres et al. 2008). Increasing side-channel and floodplain connectivity can also affect aquatic habitat by increasing hyporheic flow through the floodplain (Hester and Gooseff 2011). Increasing hyporheic flow through the floodplain carries water with higher dissolved oxygen (DO) concentrations (relative to substrate concentrations), lower temperatures, and more available nutrients that help salmonid eggs grow and ecologically important benthic macroinvertebrates survive (Hester and Gooseff 2011). Thus, understanding how these interactions change with reconnection is important to evaluating project effectiveness in improving habitat quality (WDFW 2009).

Aquatic and benthic macroinvertebrates are important components of river and floodplain ecosystems, directly influencing nutrient cycling and salmonid production, and their abundance and diversity are related to lateral connectivity between a river and its floodplain (Richardson 1993, Nelson 2005; Wallace and Webster 1996; Gallardo et al. 2008; Karaus et al. 2013). Shredding, grazing, and predatory macroinvertebrates help process coarse particulate organic matter and fine particulate organic matter, and filter feeders decrease the spiraling length of nutrients (increase the efficiency of nutrient use) in the stream (Cole and Weihe 2016; Wallace and Webster 1996). Increasing macroinvertebrate production has also been tied to increased fish yields and growth rates, with higher macroinvertebrate biomass increasing food availability (Nelson 2005; Roni et al. 2008). These macroinvertebrates not only reside in surface water, but also in the interstitial spaces of sediment where hyporheic and groundwater flows, and even those living in the ground can be a large source of food for aquatic species as they enter surface water (Gallardo et al. 2008; Karaus et al. 2013).

A critical aspect of monitoring habitat restoration is to collect and compare water quality in side-channel habitat before and after a restoration project (Roni et al. 2008). Water quality metrics such as temperature, pH, dissolved oxygen (DO), and turbidity are used as indicators of stream habitat quality, while temperature and specific conductance, a proxy indicator of differences in dissolved mineral content, are used as indicators of surface-groundwater interactions (Roni et al. 2008; Jeffres et al. 2008; Torgersen and

Ebersole 2012). While these are not the only measures of aquatic habitat health, they are well-established and representative indicators of habitat health (Lambing 1983).

Water Quality and Quantity

Stream temperature has been identified as one of the most important metrics of aquatic habitat quality, affecting overall biological production, and reducing stream temperatures during the summer months is a common goal in habitat restoration projects (Bernhardt et al. 2005; Rumps et al. 2007; Katz et al. 2007; Sampson and Fast 2016). Surface water-groundwater interactions significantly affect river and side-channel water temperatures in alluvial streams, as hyporheic exchange (stream water-groundwater mixing) moderates stream temperatures and base flows in summer (Torgersen and Ebersole 2012). Increasing hyporheic flow and surface-groundwater interaction in the floodplain can help moderate water temperatures in side-channels (Brunke et al. 1997; Torgersen and Ebersole 2012). Side-channels provide resting and rearing habitat for fish, and are important for minimizing temperature stress on migrating fish, such as chinook (*Oncorhynchus tshawytscha*), coho (*Oncorhynchus kisutch*), and sockeye (*Oncorhynchus nerka*) salmon by providing thermal refugia (Roni 2006; Yakama Nation 2016). Thermal refugia—areas where water temperature is more favorable than the surrounding water—are critical for anadromous fish survival during periods of extremely high or low air temperatures (Torgersen and Ebersole 2012).

DO is a common measurement of stream habitat health, and is influenced by surface-groundwater interactions (Roni et al. 2008; Boulton et al. 2010). DO is also affected by temperature, with warmer water losing its capacity to hold dissolved gasses, creating a stressful environment for salmonids (Skelton-Groth and Wu 2002). Monitoring

DO provides another useful metric for habitat quality as it can be a limiting factor for fish and other biota (England, Skinner, and Carter 2008).

Temperature and specific conductance can be useful measures of surface-groundwater interactions, specifically where groundwater is discharging into surface water, with relatively higher or lower temperature or higher specific conductance readings indicating groundwater entering stream flow (Lee et al. 1997; Vaccaro and Maloy 2006; Rosenberry and LaBaugh 2008). Lee et al. (1997) towed a probe measuring electrical conductivity behind a boat down the Columbia River, Washington to locate areas of relatively higher electrical conductance along the river bed, installing piezometers to measure the vertical movement and electrical conductance at several locations of elevated readings. Groundwater inputs to the stream at these locations were confirmed with piezometer water levels, subsurface/surface conductivity, and water chemistry analyses. Vaccaro and Maloy (2006) conducted water temperature profiles along the Yakima River during summer and fall to identify areas of relatively cooler water that indicated groundwater input. The authors were able to establish the reproducibility of the method by conducting many profiles over two separate surveys. Temperature and conductivity profiles with data loggers are still commonly used, and are recommended by the Environmental Protection Agency to identify groundwater inputs as they relate to cold-water refugia for fish (Torgersen and Ebersole 2012).

Improving side-channel connectivity and surface-groundwater interactions can be important to resource managers in terms of water storage (aquifer recharge) for human use. Increasing connectivity increases surface-groundwater interactions, which slow the velocity of stream flow and increase the water residency time, potentially increasing the percolation of shallow groundwater into the aquifer below (Vaccero 2011; Westbrook et al. 2006). Westbrook et al. (2006) used a network of 95 monitoring wells in a floodplain of the Colorado River to monitor the changes in hydrology caused by beaver dams in the area. The authors found that areas inundated by beaver dams not only increased the water table elevation, but also increased surface water levels to the point that flooding occurred. Flooding helped increase the surface area for water to infiltrate the surface and potentially percolate through the water table, and it helped expand the riparian cover in the area. These results indicate that floodplain reconnection can be a valuable tool for increasing aquifer storage. Vaccaro (2011) used minipiezometers, well data, and surface water stage and discharge recorders to characterize stream-aquifer interactions along the Yakima River over several years. The author describes the Toppenish reach as a gaining reach, meaning that groundwater discharges to the stream over its course.

Statistical and geostatistical methods can be used to find relationships between changes in water elevations at wells and surface water stage recorders (Prinos 2005; Nikroo et al. 2010; Kumar and Remadevi 2006; Kumar 2007). Statistical relationships can be explored with a Pearson r association test, and kriging interpolation can be used to look at geostatistcal patterns in the water table. Statistical relationships reveal patterns of seasonal water movement through an area, but need to be combined with further analysis because correlation does not prove a causal relationship (Prinos 2005). Statistical relationships can also be used to determine if wells are unnecessary, as wells that are highly correlated may indicate redundancy in the well network; seasonal correlations need to be accounted for, though, since the strength of the relationship may not be consistent between seasons (Prinos 2005).

Interpolated surfaces using kriging give an idea of the depth to water table in between monitoring wells and thus the direction of flow through the floodplain (Nikroo et al. 2010; Kumar and Remadevi 2006). Nikroo et al. (2010) used several kriging interpolation methods (simple, ordinary, co-kriging, residual kriging) and found that simple and residual kriging interpolations were acceptable for predicting groundwater elevation data with large distances (4 km) between wells. Kriging is also considered more robust than other interpolation methods such as inverse distance weighted when interpolating depths to the water table in a floodplain (Kumar and Remadevi 2006). Kumar and Remadevi (2006) used kriging interpolations during pre and post-monsoon seasons in India for six years using at least 50 wells and found that kriging performed better at predicting groundwater depths than inverse square distance, having smaller variance and less extreme troughs and valleys in the predicted surface. Kumar (2007) conducted a similar study in pre and post-monsoon seasons in India, comparing kriging with inverse distance weighted interpolation and concluded that kriging provides more realistic results, and that combining the kriging interpolated surface with ground elevation is useful for identifying water logged and inundated areas.

Monitoring Effectiveness

How Monitoring is Done

Post-project monitoring is necessary to study ecological responses to floodplain reconnection (Roni et al. 2008). Past studies assessing floodplain reconnection have focused on monitoring physical and biological habitat characteristics, such as lengths of channels reconnected, water quality, surface flow, macroinvertebrate counts, and fish growth rates in disconnected side-channels (Ward et al. 1999; Snyder and Gabriel 2004;

Bernhardt et al. 2005; Gabriel and Snyder 2006; Rumps et al. 2007; Roni et al. 2006). Rumps et al. (2007) found through interviews with people involved in restoration projects that 55 percent of monitoring efforts focused on chemical and physical metrics, while 15 percent monitored only chemical (e.g. pollutants) aspects, and 21 percent took photos or made visual observations. A combination of these monitoring efforts gives a better picture of the overall project effectiveness, and should be considered for project monitoring.

Roni et al. (2008) reviewed 90 project effectiveness studies for floodplain reconnection projects from 16 countries, finding that physical measurements of the area and length of reconnected habitat were the most common measure of project effectiveness, along with lateral connectivity when levee set-backs were conducted. Projects around the world—in Europe, Southeast Asia, and the United States—have demonstrated increases in plankton production, fish diversity and biomass, nutrient transport, and lateral channel movement with side-channel reconnection and levee setbacks (Roni et al. 2008). Little difference has been found in fish biomass production between natural and artificial ponds and disconnected channels, indicating floodplain habitat reconnection is beneficial in general (Roni et al. 2008; Rosenfeld et al. 2008)

Problems arise when trying to review the effectiveness of restoration projects because post-project monitoring records are rarely accessible to the public, if they are able to be located at all. Palmer et al. (2007) describe the issue as arising from the lack of funding and organizing systems to maintain monitoring records, and the loss of files as employees leave positions. The authors suggest this loss of information is holding back the potential of restoration projects as managers do not have experience to draw on to inform decisions. Strategic monitoring of restoration projects with plans for the dissemination of collected information incorporated in project design are needed to maximize restoration effectiveness (Palmer et al. 2007).

There has been criticism that monitoring efforts are often too limited in their temporal scale (most monitor less than 5 years) to be able to draw significant conclusions about how effective floodplain reconnection efforts are at rehabilitating fish populations, even with demonstrated short-term benefits. This could be because floodplain reconnection is still a relatively new habitat restoration technique (Rumps et al. 2007; Roni et al. 2008). Further criticism of monitoring programs has focused on the metrics that some projects include as part of their monitoring efforts, arguing that fewer than half of 317 restoration projects set objectives that could be measured, opting instead for measures such as visual assessments and public opinion (Bernhardt et al. 2005; Palmer et al. 2007). As mentioned before, most river restoration projects are undertaken without monitoring project effectiveness (Bernhardt et al. 2005). Researchers have argued that implementing restoration projects is not enough; monitoring project effectiveness is necessary to inform the development of future projects, and helps to develop a comprehensive approach to watershed management (Roni et al. 2002; Wohl et al. 2005; Palmer et al. 2007; Katz et al. 2007; Rumps et al. 2007). Since the rehabilitation of natural processes can require many years to materialize, longer term (>2 years) monitoring of habitat quality and quantity metrics should be planned (Palmer et al. 2007; Tompkins and Kondolf 2007).

Monitoring Groundwater

Assessing changes in lateral connectivity between the main channel of a river and disconnected side-channels or ponds in its floodplain are commonly used to monitor levee modification projects (Roni et al. 2008). This is accomplished by observing changes in the depth to the water table at different distances from a stream, or by observing changes in the stage of ponds and side-channels that are only connected to a stream by groundwater flow. Before being able to monitor changes in the water table, information about the position of the water table must be collected. One of the simplest and most effective ways to monitor changes in the water table is to install a grid of groundwater monitoring wells with water level data loggers placed inside of them (Vaccaro and Maloy 2006; WRAP 2000; Sprecher 2007). Piezometers can also be used to monitor groundwater levels, but are problematic when attempting to observe the water table (Rosenberry and LaBaugh 2008).

Piezometers differ from monitoring wells in that piezometers are only open to groundwater exchange at the bottom of the pipe, while wells are perforated for the length of the pipe (WRAP 2000; Rosenberry and LaBaugh 2008). Single piezometers present a problem in measuring the actual depth of the water table, as the water level inside a piezometer may not reflect the actual position of the water table. This occurs because the piezometer measures the hydraulic head at a given location, and so the water level inside a piezometer with the screened interval below the water table is susceptible to the vertical aspects of groundwater movement. A monitoring well avoids this problem by being slotted along the entire length of the well that will intersect the water table (WRAP 2000; Rosenberry and LaBaugh 2008). A group of piezometers allows for the creation of a flow net from which the location of the water table can be calculated, and the amount of vertical flow can be derived from several “nested” piezometers installed next to each other (WRAP 2000; Rosenberry and LaBaugh 2008).

A pressure sensor suspended from the top of the well records changes in the water table as the water level inside the monitoring wells moves up or down, allowing comparisons between pipes to be made after correcting for changes in elevation (WRAP 2000). Comparing water levels between monitoring wells provides an understanding of how surface water and shallow groundwater move through the floodplain, indicating whether areas are reconnected by the restoration. Combining these data with other measures such as side-channel water depth and surface water specific conductance provides a clearer picture of how subsurface flow responds to changes in surface flow (Vaccaro and Maloy 2006).

Ground penetrating radar has also been used to investigate groundwater levels and substrate characteristics (Olhoeft 2002; Bowling et al. 2005; Lane et al. 2016). Significant radar reflections and attenuation can be used to infer subsurface features such as the water table, boundaries between sediment types, and solid objects (Bowling et al. 2005; Lane et al. (2016). Highly contrasted lines of black and white indicate strong reflections that generally reveal changes in substrate material and/or moisture content. The saturated zone below the water table can also be identified by strong attenuation of radar return signals, as water quickly absorbs them. Higher frequency antennae are appropriate for higher resolution, shallower sub-surface investigations, while lower frequencies penetrate further into the ground but sacrifice resolution. 500MHz is in the middle of the range of frequencies used for environmental monitoring (Olhoeft 2002).

Care must be taken when using GPR to locate subsurface features, as cell phones and over-land structures (such as telephone wires) can interfere with data collection, but GPS units are not likely to alter observations (Olhoeft 2002).

Relationships between surface and groundwater can be investigated using ratios of stable isotopes such as deuterium and ^{18}O (Zhao et al. 2013; Gazis and Feng 2004; Gat 1996). As surface water and shallow groundwater evaporate, they are enriched with ^{18}O, while deep groundwater is not affected by evaporation and retains ^{18}O concentrations similar to its source water. Groundwater is more affected by evaporation during long hot and dry periods, such as in desert soils (Gat 1996). The sources of mobile and immobile soil waters can be differentiated by their isotopic ratios when compared over time and with precipitation isotopic concentrations (Gazis and Feng 2004). Comparing isotopic ratios with precipitation and snowmelt during specific events can also be used to investigate water sources and subsurface flow and mixing, which are usful for informing hydrologic models of watersheds (Zhao et al. 2013). Comparing Oxygen-18 and Deuterium ratios can provide insight into the source of surface and groundwater when compared to global and local meteoric water lines (GMWL, LMWL). The GMWL represents an equation that describes the global average relationship between isotopes ^{18}O and ^{2}H in natural freshwater that has not undergone heavy evaporation (Gat 1996). The LMWL describes this relationship for a particular area and can vary from the GMWL due to heavy evaporation and precipitation.

CHAPTER III

STUDY AREA

Research Area

Setting

The Yakima River basin drains the east slope of the Cascade Mountains in central Washington State, covering over 16,000 square kilometers from the Cascade Mountains to the Columbia River (Anchor QEA 2011)(Figure 1). The Yakima River headwaters are located in upper Kittitas County, flowing south for 344 kilometers through Yakima County and along the Yakama Reservation, until joining the Columbia River at Richland, WA (YSFWPB 2004). The Yakima River and its tributaries play an vital role for humans and wildlife by providing irrigation and habitat, especially in the more arid eastern and southern areas of the basin. Over 150 years of water resource development in the basin has led to an increasingly regulated river, with positive consequences for many people, and negative consequences for many fish (Anchor QEA 2011).

Hydrology

The modern flow regime of the Yakima River differs significantly from the historic flow regime. These changes in the flow regime are due to regulation by dams and development of the river as a source of irrigation (Tuck et al. 1999). Before regulation by dams and irrigation diversions, it was characterized by moderate flows (~113 m^3/s) throughout the winter, followed by high flows (~226-283 m^3/s) during the spring when rain-on-snow events (or “freshets”) would send floods down the unregulated Yakima. Low flows (~28 m^3/s) would persist from mid-summer through autumn (Tuck et al. 1999). The highest flow event recorded at the Yakima River gage station near Parker in

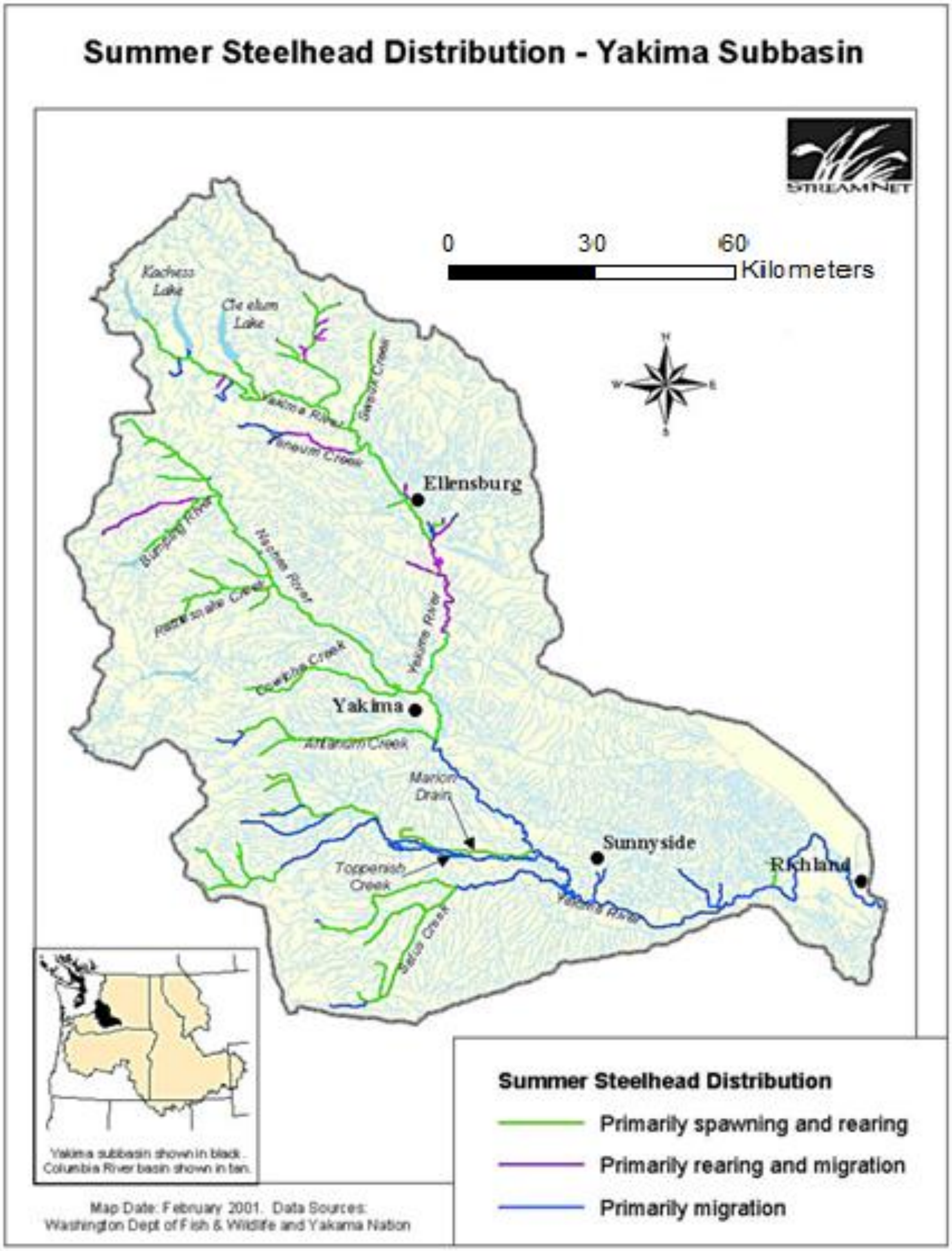

Figure 1. Location of the Yakima River basin, illustrating its hydrologic network and historic range of summer steelhead. The study area is located just to the right of the Marion Drain label, in "primary migration" habitat. (Adapted from YN and WDFW 2004, p.18).

the last 100 years occurred on February 8-10, 1996, when discharges were 925 m^3/s (02/08), 1530 m^3/s (02/09), and 1133 m^3/s (02/10) (Bureau of Reclamation, 2018). The second highest discharge event at the location was on and around December 30, 1917, with a flow of 1402 m^3/s. Less frequent and lower intensity high flow events, low flows that occur earlier in the year, and smaller discharges than historic low flows, constitute the modern flow regime of the Yakima (Figure 2).

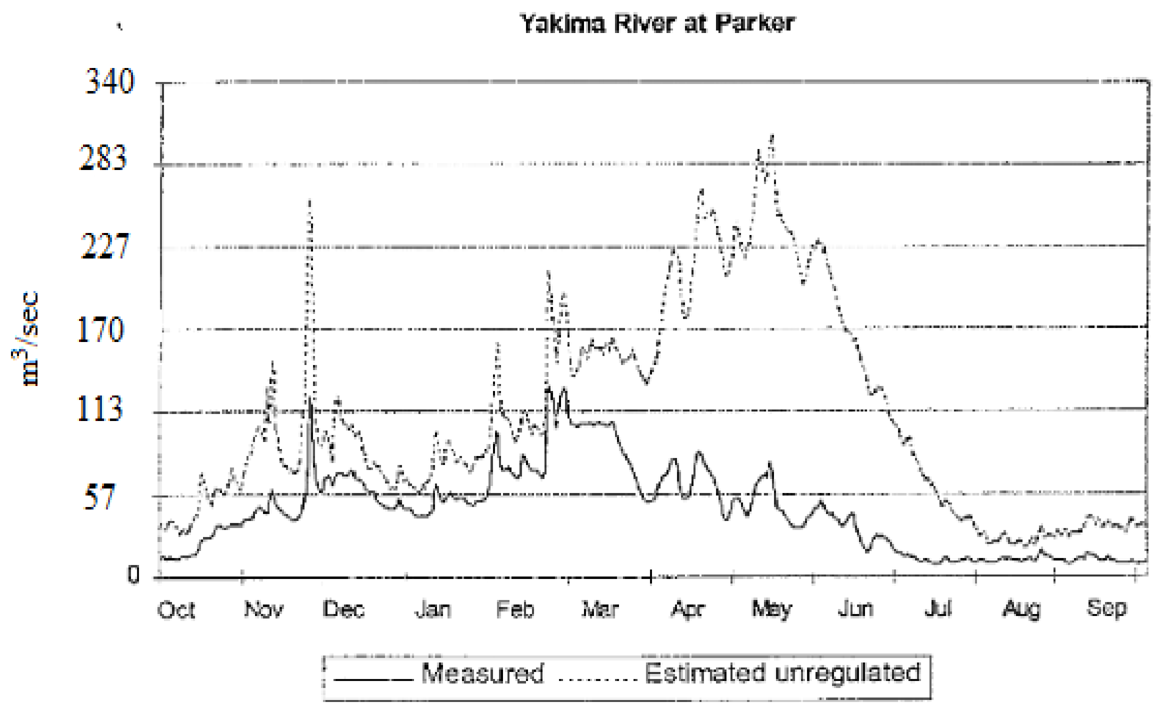

Figure 2. Hydrograph illustrating differences between the historic (unregulated) discharge of the Yakima River, versus the modern dammed and diverted river discharge at a USGS gauge at Parker, Washington, north of Meninick Wildlife Area. (Adapted from Tuck et al. 1999 p. 2-10).

Climate

The climate of the Yakima Basin changes moving east from the Cascade Mountains to the Columbia Plateau, becoming increasingly arid and slightly warmer throughout the year (Western Regional Climate Center 2017; World Climate 2017) (Figure 3). The wettest and coldest periods occur during the autumn and winter, with the driest and warmest periods occurring in the summer throughout the basin. Drought is a threat in the more arid regions, with the last drought in the region declared in 2015. Droughts cause low flows in channels due to low precipitation and can stress fish with higher water temperatures (WSDOE 2017; WDFW 2005).

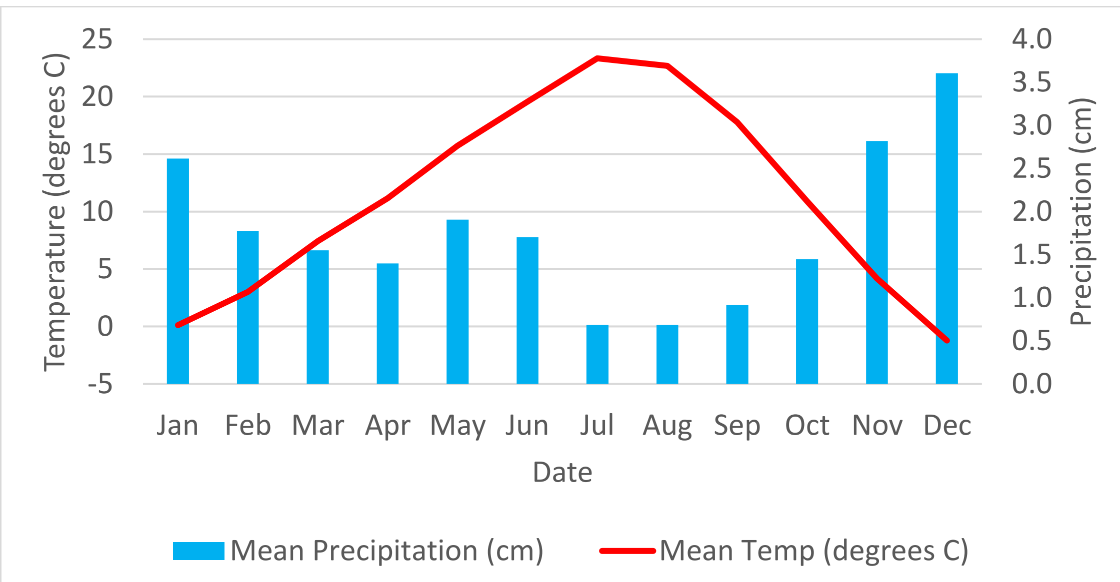

Figure 3. Climograph of Wapato, WA. Modified from WRCC data.

Study Site

Location

The study site is located in the lower Yakima River basin in south-central Washington State, along about 5.5 km of the Wapato reach of the Yakima at river mile

89.5 (Figure 4). Several land purchases and leases by the Yakama Nation make up the 6.2 km^2 Meninick property, named after Johnson Meninick and his family, who have been active in fighting to preserve native fishing rights in the area throughout the 20th and into the 21st century (Prengaman 2015). The purchases of the Meninick properties were made in 2000 and 2001 with the goal of restoring floodplain habitat that had been cut off by the installation of a levee to protect agricultural land (Hames 2008; Hames 2006; Yakama Confederated Tribes 2016). The levee is located on the main stem of the Yakima River at river mile 89.3-89.7, and is about 740 meters long and 4-5 meters high from the current water level (ICFI and R2C 2012).

In 2019 the Yakama Nation is planning on carrying out a floodplain reconnection project in the study area. They will be pursuing multiple strategies to increase and enhance aquatic and terrestrial habitat, as well as increase groundwater storage in and around the Meninick property. The project is intended to increase side-channel and floodplain connectivity to the Yakima River, and will include excavating material and installing woody material structures to divert flow into side channels and onto the floodplain (Lind and Miller 2018). The project is designed so that side-channels and the floodplain in the area will be activated at a Yakima River discharge of 28.3 m^3/s (1000 cfs), instead of the 198.2 m^3/s (7000 cfs) that is currently estimated to be needed for activation. Native vegetation will be seeded and planted in areas disturbed by excavation, site access, and material storage.

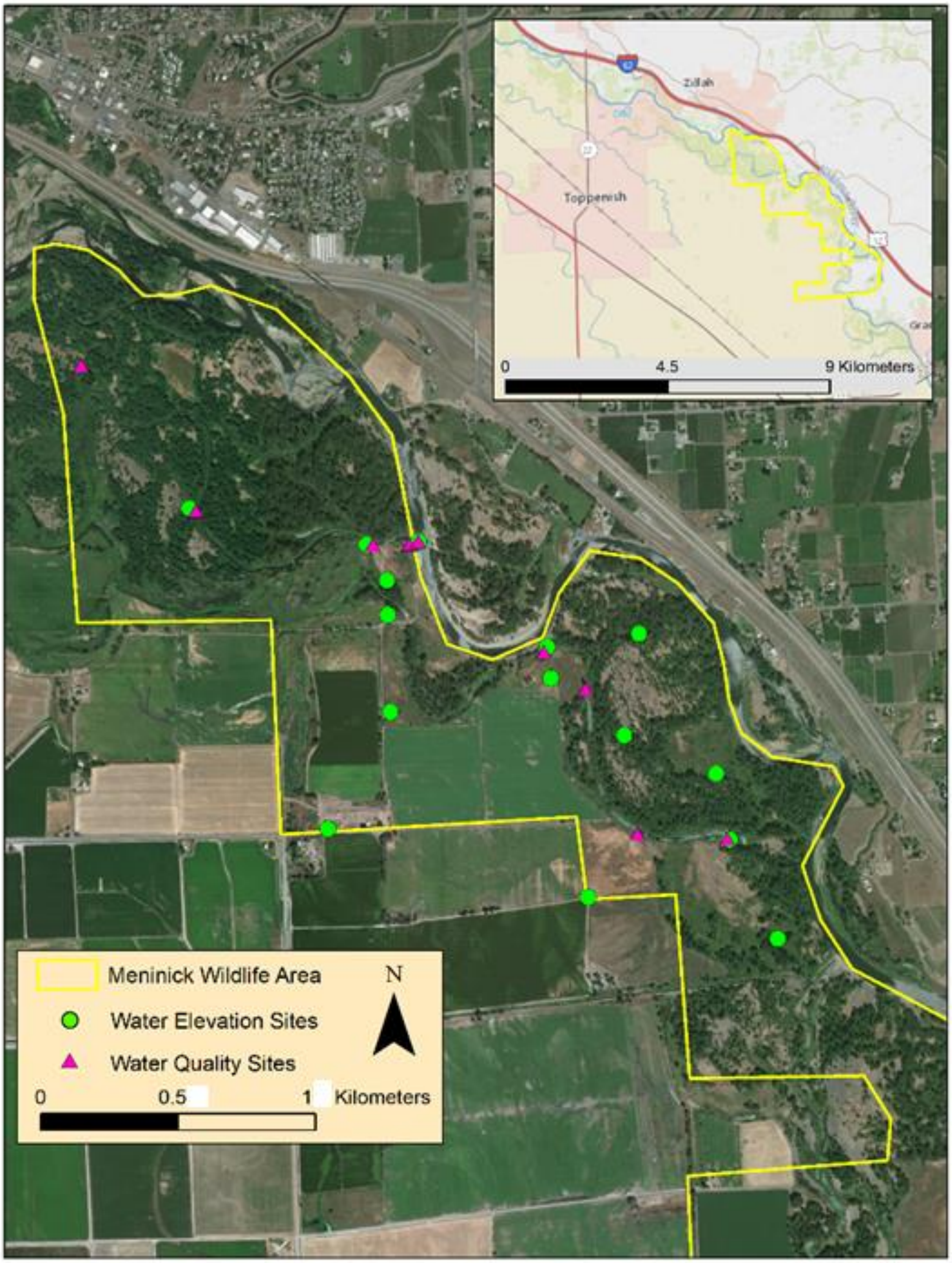

Figure 4. Meninick Wildlife Area with water quality and monitoring well sites, and locations of levee removal and check dam installation.

Geology

Much of the Wapato reach of the Yakima River, especially in the study area, which is almost exclusively Yakima River flood plain deposits, is composed of alluvial deposits that overlay ancient basalt flows by more than 660 meters in some locations (Jones, Vaccaro, and Watkins 2006). The study area is made up entirely of alluvium from the Yakima River, with a slope of less than 3% (Geomorphological Research Group 2016).

Gigantic ancient (~18-12 Ka ago) ice age floods originating in Idaho and Montana, known as the Missoula Floods, backed up into the valley leaving deposits of silty soils along with the alluvium from Toppenish Creek and the Yakima River (Uebelacker et al. 2002). Soils in the study area play a role in controlling subsurface flow, with water traveling faster through material with higher hydraulic conductivity (higher ability of water to flow through), and slower through material with lower hydraulic conductivity (Rosenberry, Labaugh, and Hunt, n.d.). Soils in the study area range from silty clay loams to gravelly loams, with hydraulic conductivities ranging from 1.4-141.1 micrometers per second (NRCS 2017)(Figure 5).

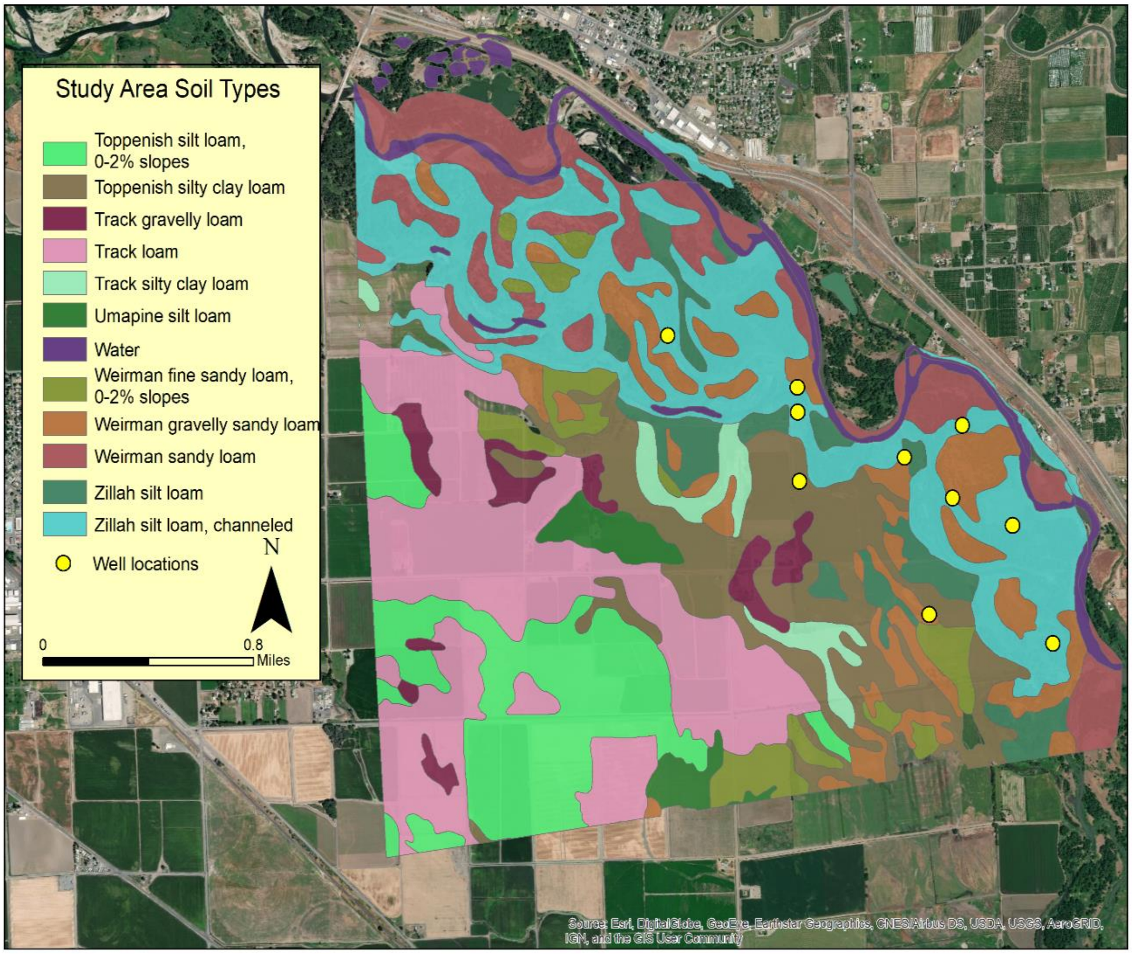

Figure 5. NRCS soil type definitions in the study area and locations of monitoring wells. Data from ESRI et al., Soil Data Viewer, ArcMap.

Floodplain Connectivity

Human activities, such as road building and levee construction, have led to a surficial disconnection of the Yakima River from its historic floodplain (Uebelacker et al., 2002) (Figure 6). A large portion (~70%) of the floodplain was altered and disconnected by the early 20th century, with further regulation of the river and disconnection occurring over the next 100 years (Uebelacker et al., 2002). Over 18,000 ha of Holocene floodplain connected to the Yakima River were disconnected from 1884-1915, over 1,000 ha were lost from 1916-1964, and another >3000 ha lost from 1965-2002 (Uebelacker et al., 2002). Only about 15% of the pre-1884 Holocene connected floodplain remained in 2002, severely limiting the lateral movement of the Yakima River in many places. Levees in the area have disconnected floodplain habitat in order to protect agricultural land from high flows and disturbances by the adjacent river; reconnecting habitat is a primary restoration goal along the Wapato reach (ICFI and R2C 2012).

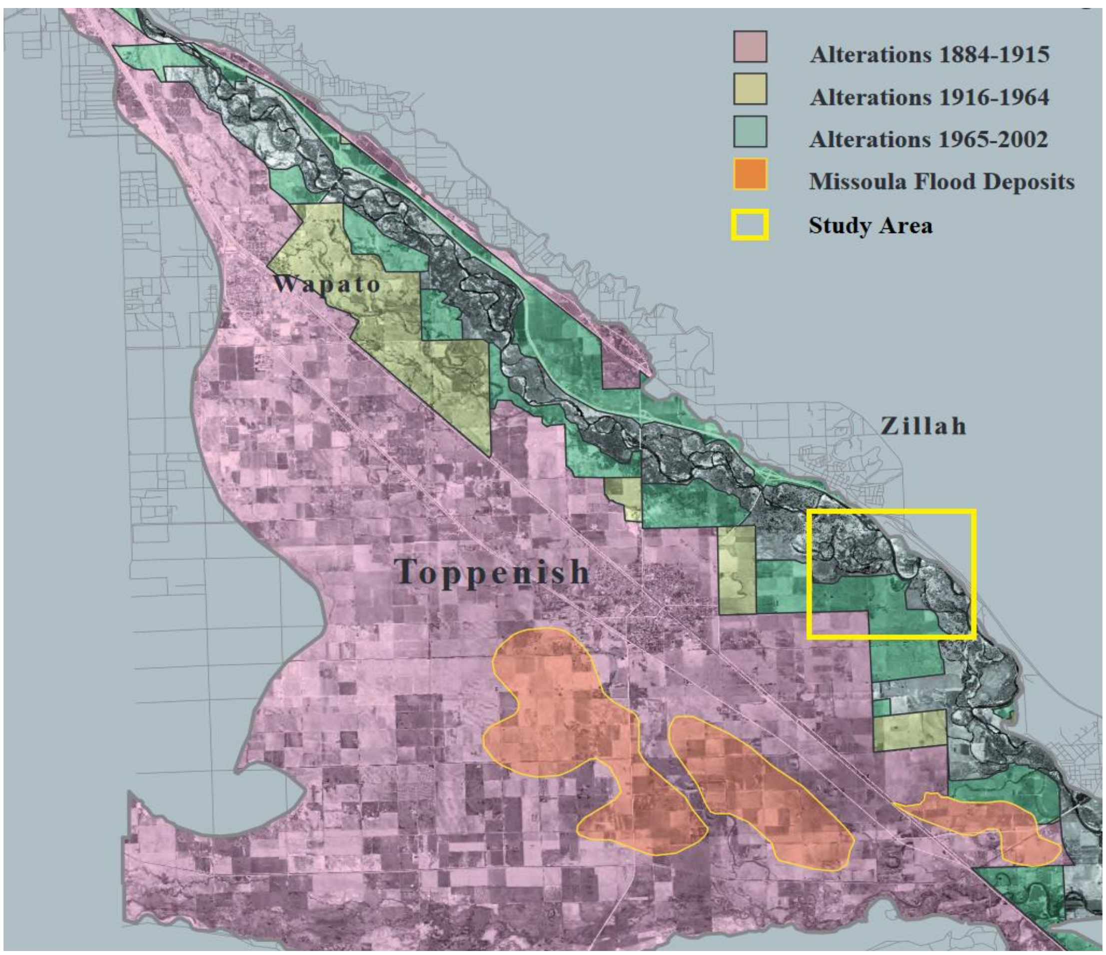

Figure 6. Historic disconnection of the Yakima River from its floodplain over the years 1884-2002. (Adapted from Uebelacker et al. 2002).

CHAPTER IV

METHODS

The Yakama Nation will reconnect approximately one square kilometer of floodplain by providing water to two kilometers of side-channels for cold water fish refugia (Yakama Nation IP Habitat Proposals 2017-2019, 2016). There were four main objectives in this research, using a variety of methods:

1) To use statistical analyses and GIS to quantify changes in water quality measures, side-channel flow, and water levels inside groundwater monitoring wells before check-dam installation and levee removal to determine seasonal changes in and relationships between surface and subsurface flow; and
2) To measure water table elevation and side-channel water level data from groundwater monitoring wells and side-channel stage recorders;
3) To use findings of this research to make recommendations regarding future floodplain reconnection efforts along the Yakima River.

Water Quality

Water quality data were collected at nine sites, including seven that have been studied in the past by Snyder and Gabriel in 2004 and 2006 (Figure 7). Four sites were located on a connected side-channel (CSC 0-3), three sites were located on a disconnected side-channel (DSC1-3), one site was in a disconnected pond (DP), and one site was the main channel of the Yakima River (MC). These sites were selected because they are easily accessible at different stage heights, and they provided longitudinal profiles of water quality. Data were collected biweekly while the sites were accessible, then monthly or bi-monthly while they were less accessible during times of excessive ice and snow cover or high side-channel flows that cut off access (November 22, 2016 – March 13, 2017).

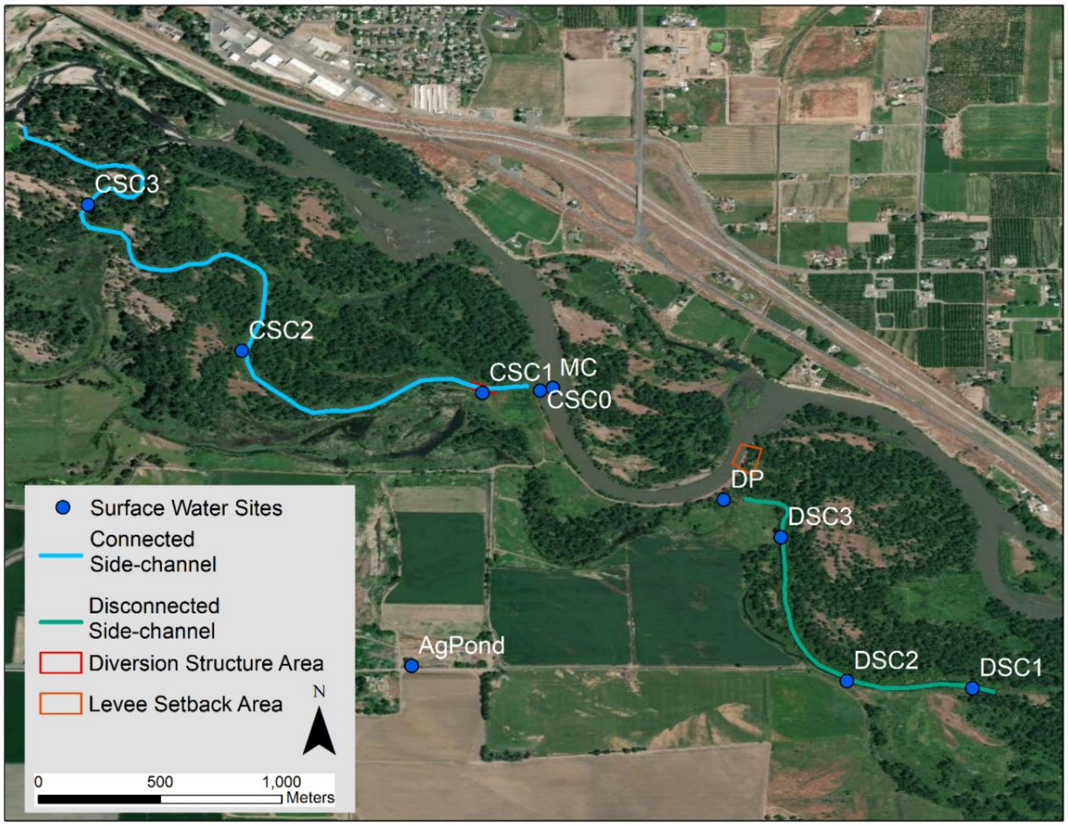

Figure 7. Surface water quality and stage sites, side-channels, and project sites.

Measured water quality parameters were DO (mg/L, percent saturation), conductivity and specific conductance (microsiemens per centimeter (µS/cm)), pH, turbidity (NTU), and temperature (°C). DO, conductivities, and temperature were measured in the stream with a YSI 85 water quality meter. Turbidity and pH were measured in the lab from water samples taken from water quality sites in jars at a depth of 0.5 meter using an Orbeco-Hellige turbidity meter and an Isfet pH meter. Flow (m^3/s) from the connected side-channel was collected using cross-section measurements and a Marsh McBirney Flo-Mate flow meter at CSC0, where it flows back into the Yakima River. This flow meter measured velocity in m/s, which was multiplied by the cross-sectional area of water measured at every meter or half-meter, depending on stream width.

Surface water and groundwater samples were collected once in February 2018 for stable isotope analysis. Water samples were collected at all wells while there was no standing water at the surface at the wells to contaminate the sample using a small hand pump. Water was pumped only partway up a 3m tube inside the well to avoid cross-contamination within the pump. The water was put into a plastic bottle and frozen until thawed for sampling. Surface water samples were collected at three sites on the same day—DSC2, CSC2, and MC—to represent water with different degrees of connection to the Yakima River. Water samples were run through a Picarro L2130-i water isotope analyzer, using 20 mL water samples.

Longitudinal temperature and specific conductance profiles were created along the connected and disconnected side-channels using Onset data loggers that were dragged behind a kayak collecting readings every second with a GPS unit that recorded location every second (USEPA 2014). The location and logger data were combined into a single table based on time and joined with a shapefile for mapping. Conductivity readings were compensated by Onset software to create specific conductance measurements at 25^{o}C. These measurements identified locations of changes in stream temperature and conductivity, indicating areas with groundwater input and/or hyporheic connectivity with the Yakima River.

Water Level Elevations

Water table depth was measured using 10 monitoring wells placed throughout the study area (Figure 8). Wells were built with 5 cm wide and 3 meter long PVC pipes with three staggered columns of 3 mm slits cut along their lengths that were wrapped with filter fabric to keep out sediment (Figure 9). Each pipe was installed in the ground by digging a hole with a backhoe, inserting the pipe with a protective larger pipe around it, and backfilling the hole while removing the protective pipe. Perforations allowed water to flow through the pipe and exert pressure on a Diver or Onset pressure sensor data logger that measured the water pressure above it, which allows calculation of the level of water inside the pipe.

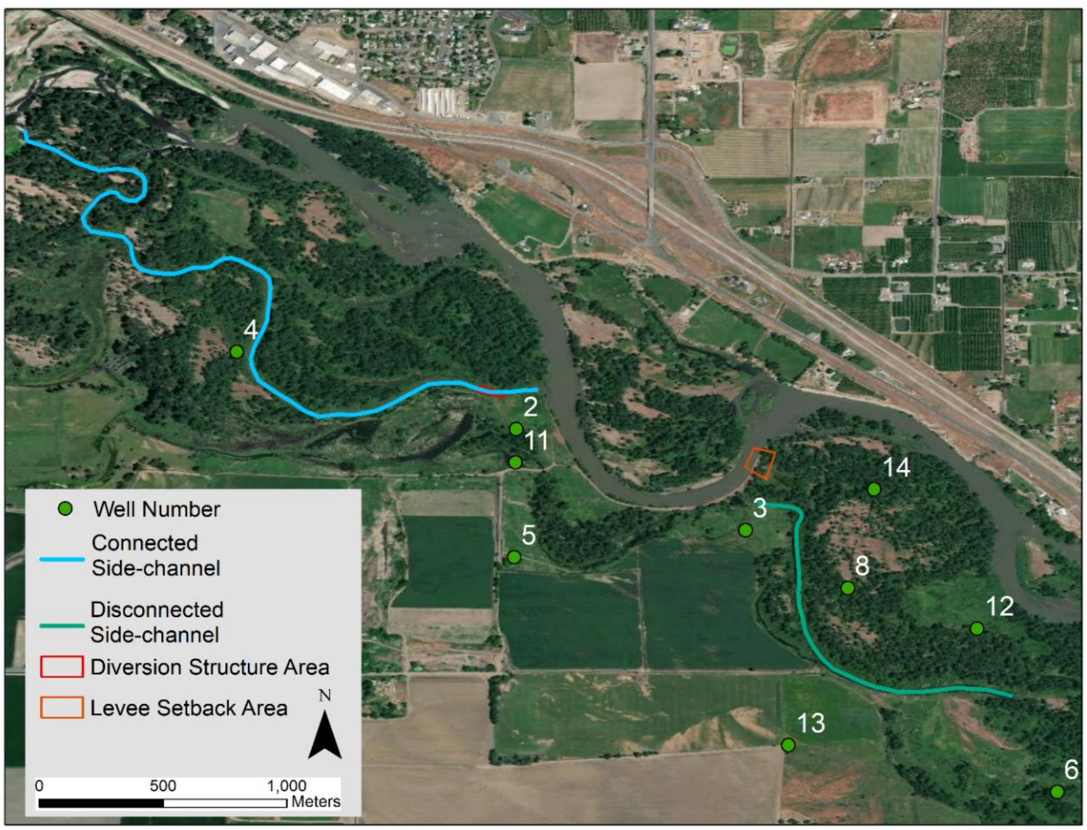

Figure 8. Locations of wells sites, side-channels, and project sites.

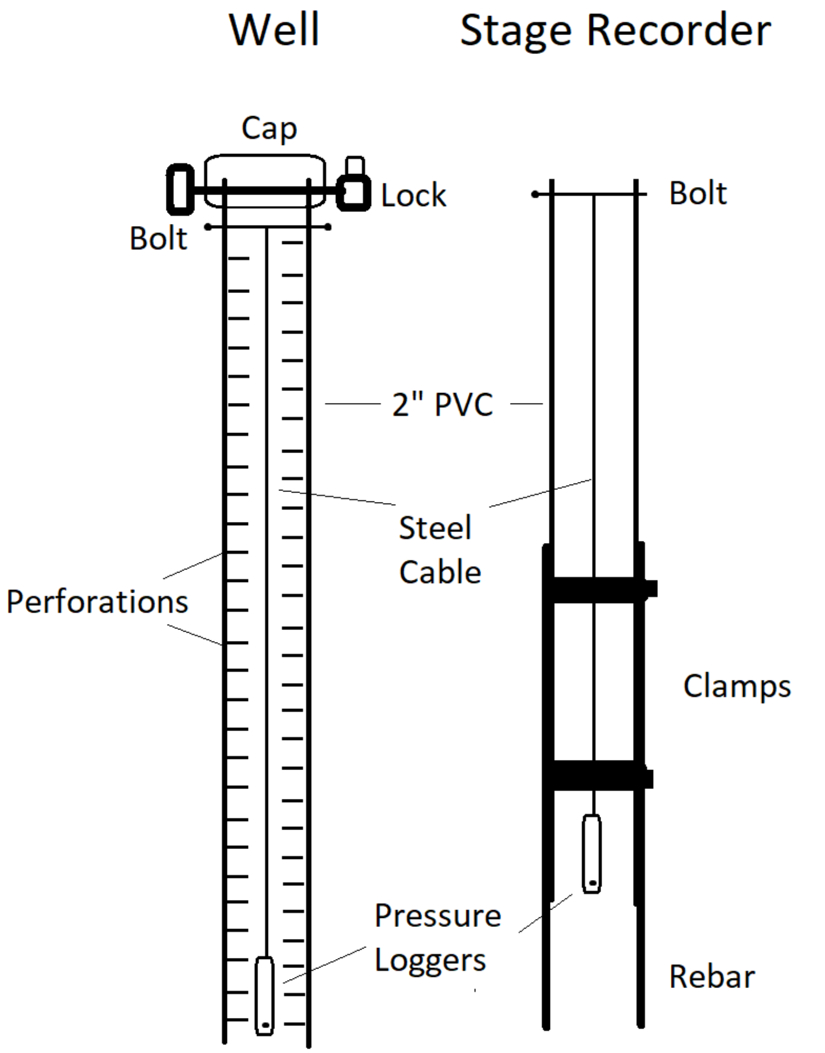

Figure 9. Diagrams of monitoring well and stage recorder designs. Not to scale.

The wells were initially installed on June 1, 2017 when water table elevations in the area were still very high, complicating digging to a depth where the wells would intersect the water table throughout the year (Figure 10). The wells were reinstalled in the same location on August 18, 2017 because the water table had dropped below several sensors.

Figure 10. Initial installation of monitoring wells. A larger pipe was used to protect the well and filter fabric wrapped around it during installation. Note the high water table that did not allow digging below a meter in gravel areas.

Ground penetrating radar (GPR) was used to help characterize the substrate and investigate the water table surrounding the wells after installation (Figure 11). Two different high frequency Sensors and Software pulseEKKO GPR configurations were used, a SmartTow design with 250 MHz shielded transducers, and a SmartCart design with 500 MHz shielded transducers. Only readings from the 500 MHz setup were used because the greater depths provided by the 250 MHz were not necessary to intersect the water table at each location, and the lower frequency sacrificed resolution. One GPR transect was taken at each location, with lengths ranging from 3m to 39m. Tree roots and vegetation limited the length of some transects, and changes in elevation from topographic variation were avoided. GPR data collection settings were left at the default for each transducer type, and Ekko_Project software was used to view GPR data. A separate handheld Garmin GPS unit recorded GPR position points every second along transects.

Figure 11. Sensors and Software GPR SmartCart setup with 500 MHz transducers recording readings at Well 13.

A digital elevation model was used to obtain surface elevations at the well sites to calculate the elevation of the water table at each well. A pressure sensor located in the middle of the study area measured barometric pressure readings to compensate for atmospheric pressure changes that influence water level data. Readings, collected at one hour intervals, were downloaded monthly from the data loggers. Hourly water table elevations were converted to daily average elevations. The measurements used to calculate water table elevations are shown in Figure 12 below. First, the Onset data logger measurements were converted from kilopascals (kPa) to centimeters of water (cmH2O), where 1 kPa equals 10.1987 cmH2O; the Diver data loggers already record in cmH2O. Second, barometric pressure was subtracted from the total observed pressure of each sensor to determine the depth of the water column above the sensor in centimeters. In wells, the water column was subtracted from the depth of the sensor below the ground surface to give the water table depth below the ground. Subtracting the water table depth from the surface elevation gave the water table elevation.

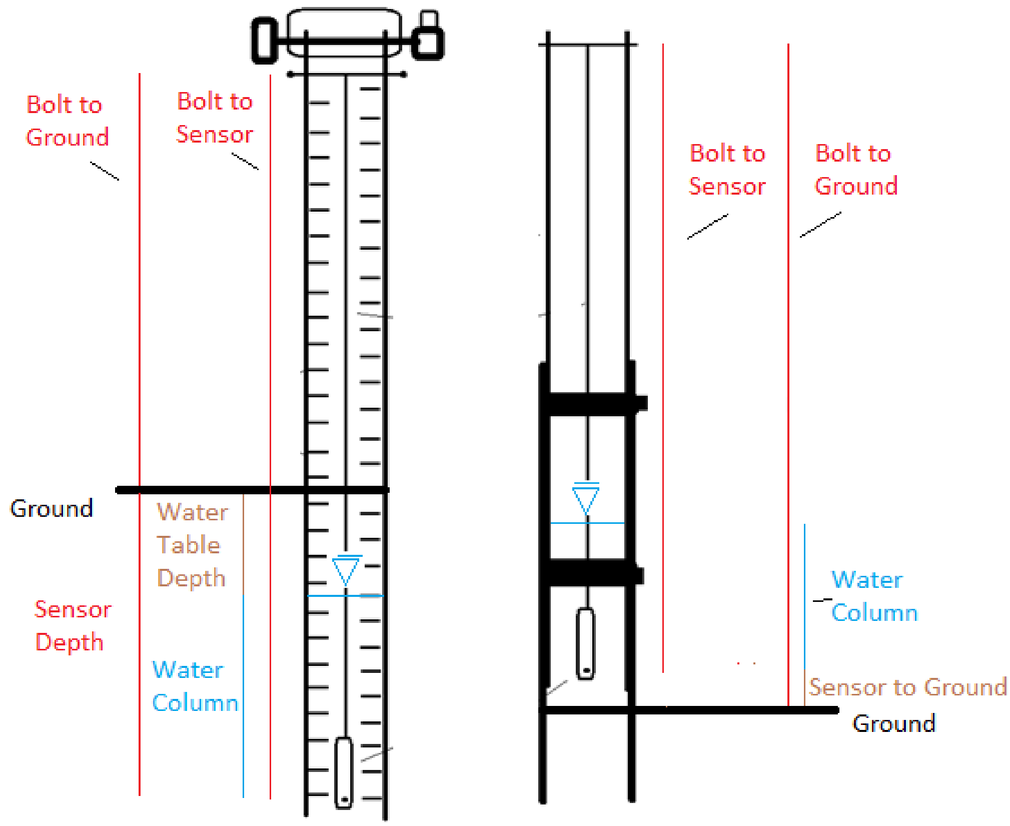

Figure 12. Measurements used to calculate water level elevations from digital elevation model raster values.

Surface water depths were measured using five stage recorders with similar designs to the monitoring wells; except the stage recorders were not perforated along their lengths. Stage recorders were strapped to one or two lengths of ~2cm rebar that were pounded into the substrate to a depth sufficient to keep the recorder in place. Surface water elevations were calculated by adding the depth of the water column to the height of the sensor above the stream bed and the elevation of the stream bed. Readings, collected at one hour intervals, were downloaded monthly from the data loggers. Hourly water table elevations were converted to daily average elevations.

A groundwater conceptual model was created in an attempt to run numerical models of shallow groundwater movement in the floodplain. Water level and stage recorder measurements, estimated soil hydraulic conductivities and porosities (percentage of space taken up by pore space in a volume of soil), and stage height of the Yakima River from a Bureau of Reclamation gage station were used as inputs in the Visual MODFLOW Flex groundwater flow modeling program. A 3m thick three-dimensional zone was created using two two-dimensional surfaces derived from a 1-meter DEM sourced from Washington State Department of Natural Resources (Figure 13). The three-dimensional zone was created by subtracting 3m from the pixel values across the original DEM to create a second layer 3m below the original DEM. This 3-D zone is where the program calculates water movement. The axes are in meters; z-axis is elevation, the y-axis is north/south location, and the x-axis is east/west location, in UTM Zone 10.

Properties of soil types in the area were sourced from the NRCS web soil survey data portal to inform generalized horizontal and vertical hydraulic conductivities, as well as specific yield and storage to characterize the model zone. A universal set of properties were used to simplify the workflow for the unconfined alluvial aquifer until further refining was possible. In other words, the characteristics of the model were kept simple

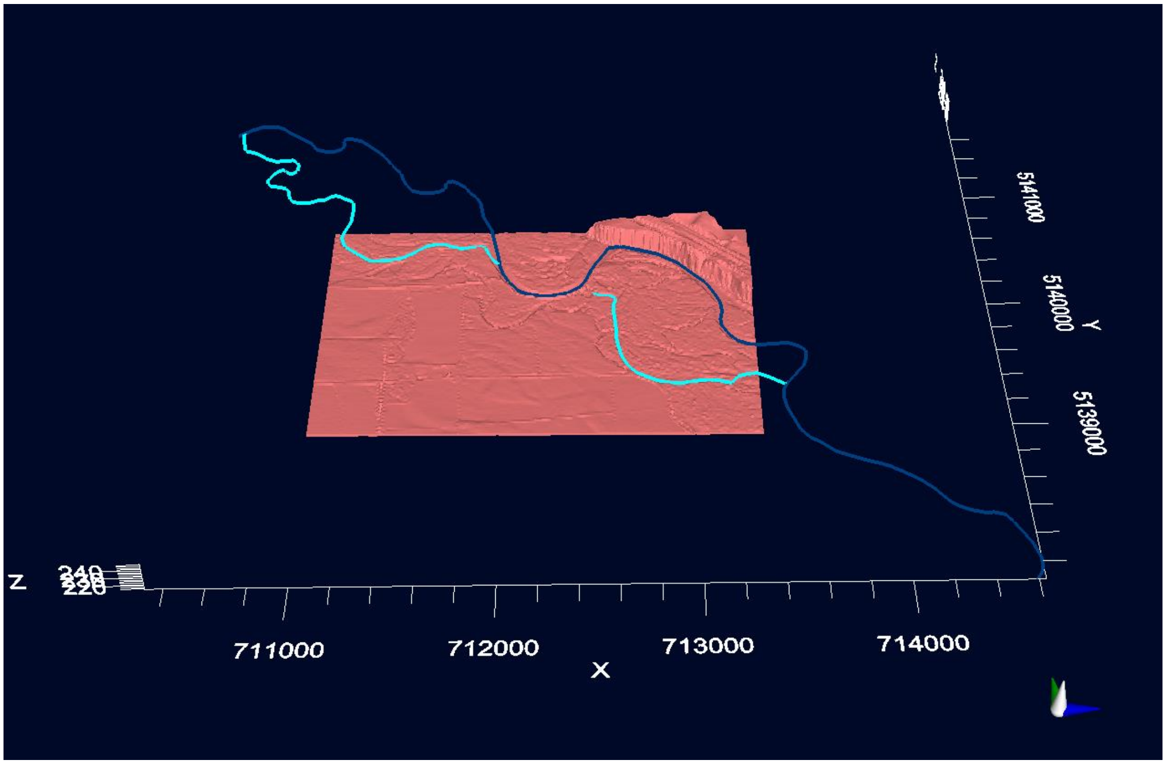

Figure 13. Three-dimensional zone based off a WDNR DEM and derived layer (5x vertical exaggeration). The main channel Yakima River is in dark blue, side-channels are in light blue.

until it was possible to add complexity and make the model more realistic. Boundary conditions in the model are objects and attributes that describe how the model area influences and is influenced by the region surrounding it. These include lines and polygons to show rivers, side-channels, evapotranspiration and recharge areas, lakes, drains, pumping wells, as well as time series attribute tables. Objects imported to the model were created in ArcGIS. An unstructured V-grid was used to create individual cells within the model (Figure 14).

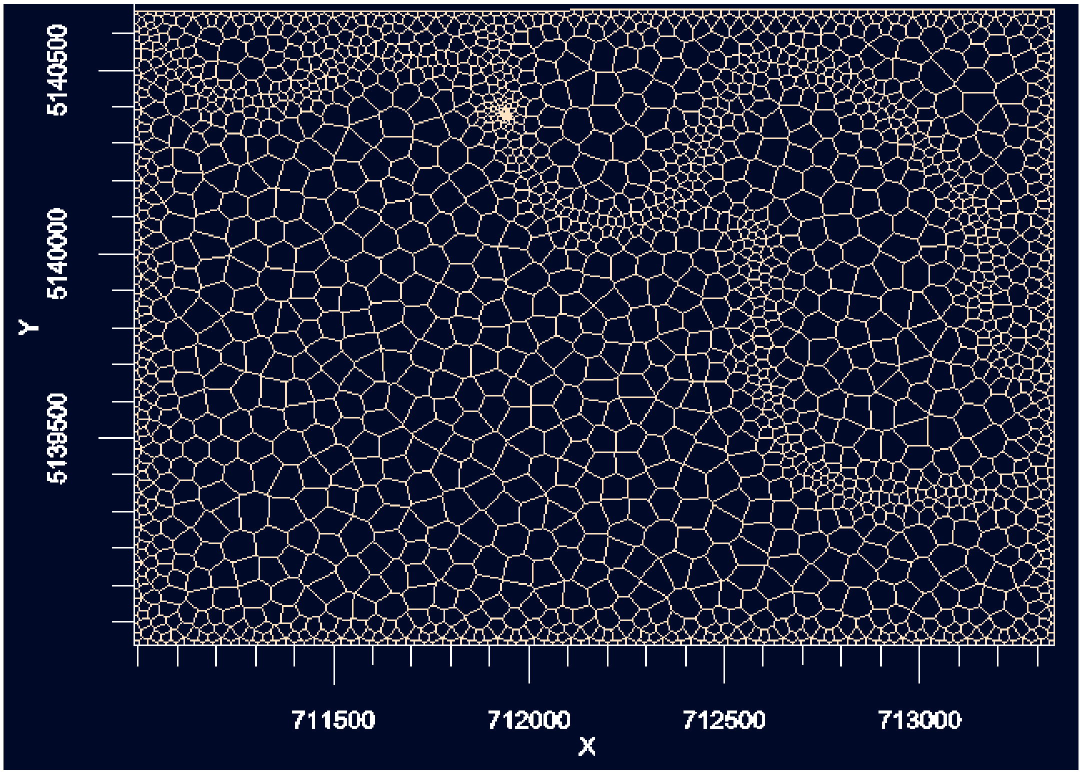

Figure 14. Unstructured V-grid created individual cells in Visual MODFLOW Flex. Cells are more dense around side-channels to increase the resolution of interactions around them.

Geostatistical Analysis

A GIS (ArcMap 15.1) was used to interpolate water table elevations from stage recorders and monitoring well points using the Empirical Bayesian Kriging tool. Kriging is a geostatistical interpolation method that takes into account autocorrelation (i.e. statistical relationships) between points. Kriging interpolation was chosen over deterministic interpolation methods (e.g. inverse distance weighted) because it incorporates statistical correlations that are known to exist between most of the locations. Empirical Bayesian Kriging is a method of running the interpolation many times to reduce the error in calculating the spatial correlation between two locations. Raster surfaces created by the interpolations were then converted to elevation contours using the Contour tool. These contour lines are most useful for visualizing the direction of water movement, as water moves from higher to lower elevation, and at right angles to the contour lines. Contour maps were created for peak surface water flows, times of groundwater pulses, and at weekly intervals. Weekly intervals contour maps were used to create an animation of water table changes.

Statistical Analysis

Water quality data collection took place during the 1.5-year period before the levee set-back and check dam installation will occur. Descriptive statistics were created to compare measures of central tendency for each water quality parameter. Statistical tests included the Mann-Whitney U (Wilcoxon Rank Sum), Kruskal-Wallis, and Wilcoxon Signed Rank tests. Water quality data were also compared between and among connected and disconnected sites, and between seasons for statistically significant differences. Seasons were defined as summer (June-August), fall (September – November), and winter (December – February). Percent saturation of DO, and conductivity were not reported in final results.

Comparisons among surface water and groundwater elevations were made using Pearson correlation tests for the entire study period, and for each season. Four of the five stage recorders were used due to significant gaps in data at site CSC 3. The degrees of relationship between sites were created at correlation coefficients of 0.00-0.40 (weak), 0.41-0.60 (moderate), 0.61-0.80 (moderately strong), and strong (0.80-1). Correlation coefficients were mapped to site locations using ArcGIS to display these relationships spatially.

CHAPTER V

RESULTS

Water Quality

Significant differences in several water quality parameters were found between seasons (spring, summer, and fall) over the period of study (09/19/16-11/07/17) (Kruskal-Wallis $p < 0.05$). Temperatures were significantly higher in summer (median range 19-24^{O}C) than spring (median range 9.1-13.4^{O}C) and fall (median range 11.1-12.4^{O}C) (Figures 15 and 16, Table 1). The largest seasonal variations in temperature occurred in fall across all sites (IQR range of 5.4-8.8^{O}C).

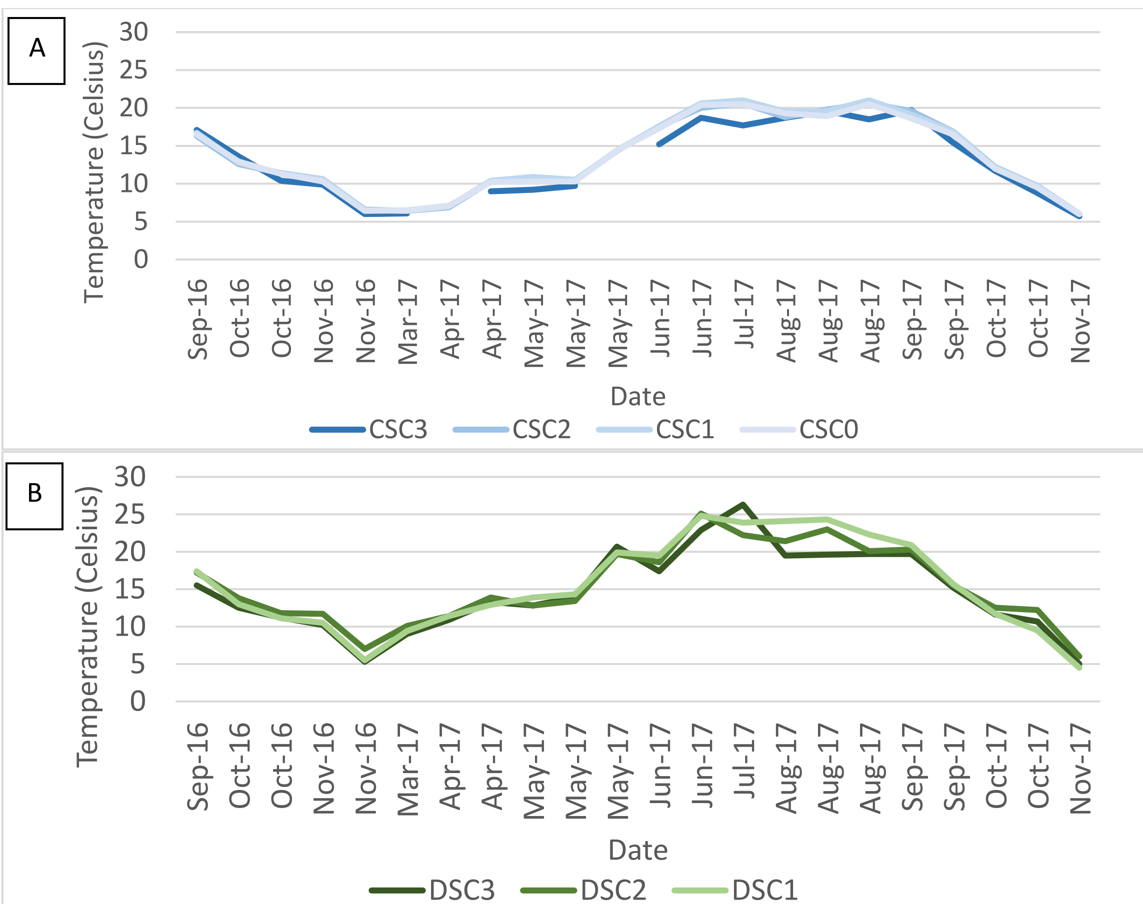

Figure 15. Water temperatures at connected side-channel (CSC) (A) and disconnected side-channel (DSC) (B) sites over the study period.

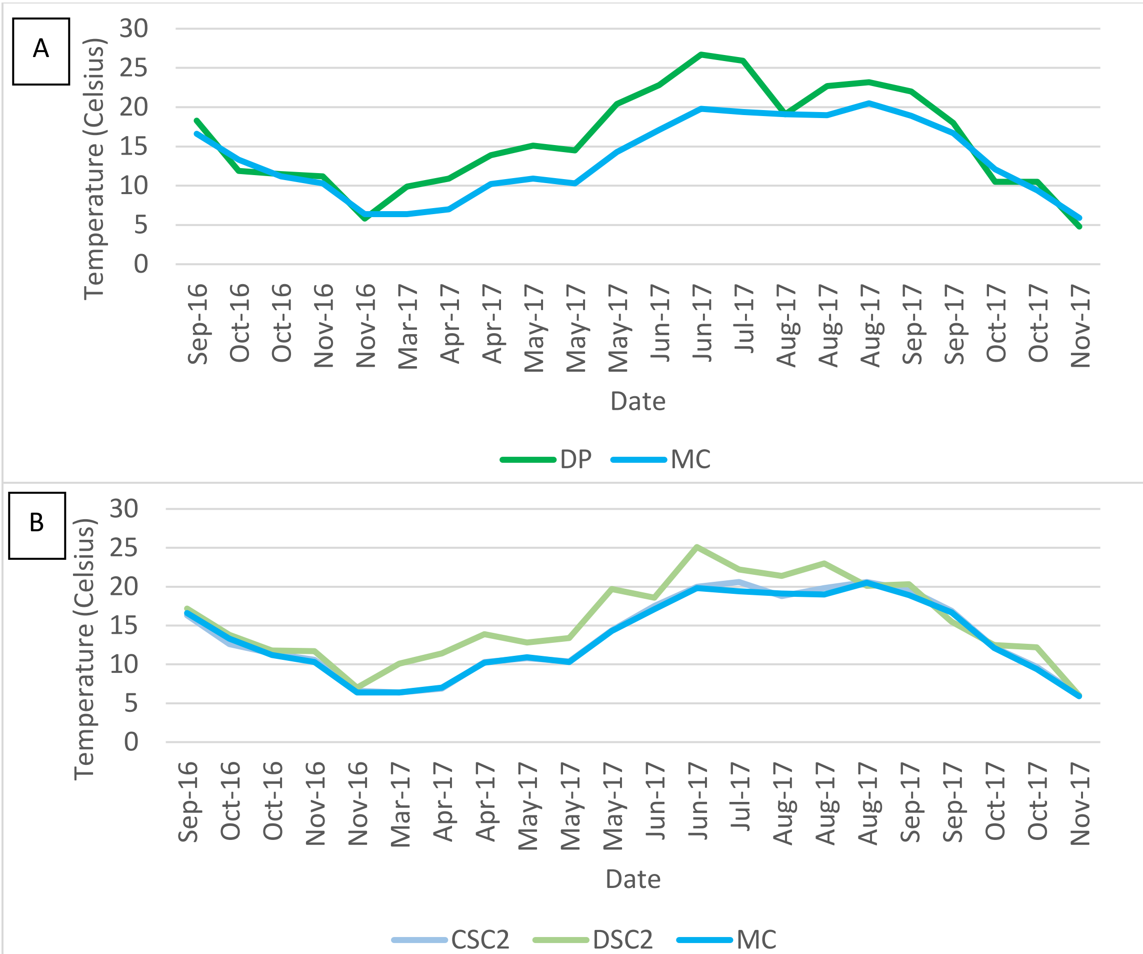

Figure 16. Comparisons of temperature (Celsius) at sites over the study period at disconnected pond (DP) vs. main channel Yakima (MC) (A), and connected side-channel (CSC2), disconnected side-channel (DSC2) and main channel Yakima (MC) (B).

Table 1. Median (interquartile range) of temperature (Celsius) at each site over the total study period and during each season.

Temperature (Celsius)	CSC0	CSC1	CSC2	CSC3	DSC1	DSC2	DSC3	DP	MC
Total	12.5 (8.7)	12.5 (9.0)	12.4 (8.8)	12.7 (9.2)	14.1 (10.3)	13.8 (8.3)	13.6 (8.7)	15.1 (11.7)	12.7 (8.9)
Spring	10.3 (4.4)	10.5 (4.9)	10.4 (4.9)	9.1 (2.8)	13.4 (4.8)	12.6 (3.9)	13.1 (5.2)	14.2 (5.8)	10.3 (4.9)
Summer	19.9 (2.0)	20.1 (2.0)	19.9 (2.1)	18.6 (1.9)	24.0 (2.8)	21.8 (3.8)	19.7 (4.8)	23.0 (4.3)	19.3 (1.5)
Fall	11.7 (7.8)	11.7 (7.9)	11.8 (7.5)	11.1 (7.7)	11.4 (7.6)	12.4 (5.4)	11.4 (6.3)	11.4 (8.8)	11.7 (8.0)

Seasonal specific conductance was significantly different at all sites except DP and DSC1: the highest values for all sites occurred during the fall (median range 132.1-297.6 uS/cm); the lowest values for CSC sites occurred in spring (median range 114.8-116.1 uS/cm); the lowest DSC values occurred in spring (median range 154.7-212.8 uS/cm) (Figures 17 and 18, Table 2). Median specific conductance was significantly higher in DSC sites than CSC sites over the study period (DSC median range 193.3-263.6 uS/cm, CSC median range 119.9-122.6 uS/cm).

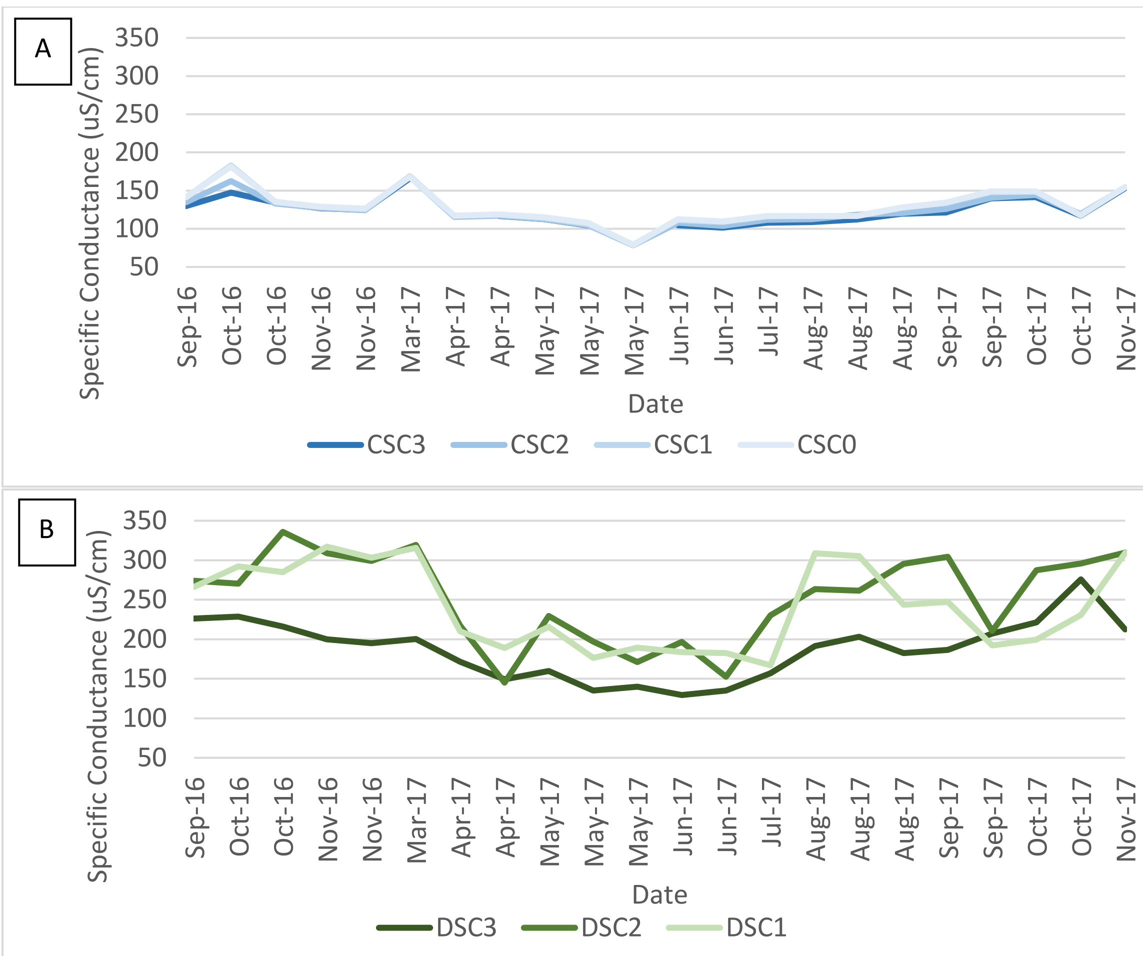

Figure 17. Comparisons of specific conductance (uS/cm) at connected side-channel (CSC) (A) and disconnected side-channel (DSC) (B) sites over the study period.

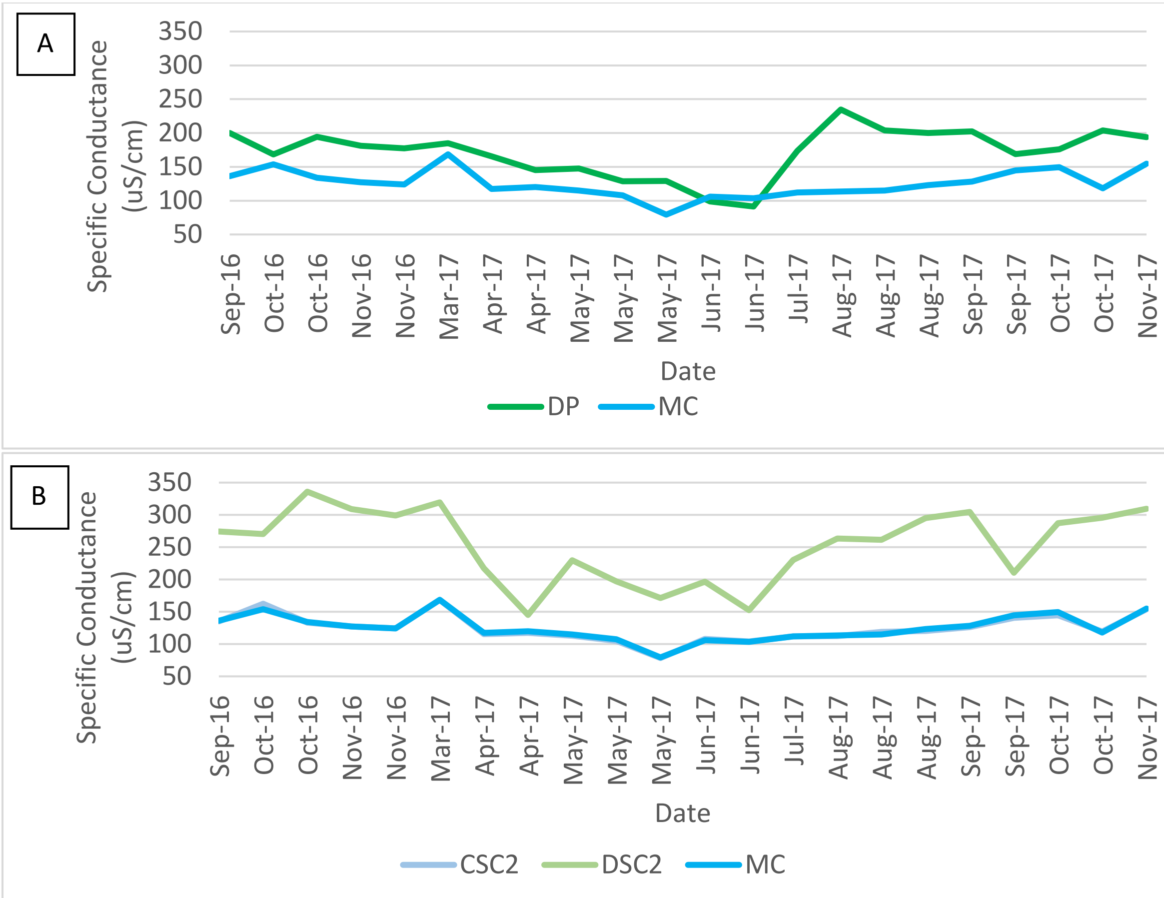

Figure 18. Comparisons of specific conductance (uS/cm) at sites over the study period at disconnected pond (DP) vs. main channel Yakima (MC) (A), and connected side-channel (CSC2), disconnected side-channel (DSC2) and main channel Yakima (MC) (B).

Table 2. Median (interquartile range) of specific conductance (µS/cm) at each site over the total study period and during each season.

Specific conductance (µS/cm)	CSC0	CSC1	CSC2	CSC3	DSC1	DSC2	DSC3	DP	MC
Total	122.6 (27.1)	122.0 (26.7)	119.9 (24.0)	120.5 (28.8)	237.1 (114.3)	263.6 (91.2)	193.3 (58.5)	177.1 (43.6)	121.5 (25.2)
Spring	116.1 (30.9)	115.6 (31.7)	114.1 (32)	114.8 (47.7)	199.8 (54.8)	212.8 (61.4)	154.7 (39.9)	146.3 (41.4)	116.2 (31.5)
Summer	116.7 (7.7)	116.6 (8.9)	112.1 (12.3)	108.5 (10.2)	213.6 (127.5)	245.9 (85.9)	169.6 (60.7)	186.9 (114.5)	112.7 (11.7)
Fall	138.4 (22.2)	138.0 (22.4)	134.1 (21.0)	132.1 (19.0)	275.8 (81.9)	297.6 (35.9)	214.5 (28.1)	187.4 (26.4)	135.0 (24.1)

Differences in seasonal turbidity were significant in three out of four CSC sites, and the main channel Yakima River (Figures 19 and 20, Table 3). CSC turbidity was generally highest in the spring (median range 8.5-11.2 NTU), followed by fall (median range 2.7-3.6 NTU), then summer (median range 2.5-3.6 NTU). Variations in turbidity in CSC (IQR range 8.1-10.3 NTU) were similar to those in the main-channel Yakima (IQR 8.8) in the spring.

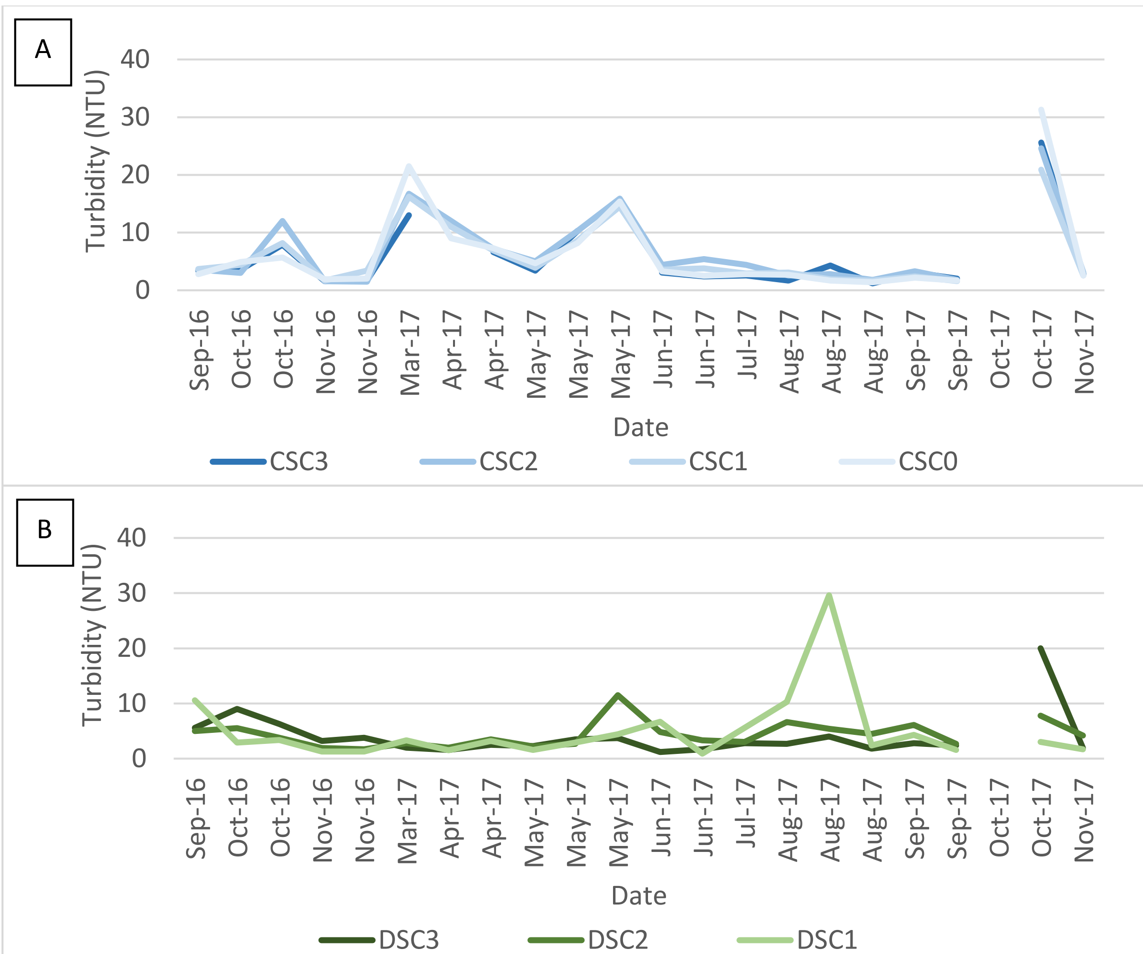

Figure 19. Comparisons of turbidity (NTU) at connected side-channel (CSC) (A) and disconnected side-channel (DSC) (B) sites over the study period.

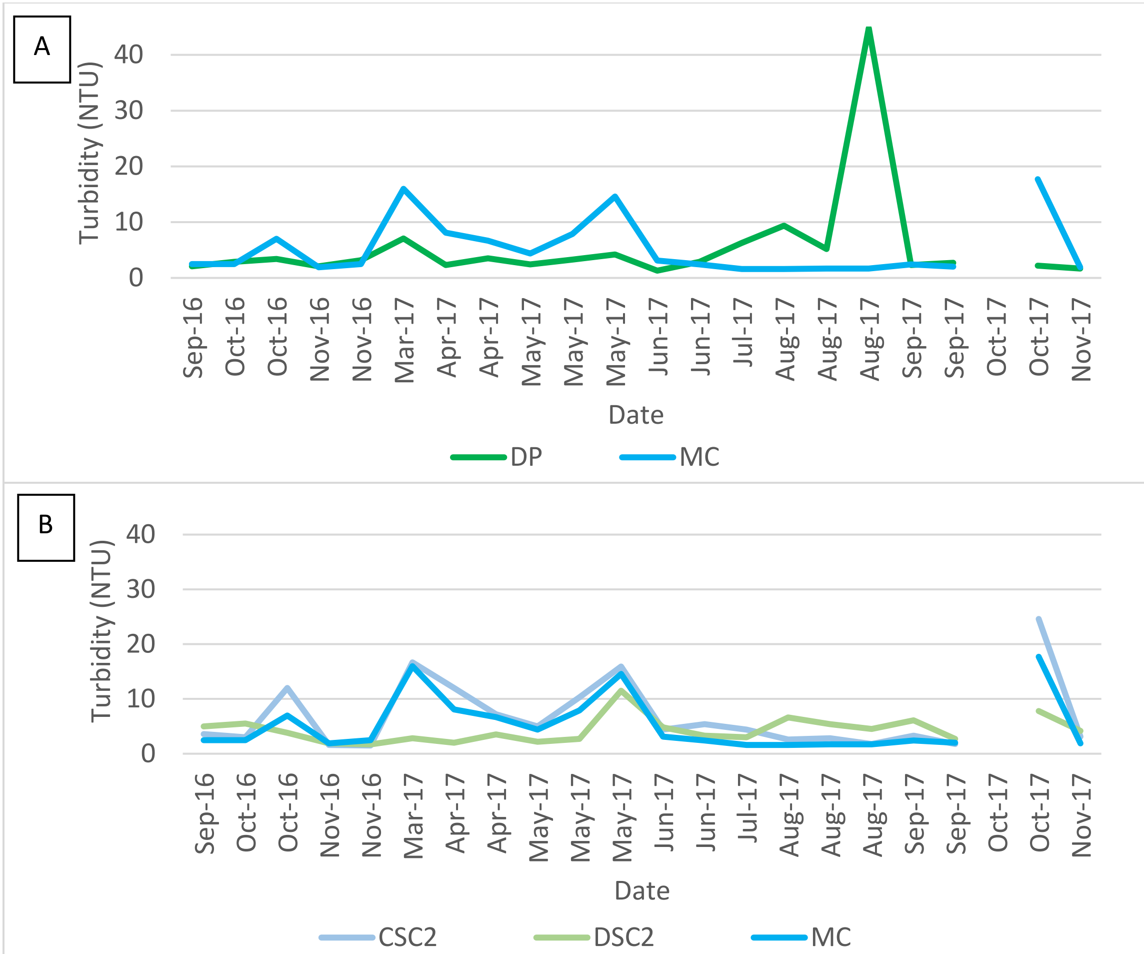

Figure 20. Comparisons of turbidity (NTU) at sites over the study period at disconnected pond (DP) vs. main channel Yakima (MC) (A), and connected side-channel (CSC2), disconnected side-channel (DSC2) and main channel Yakima (MC) (B).

Table 3. Median (interquartile range) of turbidity (NTU) at each site over the total study period and during each season.

Turbidity (NTU)	CSC0	CSC1	CSC2	CSC3	DSC1	DSC2	DSC3	DP	MC
Total	2.8 (5.7)	3.7 (5.9)	4.4 (8.5)	3.1 (4.6)	3.0 (3.4)	4.0 (3.0)	2.8 (1.9)	2.9 (2.8)	2.5 (5.6)
Spring	8.6 (10.3)	9.8 (8.8)	11.2 (9.5)	8.5 (8.1)	3.1 (2.0)	2.8 (7.6)	2.4 (1.7)	3.4 (2.6)	8.0 (8.8)
Summer	2.6 (1.3)	3.0 (1.8)	3.6 (2.3)	2.5 (1.8)	6.2 (13.1)	4.7 (2.5)	2.3 (1.5)	5.8 (15.8)	1.7 (1.0)
Fall	2.7 (4.0)	3.6 (3.4)	3.2 (5.2)	3.3 (3.6)	3.0 (2.9)	4.6 (4.0)	4.7 (9.1)	2.5 (1.2)	2.5 (7.7)

There were no significant seasonal differences in dissolved oxygen at any site. DO varied less at CSC sites over the study period (IQR range 1.5-2.0 mg/L) compared to DSC sites (IQR range 2.3-3.7 mg/L) (Figures 21 and 22, Table 4). DO levels were generally higher at CSC sites in every season and over the study period, where median values for all sites during all seasons range from 9.7-11.3 mg/L, compared to the median range for all DSC sites and seasons of 3.6-8.0 mg/L. DSC1 had slightly higher DO levels compared to other DSC sites, where medians ranged from 7.8-8.0 mg/L, compared to 3.6-6.7 mg/L at DSC2 and 4.1-6.6 mg/L at DSC3.

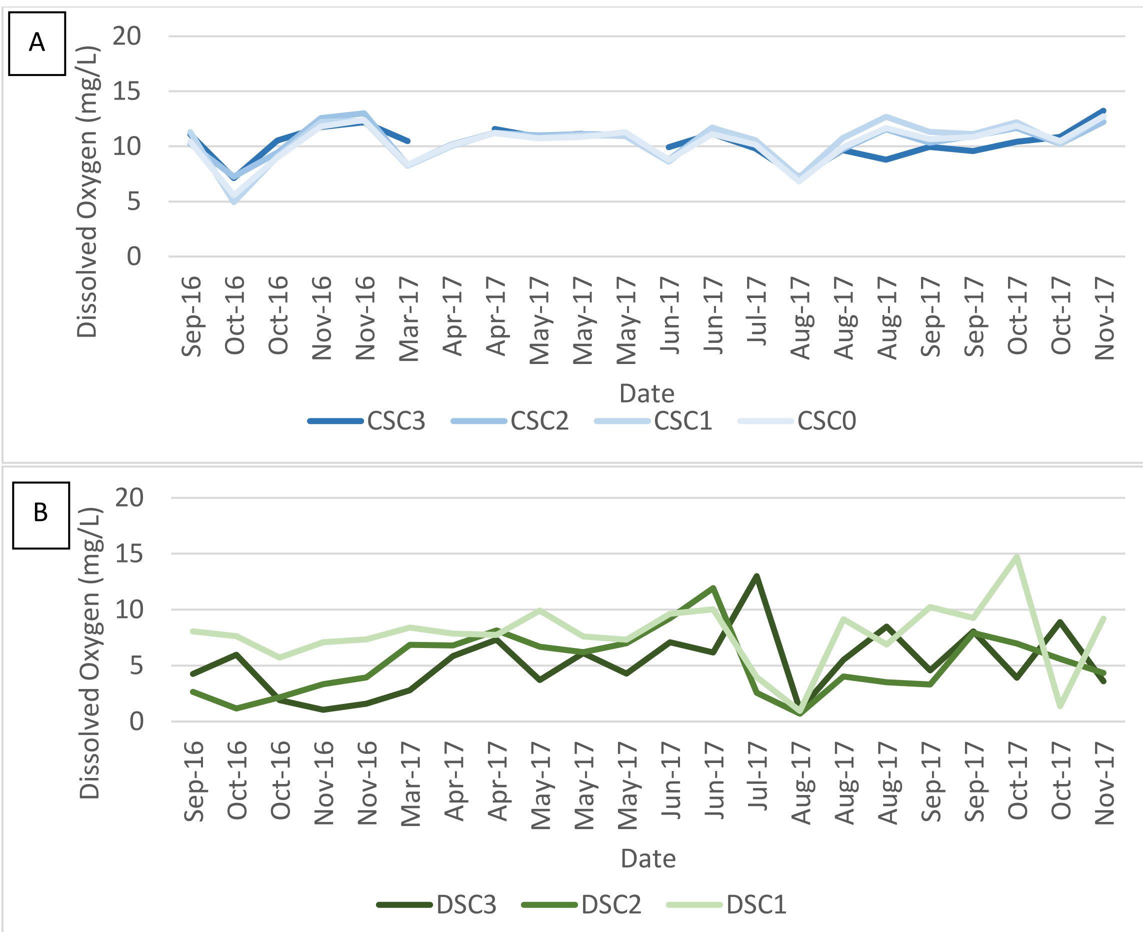

Figure 21. Comparisons of dissolved oxygen (mg/L) at connected side-channel (CSC) (A) and disconnected side-channel (DSC) (B) sites over the study period.

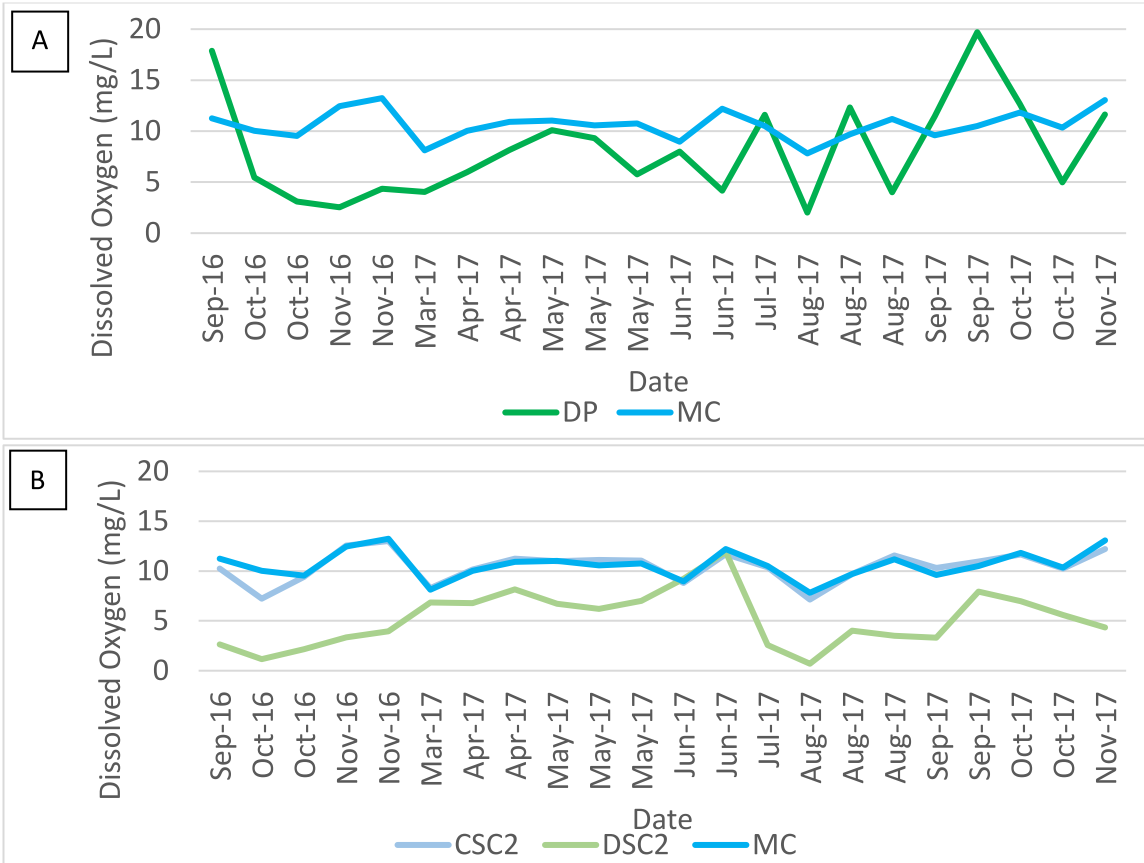

Figure 22. Comparisons of dissolved oxygen (mg/L) at sites over the study period at disconnected pond (DP) vs. main channel Yakima (MC) (A), and connected side-channel (CSC2), disconnected side-channel (DSC2) and main channel Yakima (MC) (B).

Table 4. Median (interquartile range) of dissolved oxygen (mg/L) at each site over the total study period and during each season.

Dissolved Oxygen (mg/L)	CSC0	CSC1	CSC2	CSC3	DSC1	DSC2	DSC3	DP	MC
Total	10.7 (1.7)	11.0 (2.0)	10.7 (2.0)	10.5 (1.5)	7.8 (2.3)	5.6 (3.7)	5.1 (3.7)	6.0 (7.5)	10.5 (1.7)
Spring	10.8 (1.6)	10.9 (1.5)	11.0 (1.5)	11.0 (0.9)	7.8 (1.3)	6.7 (0.8)	5.1 (2.9)	7.1 (4.2)	10.7 (1.4)
Summer	10.0 (3.0)	10.7 (3.7)	10.0 (3.2)	9.7 (1.8)	8.0 (6.5)	3.8 (7.8)	6.6 (5.2)	6.1 (8.3)	10.1 (2.8)
Fall	10.8 (1.9)	11.3 (2.3)	10.6 (2.3)	10.7 (2.0)	7.9 (2.8)	3.6 (3.4)	4.1 (4.6)	8.5 (9.9)	10.9 (2.7)

Wilcoxon signed rank tests compared water quality parameters at site pairs over the study period and among seasons (p <0.05). Site pairs included DP vs MC, CSC2 vs DSC2, CSC2 vs MC, DSC1 vs DSC3, and CSC0 vs CSC3. These sites were compared to look at differences between sites with varying distances and degrees of connection to the Yakima River, as well as to compare among the connected and disconnected sites (Table 5). Table 5 shows the results of the statistical tests, showing the significant differences at site pairs. Medians were compared to determine the direction of difference.

Table 5. Summary of significant differences of water quality parameters between disconnected side-channel (DSC), connected side-channel (CSC), main channel Yakima (MC), and disconnected pond (DP) site pairs over the study period and by season.

	Site Pairs									
	DP	MC	CSC2	DSC2	MC	CSC2	DSC1	DSC3	CSC0	CSC3
Temperature										
Total	H	L	L	H	H	L	ND	ND	ND	ND
Spring	H	L	L	H	ND	ND	ND	ND	ND	ND
Summer	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Fall	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dissolved Oxygen										
Total	L	H	H	L	ND	ND	H	L	ND	ND
Spring	L	H	H	L	ND	ND	H	L	ND	ND
Summer	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Fall	ND	ND	H	L	ND	ND	ND	ND	ND	ND
Specific Conductance										
Total	H	L	L	H	ND	ND	H	L	ND	ND
Spring	H	L	L	H	H	L	H	L	ND	ND
Summer	ND	ND	L	H	ND	ND	H	L	H	L
Fall	ND	ND	L	H	ND	ND	H	L	H	L
Turbidity										
Total	ND	ND	ND	ND	L	H	ND	ND	ND	ND
Spring	L	H	H	L	L	H	ND	ND	ND	ND
Summer	ND	ND	ND	ND	L	H	ND	ND	ND	ND
Fall	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

Note: H = significantly higher, L = significantly lower, ND = no significant difference.

Significant differences were found between DP and MC temperature, DO, and specific conductance over the study period and within seasons (Tables 5 and 6). These sites were compared because DP is directly next to the levee separating it from the Yakima River, and it is the closest disconnected water body to the river in this study. Temperature was significantly higher in DP over the study period (MC median = 12.7°C, DP median = 15.1°C) and in spring (MC median = 10.3°C, DP median = 14.2°C). DO was significantly higher in MC through the study period (MC median = 10.5 mg/L, DP median = 6.0 mg/L) and in spring (MC median = 10.7 mg/L, DP median = 7.1 mg/L). Specific conductance was higher in DP over the study period (MC median = 121.5 µS/cm, DP median = 177.1 µS/cm), and in spring (MD median = 116.2 µS/cm, DP median = 146.3 µS/cm) and fall (MC median = 135.0 µS/cm, DP median = 187.4 µS/cm).

Table 6. Comparison of median (interquartile range) of water quality parameters between sites disconnected pond (DP) and main channel Yakima (MC) seasonally and over the study period.

	Temperature (Celsius)		Dissolved Oxygen (mg/L)		Specific conductance (µS/cm)		Turbidity (NTU)	
Site	DP	MC	DP	MC	DP	MC	DP	MC
Total	**15.1 (11.7)**	**12.7 (8.9)**	**6.0 (7.5)**	**10.5 (1.7)**	**177.1 (43.6)**	**121.5 (25.2)**	2.9 (2.8)	2.5 (5.6)
Spring	**14.2 (5.8)**	**10.3 (4.9)**	**7.1 (4.2)**	**10.7 (1.4)**	**146.3 (41.4)**	**116.2 (31.5)**	**3.4 (2.6)**	**8.0 (8.8)**
Summer	23.0 (4.3)	19.3 (1.5)	6.1 (8.3)	10.1 (2.8)	186.9 (114.5)	112.7 (11.7)	5.8 (15.8)	1.7 (1.0)
Fall	11.4 (8.8)	11.7 (8.0)	8.5 (9.9)	10.9 (2.7)	187.4 (26.4)	135 (24.1)	2.5 (1.2)	2.5 (7.7)

Note: Bold numbers indicate significant differences.

Significant differences were found between CSC2 and DSC2 temperature, DO, and conductivities over the study period and within seasons (Tables 5 and 7). These sites were used for comparison because they represent the mid-points of connected and disconnected side-channels. Temperature was higher at DSC2 during the study period (CSC2 median = 12.4^{o}C, DSC2 median = 13.8 ^{o}C) and spring (CSC2 median = 10.4^{o}C, DSC2 median = 12.6 ^{o}C). DO was higher at CSC2 during the study period (CSC2 median = 10.7 mg/L, DSC2 median = 5.6 mg/L), spring (CSC2 median = 11.0 mg/L, DSC2 median = 6.7 mg/L), and fall (CSC2 median = 10.6 mg/L, DSC2 median = 3.6 mg/L). Specific conductance was higher at DSC2 over the study period (CSC2 median = 119.9 µS/cm, DSC2 median = 263.6 µS/cm), and during spring (median = 263.6 µS/cm),

Table 7. Comparison of median (interquartile range) of water quality parameters between connected side-channel (CSC2) and disconnected side-channel (DSC2) sites seasonally and over the study period.

	Temperature (Celsius)		Dissolved Oxygen (mg/L)		Specific conductance (µS/cm)		Turbidity (NTU)	
Site	CSC2	DSC2	CSC2	DSC2	CSC2	DSC2	CSC2	DSC2
Total	**12.4 (8.8)**	**13.8 (8.3)**	**10.7 (2.0)**	**5.6 (3.7)**	**119.9 (24.0)**	**263.6 (91.2)**	4.4 (8.5)	4.0 (3.0)
Spring	**10.4 (4.9)**	**12.6 (3.9)**	**11.0 (1.5)**	**6.7 (0.8)**	**114.1 (32)**	**212.8 (61.4)**	**11.2 (9.5)**	**2.8 (7.6)**
Summer	19.9 (2.1)	21.8 (3.8)	10.0 (3.2)	3.8 (7.8)	**112.1 (12.3)**	**245.9 (85.9)**	3.6 (2.3)	4.7 (2.5)
Fall	11.8 (7.5)	12.4 (5.4)	**10.6 (2.3)**	**3.6 (3.4)**	**134.1 (21)**	**297.6 (35.9)**	3.2 (5.2)	4.6 (4.0)

Note: Bold numbers indicate significant differences.

summer (CSC2 median = 112.1 µS/cm, DSC2 median = 245.9 µS/cm), and fall (CSC2 median = 134.1 µS/cm, DSC2 median = 297.6 µS/cm). Turbidity was higher at CSC2 only in spring (CSC2 median = 11.2 NTU, DSC2 median = 2.8 NTU).

Significant differences were found between CSC2 and MC temperature over the study period, specific conductance in spring, and turbidity over the study period, spring, and summer (Tables 5 and 8). These sites were used to compare water at the mid-point of a connected side channel to water in Yakima River, from where the water came. Temperature was higher at MC over the study period (CSC2 median =12.4°C, MC median = 12.7°C). Specific conductance was higher at MC during spring (median = 116.2 µS/cm). Turbidity was higher at CSC2 over the study period (median = 4.4 NTU) and in spring (median = 11.2 NTU) and summer (median = 3.6 NTU).

Table 8. Comparison of median (interquartile range) of water quality parameters between sites connected side-channel (CSC2) and main channel Yakima (MC) seasonally and over the study period.

	Temperature (Celsius)		Dissolved Oxygen (mg/L)		Specific conductance (µS/cm)		Turbidity (NTU)	
Site	CSC2	MC	CSC2	MC	CSC2	MC	CSC2	MC
Total	**12.4 (8.8)**	**12.7 (8.9)**	10.7 (2.0)	10.5 (1.7)	119.9 (24)	121.5 (25.2)	**4.4 (8.5)**	**2.5 (5.6)**
Spring	10.4 (4.9)	10.3 (4.9)	11.0 (1.5)	10.7 (1.4)	**114.1 (32)**	**116.2 (31.5)**	**11.2 (9.5)**	**8.0 (8.8)**
Summer	19.9 (2.1)	19.3 (1.5)	10.0 (3.2)	10.1 (2.8)	112.1 (12.3)	112.7 (11.7)	**3.6 (2.3)**	**1.7 (1)**
Fall	11.8 (7.5)	11.7 (8.0)	10.6 (2.3)	10.9 (2.7)	134.1 (21)	135 (24.1)	3.2 (5.2)	2.5 (7.7)

Note: Bold numbers indicate significant differences.

Significant differences were found between DSC1 and DSC3 DO over the study period and in spring, and between specific conductance over the study period and in each season (Tables 5 and 9). These sites were compared to look at differences in the disconnected side-channel with differing distances to the main channel Yakima. DO was higher at DSC1 over the study period (median = 7.8 mg/L) and during spring (median = 7.8 mg/L). Specific conductance was higher at DSC1 over the study period (median = 237.1 µS/cm) and in the spring (median = 199.8 µS/cm), summer (median = 213.6 µS/cm), and fall (median = 275.8 µS/cm).

Table 9. Comparison of median (interquartile range) of water quality parameters between disconnected side-channel sites (DSC1 and DSC3) seasonally and over the study period.

	Temperature (Celsius)		Dissolved Oxygen (mg/L)		Specific conductance (µS/cm)		Turbidity (NTU)	
Site	DSC1	DSC3	DSC1	DSC3	DSC1	DSC3	DSC1	DSC3
Total	14.1 (10.3)	13.6 (8.7)	**7.8 (2.3)**	**5.1 (3.7)**	**237.1 (114.3)**	**193.3 (58.5)**	3.0 (3.4)	2.8 (1.9)
Spring	13.4 (4.8)	13.1 (5.2)	**7.8 (1.3)**	**5.1 (2.9)**	**199.8 (54.8)**	**154.7 (39.9)**	3.1 (2.0)	2.4 (1.7)
Summer	24 (2.8)	19.7 (4.8)	8.0 (6.5)	6.6 (5.2)	**213.6 (127.5)**	**169.6 (60.7)**	6.2 (13.1)	2.3 (1.5)
Fall	11.4 (7.6)	11.4 (6.3)	7.9 (2.8)	4.1 (4.6)	**275.8 (81.9)**	**214.5 (28.1)**	3.0 (2.9)	4.7 (9.1)

Note: Bold numbers indicate significant differences.

Significant differences were found between CSC0 and CSC3 specific conductance during the summer and fall (Tables 5 and 10). These sites were compared to identify differences in water quality as water begins at the top of the connected side-channel and as it exits the connected side-channel. Specific conductance was higher at

CSC0 in summer (median = 116.7 µS/cm). Specific conductance was also higher at CSC0 during fall (median = 138.4 µS/cm).

Table 10. Comparison of median (interquartile range) of water quality parameters between connected side-channel sites (CSC0 and CSC3) seasonally and over the study period.

	Temperature (Celsius)		Dissolved Oxygen (mg/L)		Specific conductance (µS/cm)		Turbidity (NTU)	
Site	CSC0	CSC3	CSC0	CSC3	CSC0	CSC3	CSC0	CSC3
Total	12.5 (8.7)	12.7 (9.2)	10.7 (1.7)	10.5 (1.5)	122.6 (27.1)	120.5 (28.8)	2.8 (5.7)	3.1 (4.6)
Spring	10.3 (4.4)	9.1 (2.8)	10.8 (1.6)	11.0 (0.9)	116.1 (30.9)	114.8 (47.7)	8.6 (10.3)	8.5 (8.1)
Summer	19.9 (2)	18.6 (1.9)	10.0 (3.0)	9.7 (1.8)	**116.7 (7.7)**	**108.5 (10.2)**	2.6 (1.3)	2.5 (1.8)
Fall	11.7 (7.8)	11.1 (7.7)	10.8 (1.9)	10.7 (2.0)	**138.4 (22.2)**	**132.1 (19)**	2.7 (4.0)	3.3 (3.6)

Note: Bold numbers indicate significant differences.

Significant differences in several water quality parameters were found between selected sites (CSC2, DSC2, DP) seasonally and over the period of study (Kruskal-Wallis $p < 0.05$). These sites were chosen for comparison because they represent midpoints of three different types of water bodies with relatively different degrees of connectivity to the main channel (connected side channel, disconnected side channel, and disconnected pond). Sites had significantly different DO concentrations and specific conductance over the entire study period (Table 11). CSC had the highest DO levels (10.7 mg/L) followed by DP (6.0 mg/L) and DSC2 (5.6 mg/L). DSC2 had the highest specific conductance (263.6 uS/cm) over the study period, followed by DP (177.1 uS/cm) and CSC2 (119.9

uS/cm). Temperatures were significantly different between these sites only during summer, where temperatures were highest at DP (median: 23°C), followed by DSC2 (median: 21.8°C), and lowest at CSC2 (median: 19.9°C). Median DO concentrations were significantly different in the spring (CSC2 11.0 mg/L, DP 7.1 mg/L, DSC2 6.7 mg/L) and fall (CSC2 10.6 mg/L, DP 8.5 mg/L, DSC2 3.6 mg/L). Specific conductance were different between sites in all seasons, where DSC2 was always higher than DP, which was always higher than CSC2. No significant differences were found in turbidity between the sites.

Table 11. Comparison of median (interquartile range) of water quality parameters between connected side-channel, disconnected side-channel, and disconnected pond sites (CSC2, DSC2, and DP) seasonally and over the study period.

	Temperature (Celsius)			Dissolved Oxygen (mg/L)			Specific conductance (μS/cm)			Turbidity (NTU)		
Site	CSC2	DSC2	DP	CSC2	DSC2	DP	CSC2	DSC2	DP	CSC2	DSC2	DP
Total	12.4 (8.8)	13.8 (8.3)	15.1 (11.7)	**10.7 (2.0)**	**5.6 (3.7)**	**6.0 (7.5)**	**119.9 (24.0)**	**263.6 (91.2)**	**177.1 (43.6)**	4.4 (8.5)	4.0 (3.0)	2.9 (2.8)
Spring	10.4 (4.9)	12.6 (3.9)	14.2 (5.8)	**11.0 (1.5)**	**6.7 (0.8)**	**7.1 (4.2)**	**114.1 (32.0)**	**212.8 (61.4)**	**146.3 (41.4)**	11.2 (9.5)	2.8 (7.6)	3.4 (2.6)
Summer	**19.9 (2.1)**	**21.8 (3.8)**	**23.0 (4.3)**	10.0 (3.2)	3.8 (7.8)	6.1 (8.3)	**112.1 (12.3)**	**245.9 (85.9)**	**186.9 (114.5)**	3.6 (2.3)	4.7 (2.5)	5.8 (15.8)
Fall	11.8 (7.5)	12.4 (5.4)	11.4 (8.8)	**10.6 (2.3)**	**3.6 (3.4)**	**8.5 (9.9)**	**134.1 (21.0)**	**297.6 (35.9)**	**187.4 (26.4)**	3.2 (5.2)	4.6 (4.0)	2.5 (1.2)

Note: Significant differences are in bold (Kruskal-Wallis $p < 0.05$).

Water quality parameters at connected side-channel sites were compared with discharge (Q) at CSC0 from September 2016 to November 2017, with a gap in data from November 22, 2016 to May 2, 2017 (Figure 23). Correlations between changes in water quality and CSC0 discharge were also calculated to compare the degree and direction of significant relationships (Spearman Rank Correlation, $p < 0.05$). A significant strong correlation (0.96) was found between Yakima River discharge and CSC0 discharge (Figure 24). Significant moderately-strong negative correlations (-0.61 to -0.80) were found between CSC0 discharge and temperature at all CSC sites, ranging from -0.70 to -0.72. A significant moderately-strong positive correlation was also found between discharge and DO at CSC3 (0.70). No significant correlations were found between discharge and either turbidity or specific conductance.

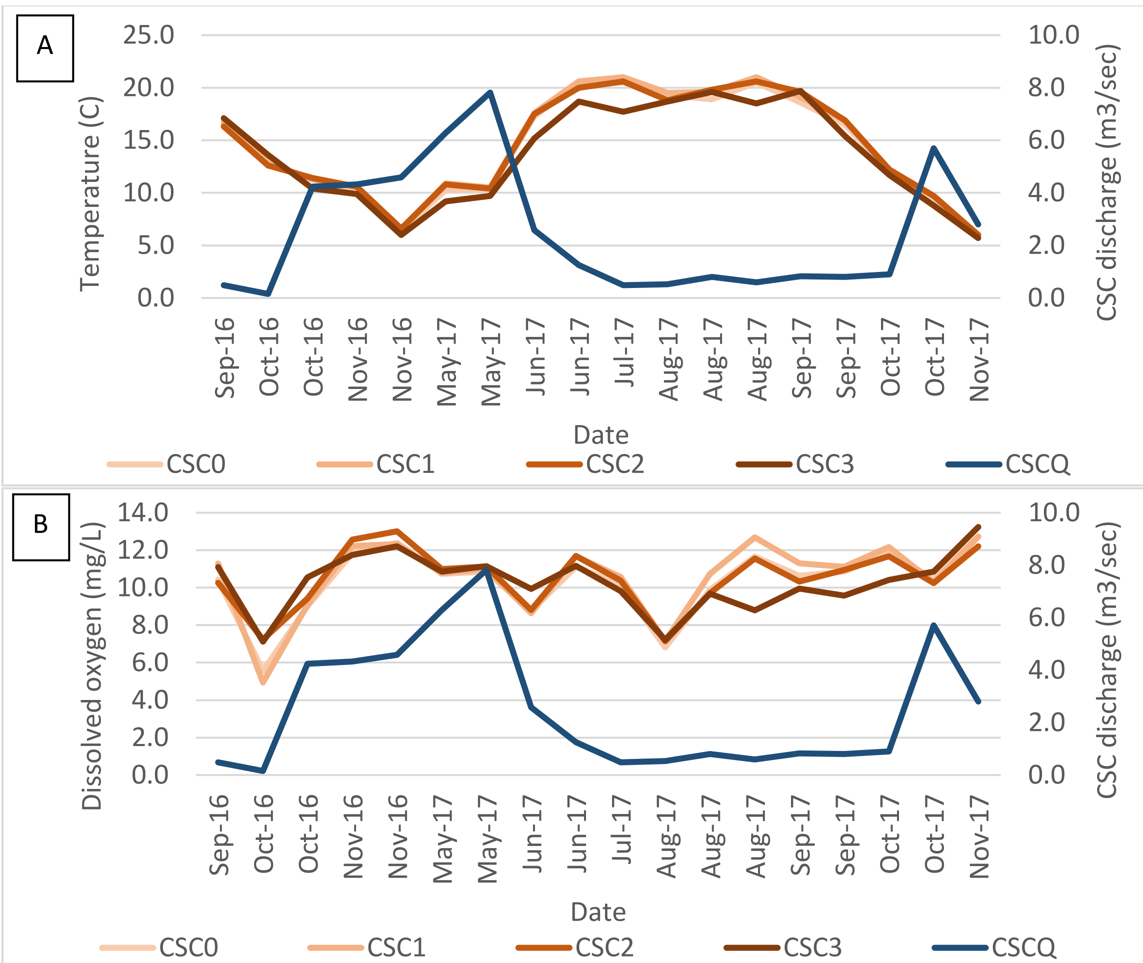

Figure 23. Water temperature (A) and dissolved oxygen (B) at connected side-channel sites (CSC) compared to connected side-channel discharge (CSCQ).

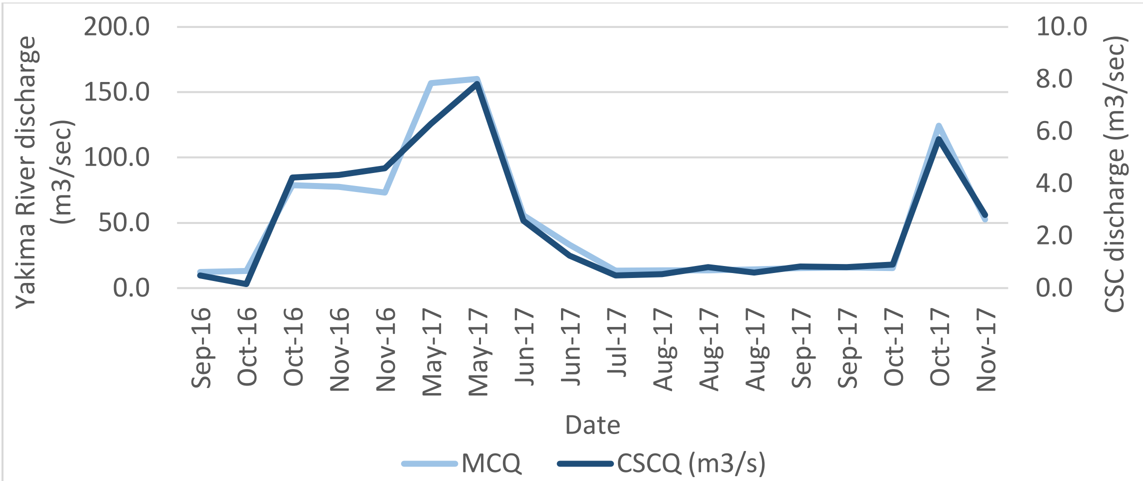

Figure 24. Connected side-channel discharge (CSCQ) vs. Yakima River discharge (MCQ) near Parker, WA.

Longitudinal Side-Channel Profiles

Longitudinal profiles revealed stark differences between connected and disconnected side-channel temperature and specific conductance, and their seasonal variations. Specific conductance in the connected side-channel varied relatively little along the length of the channel in the summer (113.8-132.2 uS/cm) and winter (111.2-126.7 uS/cm), and between seasons where winter values were slightly lower (Figures 25 and 26). Specific conductance of the disconnected side-channel varied greatly along the length of the channel in summer (147.5-367.7 uS/cm) and winter (162.7-248.1 uS/cm), and between seasons where conductance is generally lower in winter than summer (Figures 27 and 28).

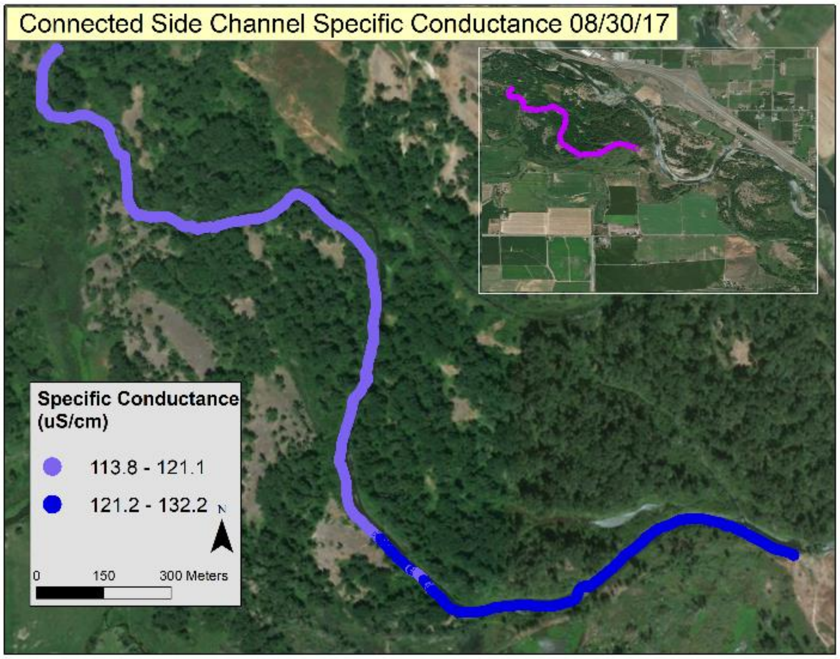

Figure 25. Specific conductance of connected side-channel in late summer.

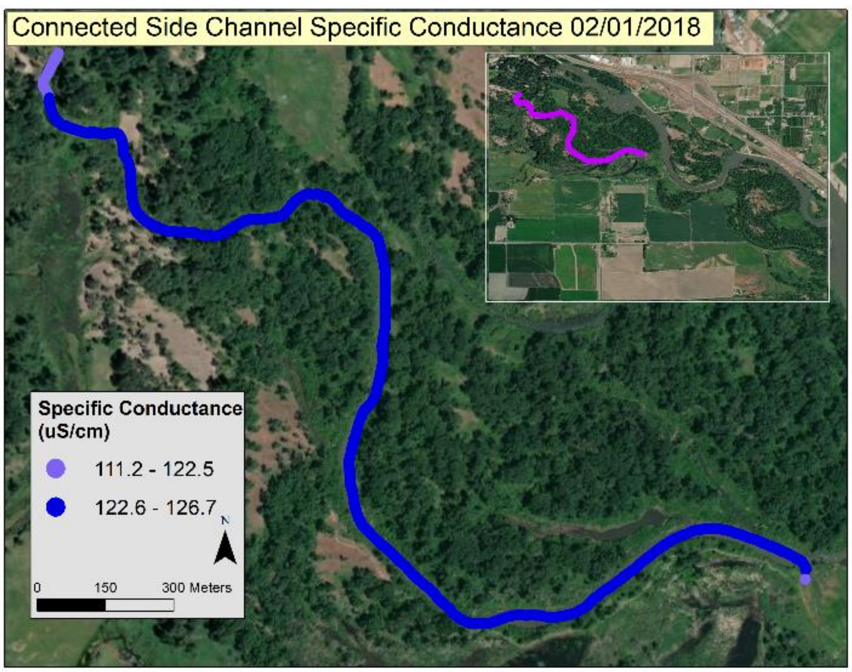

Figure 26. Specific conductance of connected side-channel in winter.

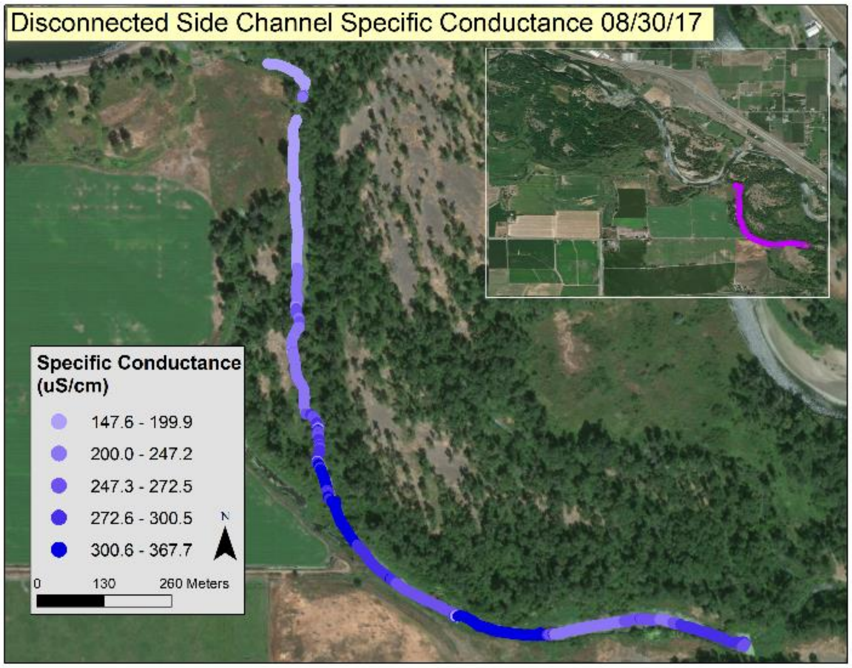

Figure 27. Specific conductance of disconnected side-channel in late summer.

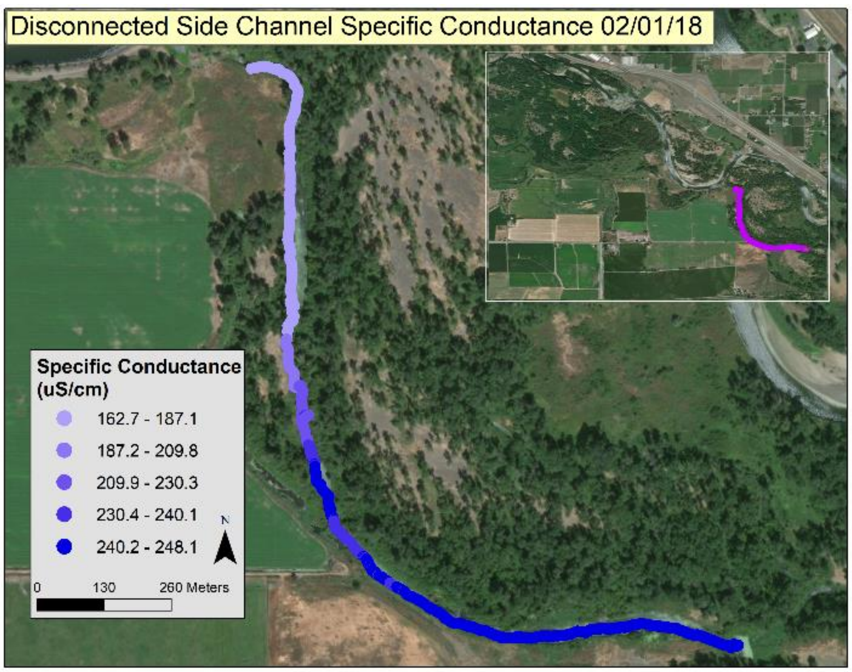

Figure 28. Specific conductance of disconnected side-channel in winter.

Temperature profiles of the connected side-channel show some variability of water temperature along the length of the channel in summer (18.7-23.7 ^{o}C) and winter (3.5-6.3 ^{o}C), but notable differences between seasons, where water temperatures are much higher in the late summer than winter (Figures 29 and 30). The variation in temperature that exists along the connected side-channel follows the same pattern in each season, where temperatures increase along its length, though the high end of the temperature scale includes readings affected by higher air temperatures.

Temperature profiles along the disconnected side-channel reveal wide variations in temperatures along its length in summer (16.0-29.6 ^{o}C) and winter (4.2-8.5 ^{o}C), and between seasons (Figures 31 and 32). The changes in temperature along its length follow opposite patterns between seasons, where areas of water that are relatively cooler in the summer are also relatively warmer in the winter. These trends can also be seen in the average daily water temperatures at DSC2, DSC3, CSC2, CSC3, and DP (Figure 33). The observed patterns in temperature changes in the disconnected side-channel were likely due to shading and groundwater influences.

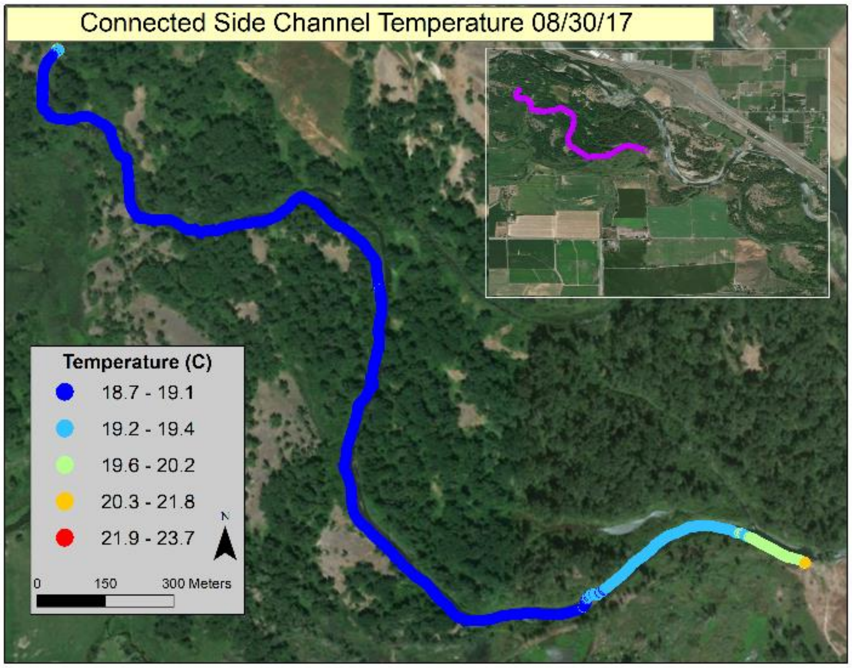

Figure 29. Connected side-channel temperature profiles for late summer.

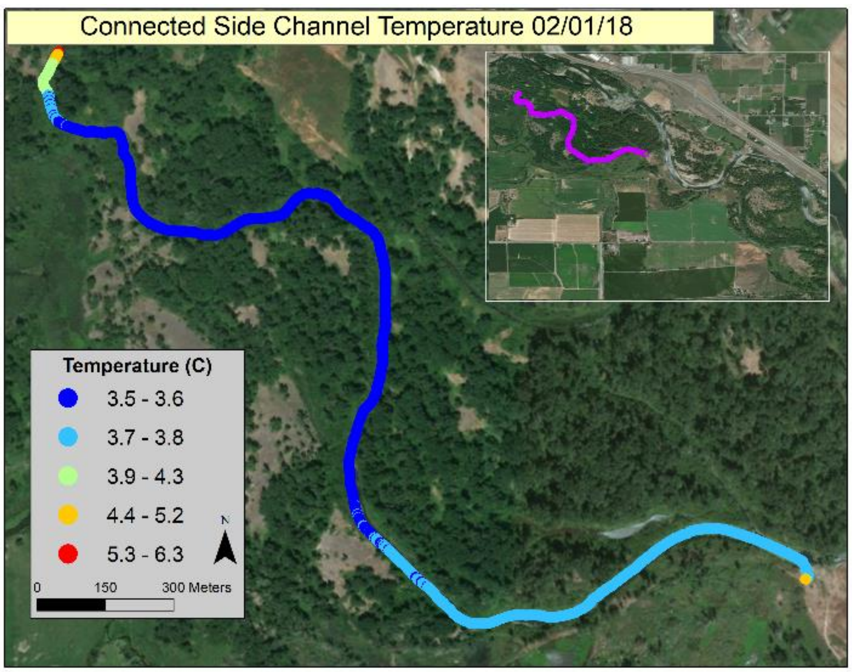

Figure 30. Connected side-channel temperature profiles for late winter.

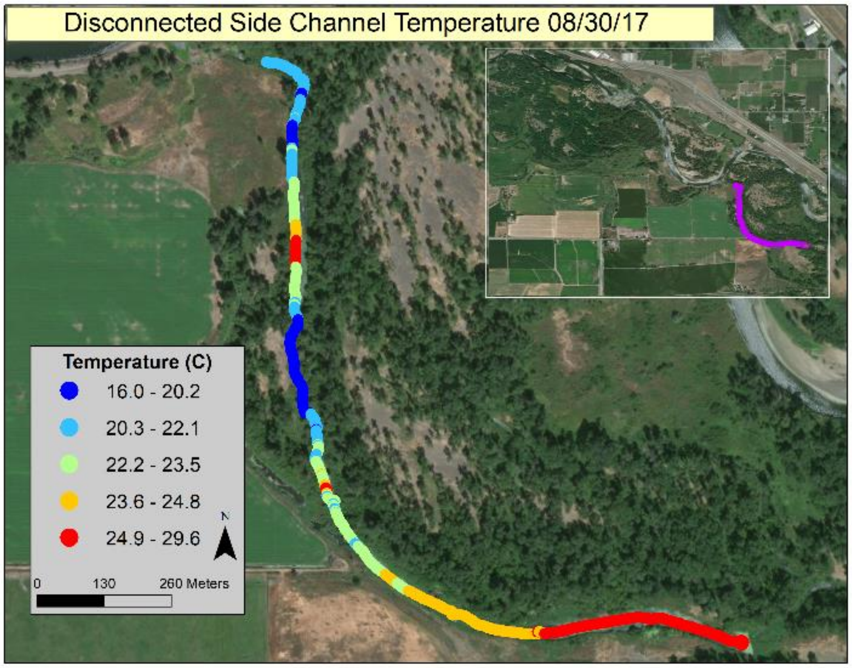

Figure 31. Disconnected side-channel temperature profiles for late summer.

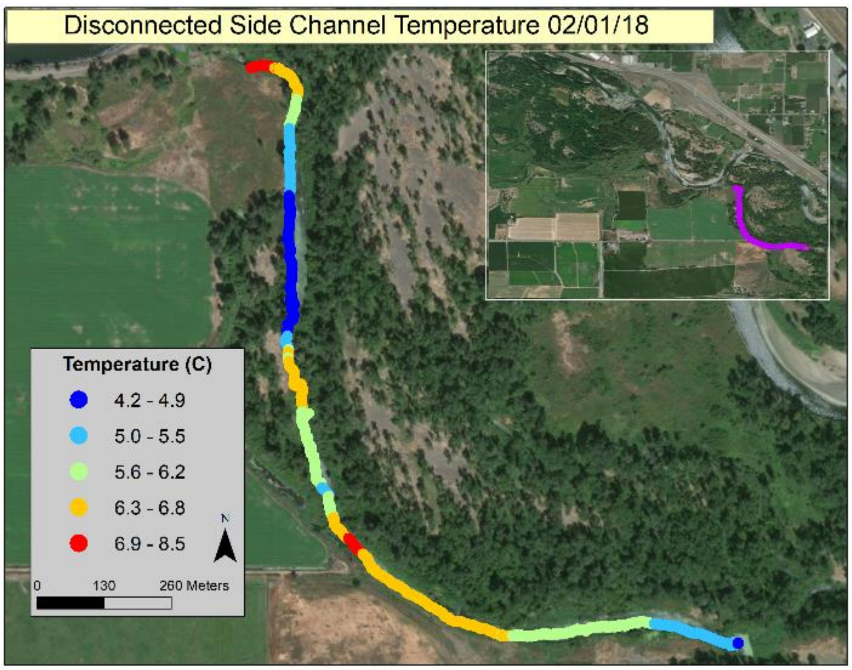

Figure 32. Disconnected side-channel temperature profiles for winter.

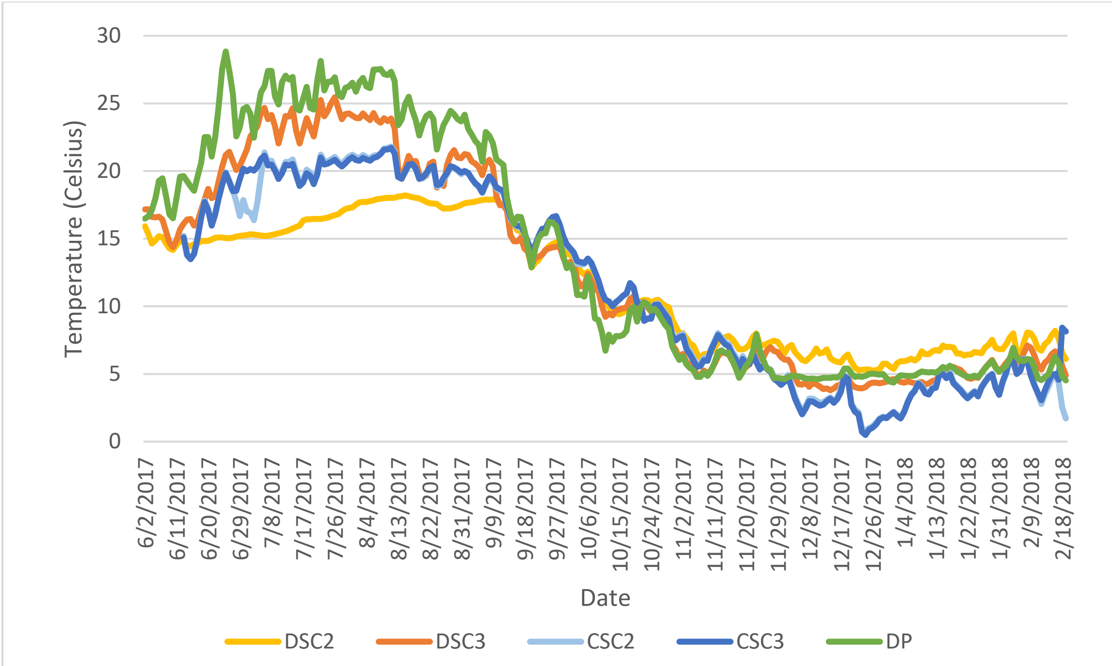

Figure 33. Surface water temperature over the study period at disconnected side-channel (DSC), connected side-channel (CSC), and disconnected pond (DP) sites.

Isotopic Analysis

Isotopic analysis was performed on seasonal water samples taken from wells and surface water to see how isotope ratios in the study site compare to the Yakima River at Union Gap and the local meteoric water line (LMWL) from observations of Ellensburg precipitation (Figure 34). Most of the observed ratios fall on or above the LMWL. The well observation that stands alone is Well 13, which is the most isolated from and least influenced by Yakima River flow, even in the winter when Yakima flow is the highest during the study period. These data may be useful to compare with post-project ratios to look for changes in groundwater residence times. Grouping can be seen among seasons and water types (surface vs ground).

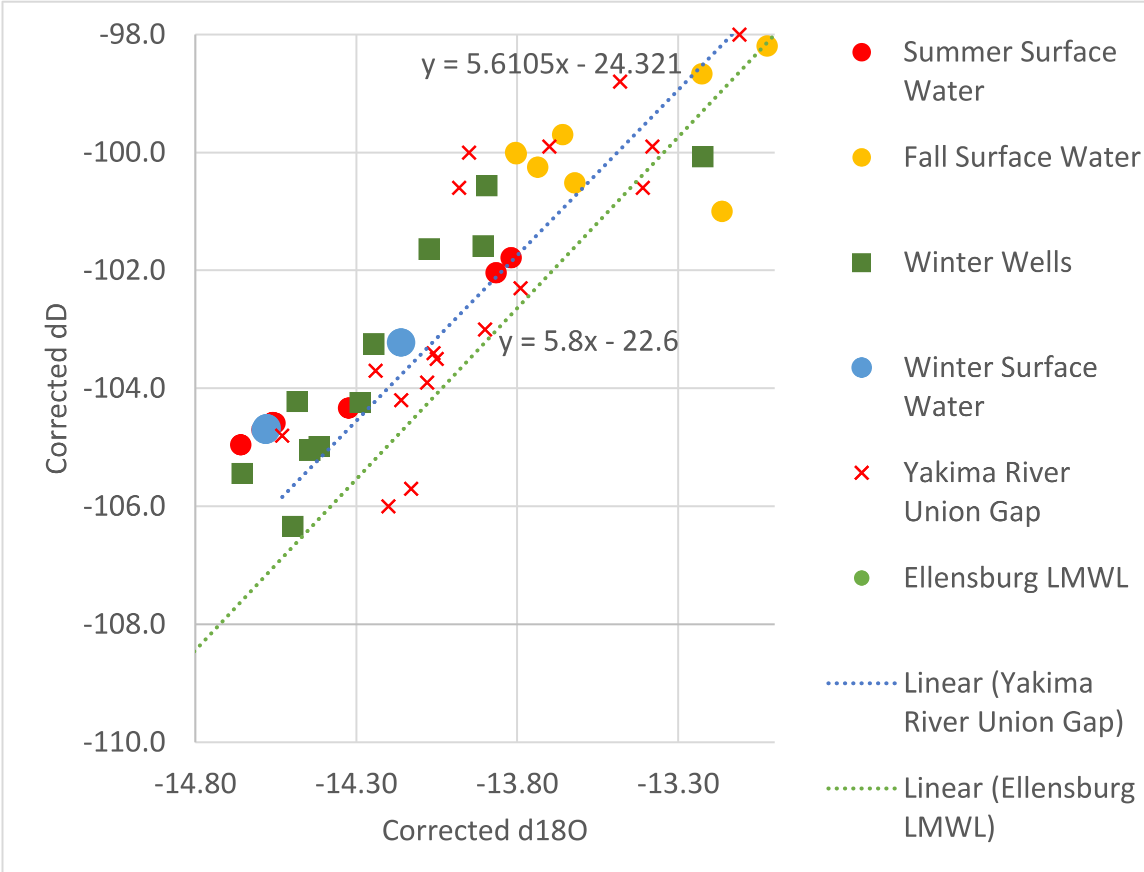

Figure 34. Isotope ratios (dD vs $d^{18}O$) for the study area compared to the Yakima River at Union Gap, and Ellensburg precipitation LMWL.

Water Elevations

Well and Stage Observations

Seasonal changes and relationships can be seen among surface water and groundwater elevations, as well as during high flow events (Figures 35 and 36). Changes in surface water elevations generally mimic those of the Yakima River, dropping off in June and generally remaining constant through the summer until high flows come through the Yakima in late October. One exception is seen at AgPond, where water levels fluctuate during the summer, peak in early fall, and are unaffected by high flows in the

Yakima River; another exception is at DSC1, where a pulse of water unrelated to flow in the Yakima River is seen increasing water depths by about a meter in late September. Flat portions of data series in the graph correspond to time when the water depths dropped below the water level sensor.

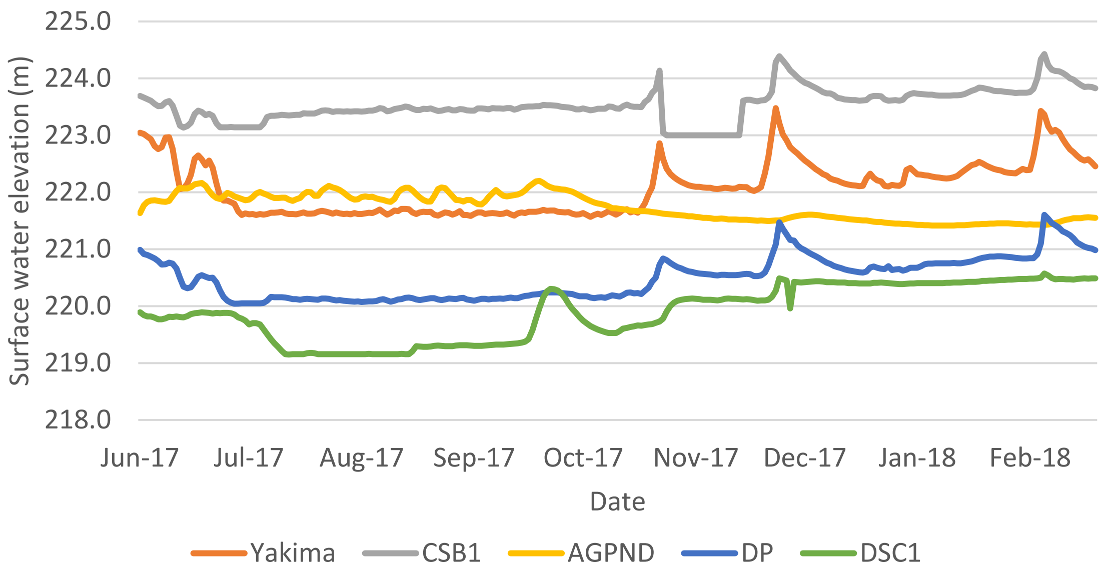

Figure 35. Surface water elevations calculated from water depths at four stage recorder sites and the Yakima River gage near Parker. Flat portions indicate water levels below sensor.

Groundwater elevations generally follow a similar trend as surface stage recorders, falling from high water in June, continuing to drop through summer, and then increasing with high Yakima River flows beginning in late October (Figure 34). Exceptions occur in late September when an increase in water table elevation occurs at every well, with an increase of over a meter at Well 11. Wells 13 and 14 vary relatively little over the study period, with minimal responses to changes in Yakima River flow. Flat portions of data series in the graph correspond to time when the water depths dropped below the water level sensor, and gaps indicate missing data. Sharp changes in middle August occur because the wells were reinstalled at greater depths.

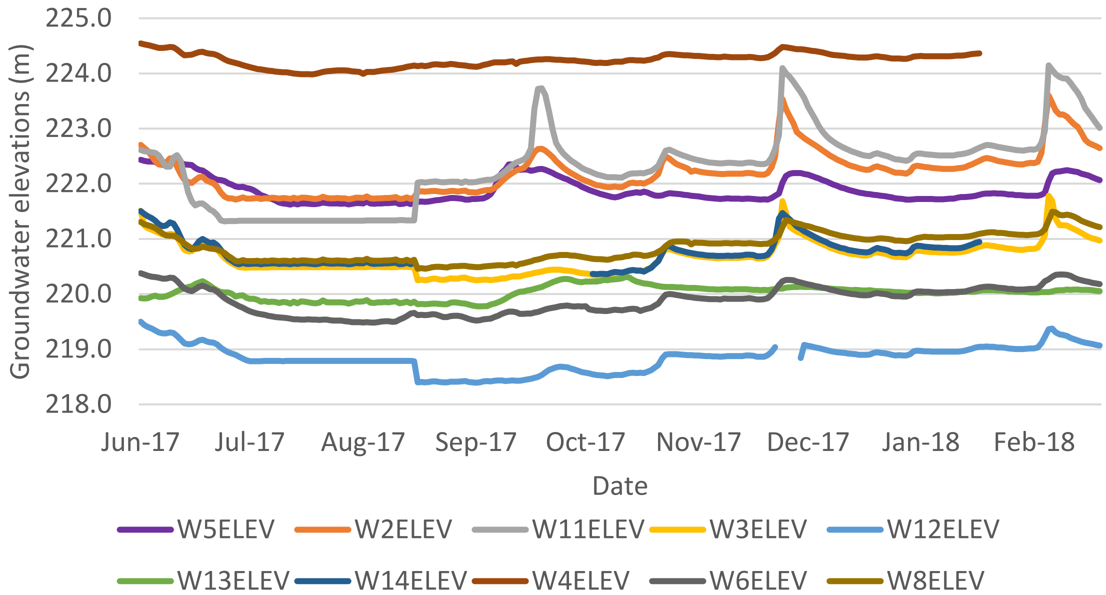

Figure 36. Groundwater elevations calculated from water table depths at 10 observation wells. Gaps in data lines indicate sensors not recording, flat portions indicate water levels below sensors.

Average seasonal surface water depths and water table levels relative to the surface are shown in Table 12. The deepest average seasonal water depth in a well occurred at Well 11 in summer (-1.8m), while the highest average depth relative to the surface of a well also occurred at Well 6 in winter (0.0m). The largest seasonal variation in a well was observed at Well 11 in fall (2.1m). The smallest seasonal variation in a well were seen at Wells 4 and 13 in winter (0.1m). The highest average seasonal surface water stage occurred at CSC1 in winter (1.6m), and the largest seasonal range was observed at Yakima River near Parker,WA in fall (1.9m). The shallowest average seasonal surface water depth was observed at AgPond in winter (0.3m). The largest seasonal variation in surface water depth occurred in fall Yakima River near Parker (1.9m). The largest variability across all surface stage sites occurred in fall ranging from 0.7m – 1.9m.

Table 12. Average seasonal surface water depths and water table position relative to the surface (m) [mean (range)].

Site	Summer	Fall	Winter
AgPond	0.7 [0.6]	0.5 [0.7]	0.3 [0.2]
CSC1	0.6 [0.7]	0.9 [1.2]	1.6 [0.2]
DP	0.9 [0.5]	0.7 [0.7]	0.4 [0.2]
DSC1	0.5 [0.8]	0.8 [1.2]	1.4 [0.2]
Yakima	0.9 [1.4]	1.0 [1.9]	1.4 [1.3]
Well 11	-1.8 [1.3]	-0.9 [2.1]	-0.6 [1.8]
Well 12	-1.1 [1.1]	-1.3 [0.6]	-1.0 [0.5]
Well 13	-1.7 [0.4]	-1.5 [0.5]	-1.5 [0.1]
Well 14	-0.9 [1.0]	-0.9 [1.1]	-0.7 [0.4]
Well 2	-1.5 [1.0]	-1.2 [1.7]	-0.9 [1.4]
Well 3	-1.0 [1.2]	-1.0 [1.4]	-0.7 [1.1]
Well 4	-0.4 [0.5]	-0.3 [0.4]	-0.3 [0.1]
Well 5	-0.9 [0.8]	-0.9 [0.6]	-0.9 [0.5]
Well 6	-0.4 [0.9]	-0.3 [0.8]	0.0 [0.4]
Well 8	-0.9 [0.8]	-0.8 [0.8]	-0.5 [0.5]

Visual MODFLOW Flex

Several problems arose while building the conceptual groundwater model and running numerical models translated from them. The most significant problem that arose early on was defining water table elevations for the edges of the model. Without knowing the elevation of the water table around the boundary of the model, the results do not reflect reality. Lack of data was also an issue when characterizing river boundary conditions, as the exact values of river bed conductance and depth were not known. Water had a tendency to unrealistically pile up over time within the model area, and water table values through the area would steadily increase, or the water table would appear to spike under river channels (Figure 37). More formal training in using the software would help clarify some major issues. The most realistic results given by the modeling currently are not more useful than the geostatistical methods that were also used (Figure 38).

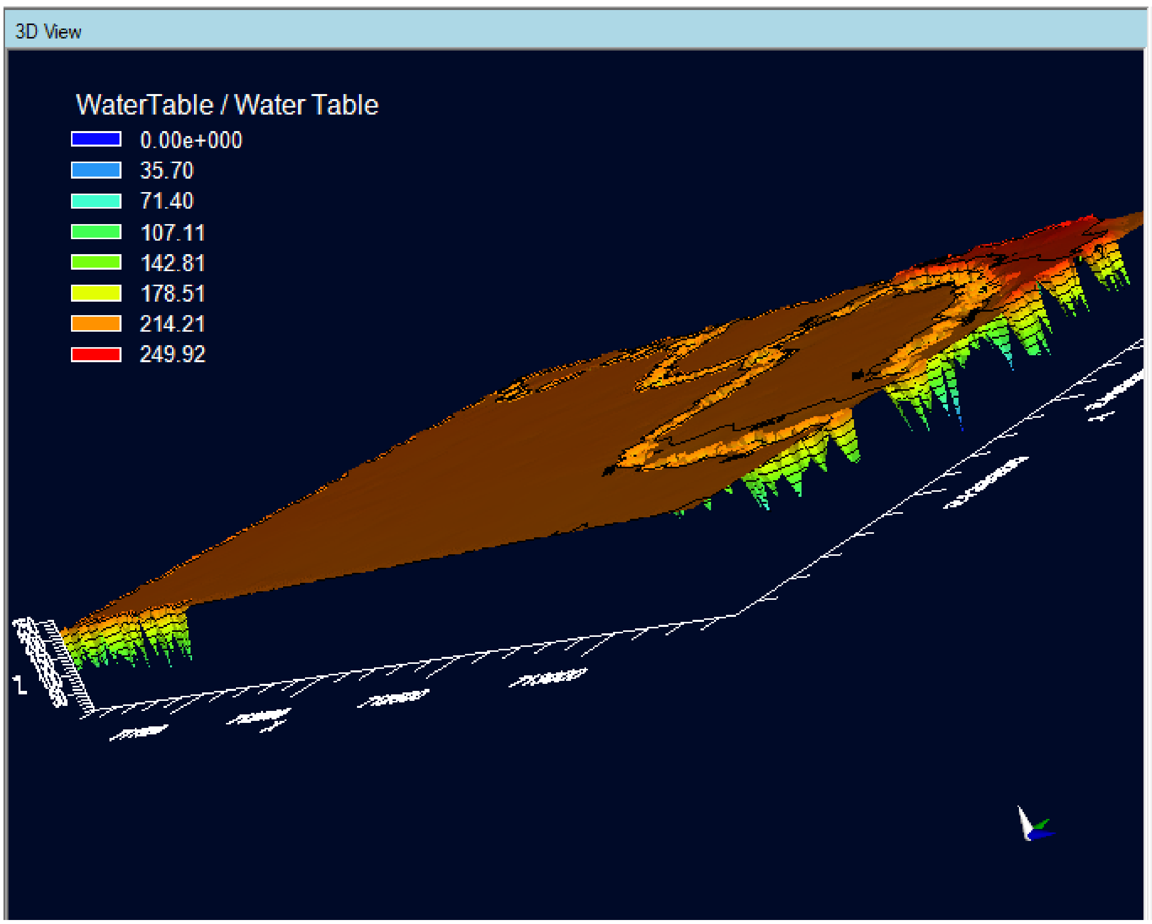

Figure 37. Unrealistic modeling result with the water table spiking below river features. The spikes mean that the software thinks the water table drops to an elevation of 0.

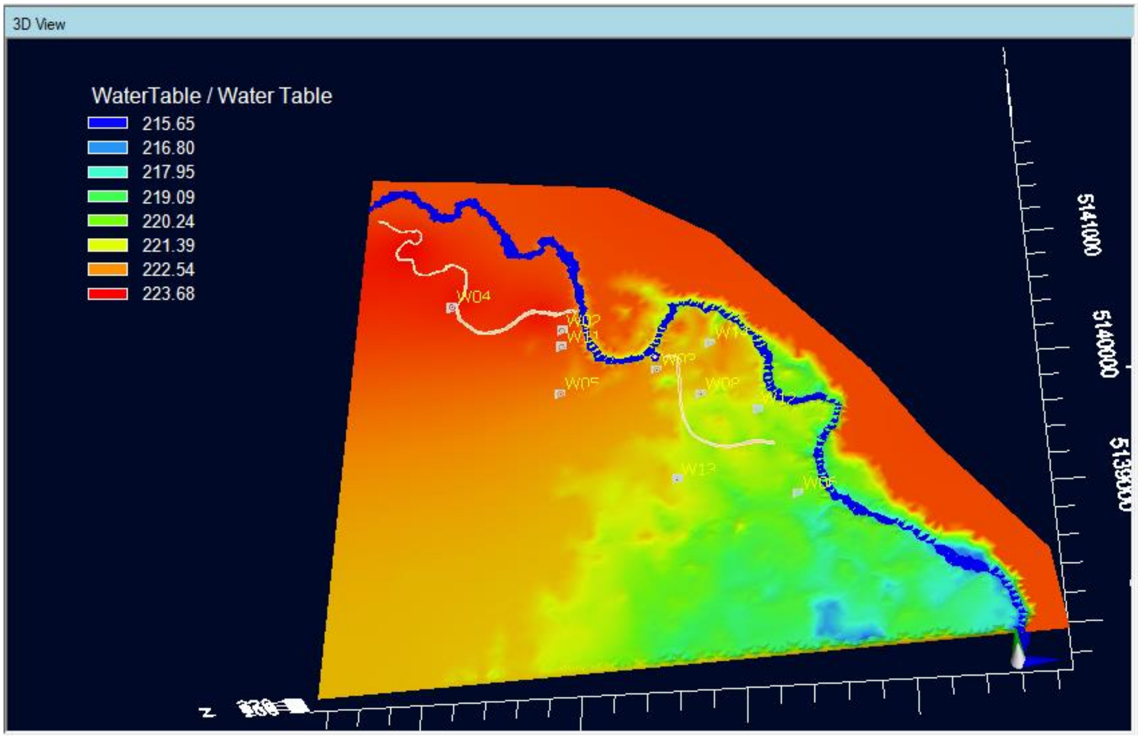

Figure 38. Calculated water table over a single one day time step on June 2, 2017.

Geostatistical Analysis

Geostatistical analysis of water level elevations was performed in ArcMap 10.5 using Empirical Bayesian Kriging interpolation, producing raster files that were converted into contour line layers (Figures 39, 40, 41, and 42). The contour line layers illustrate the overall motion of both surface and groundwater, where water moves at right angles to the contour lines, and from higher to lower elevation. Water table elevations for 09/25/2017 are representative of elevations through most of the summer, when the flow in the Yakima River has dropped to baseflow (16.3 m^3/s) levels (Figure 39). Water table elevations for 10/23/17 represent the water table during the first high flow event on the Yakima River of fall, with a discharge of 176.6 m^3 (Figure 40).

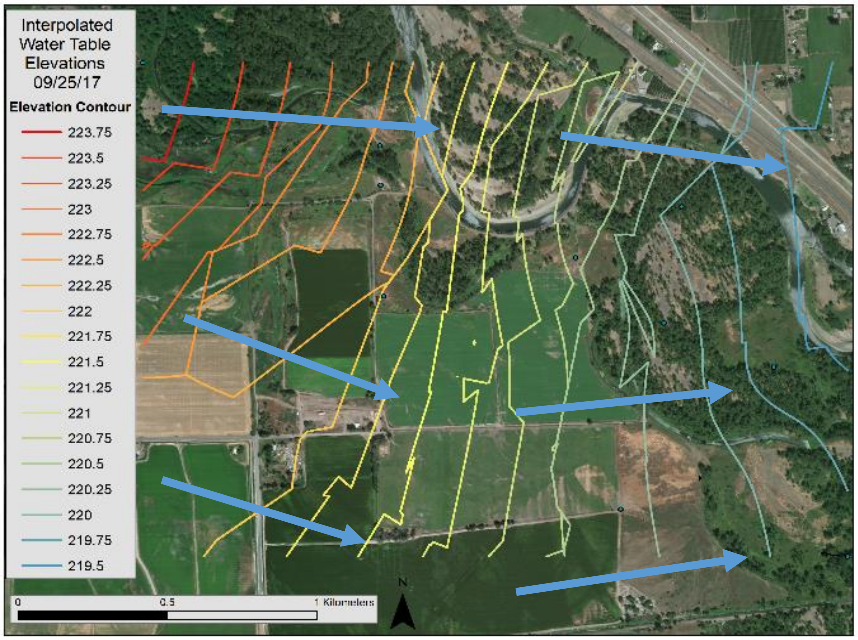

Figure 39. Water elevation contour lines interpolated from water level elevations using Empirical Bayesian Kriging in ArcMap 10.5. Blue lines indicate general direction of groundwater flow for 09/25/2017.

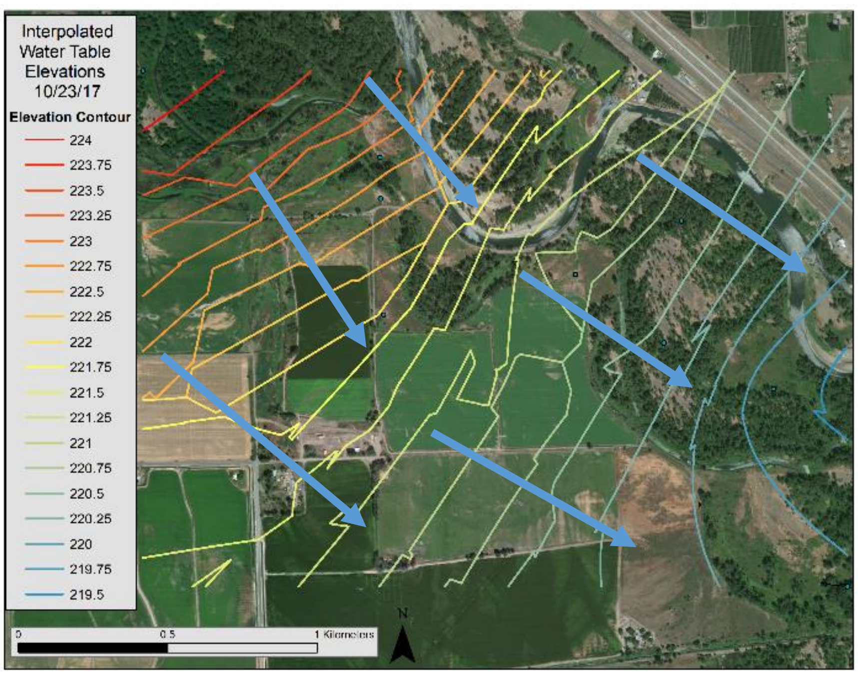

Figure 40. Water elevation contour lines interpolated from water level elevations using Empirical Bayesian Kriging in ArcMap 10.5. Blue lines indicate general direction of groundwater flow on 10/23/2017.

Elevations for 11/25/17 represent the water table a day after the highest daily average flow of the Yakima River in the study period, which had a discharge of 327.8 m^3/s. Average daily well water elevations were the highest the day after peak flows, and Yakima River discharge was 254.9 m^3/s. Elevation contours for 01/07/18 represent the water table during typical winter flow in between high flow events, with a discharge of 73.2 m^3/s. Seasonal differences can be seen in the movement of water through the floodplain, as higher Yakima River and CSC discharges shifts the overall flow. The west-east movement of water through the floodplain during summer shifts to a north-south orientation through fall and winter.

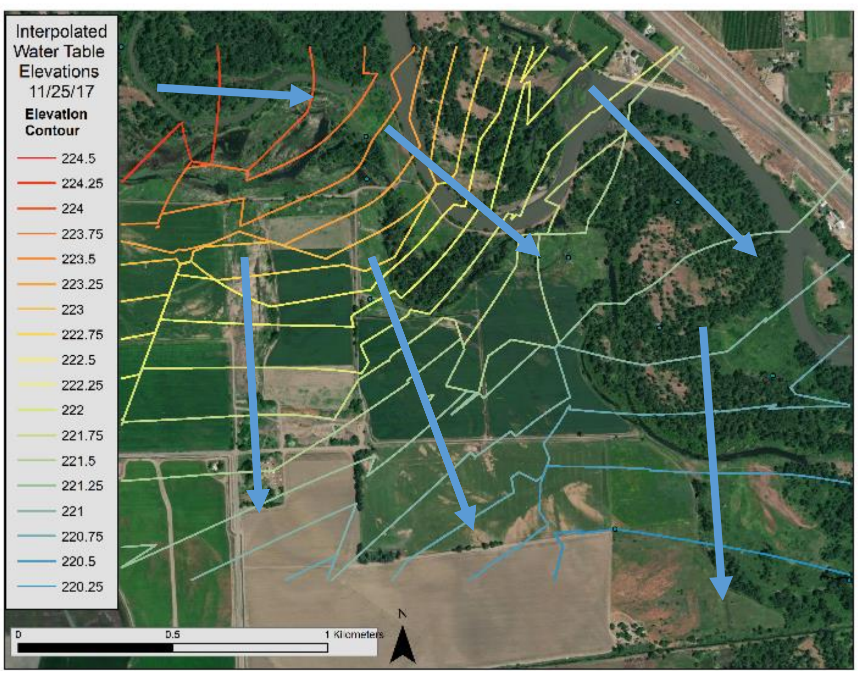

Figure 41. Water elevation contour lines interpolated from water level elevations using Empirical Bayesian Kriging in ArcMap 10.5. Blue lines indicate general direction of groundwater flow on 11/25/17.

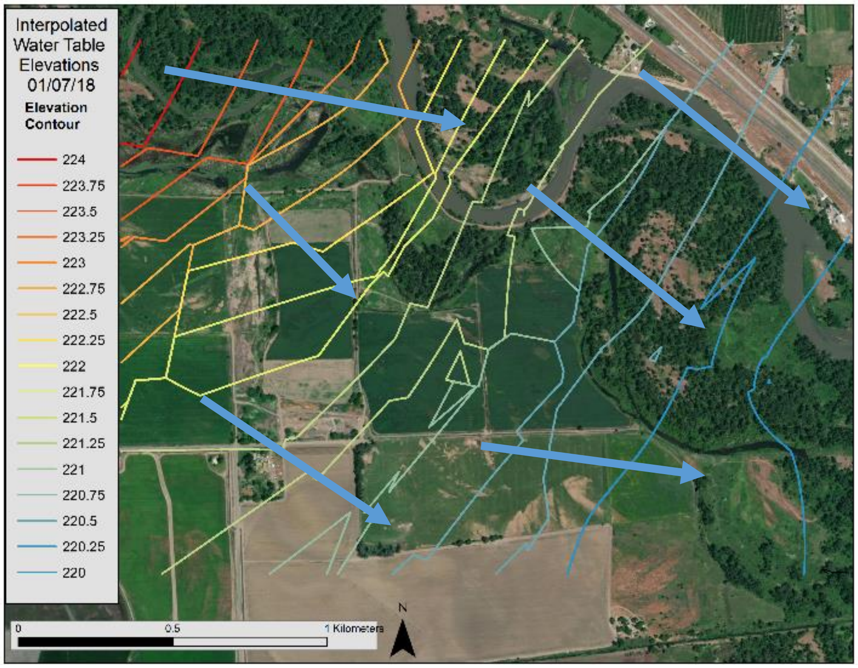

Figure 42. Water elevation contour lines interpolated from water level elevations using Empirical Bayesian Kriging in ArcMap 10.5. Blue lines indicate general direction of groundwater flow on 01/07/2018.

Pearson correlation coefficients between water elevations sites were calculated for winter and summer, with significant relationships highlighted (p < 0.05); red cells indicate a strong relationship (0.81-1.00), orange cells show moderately-strong correlations (0.61-0.80), yellow cells show moderate correlations (0.41-60), and green cells are weak correlations (0.01-0.40) (Tables 13 and 14). Cells without a color indicate a statistically insignificant correlation, and cells without values indicate a lack of data to calculate correlations. Negative values indicate negative correlations.

Table 13. Pearson coefficients of relationships between water elevation sites in winter.

Site	AGPND	CSC1	DP	DSC1	Well 11	Well 12	Well 13	Well 2	Well 3	Well 5	Well 6	Well 8	Yakima
CSC1	0.02												
DP	0.03	0.93											
DSC1	-0.08	0.68	0.72										
Well 11	0.09	0.93	0.88	0.65									
Well 12	-0.25	0.87	0.80	0.71	0.89								
Well 13	0.54	0.33	0.36	0.03	0.40	0.07							
Well 2	0.01	0.91	0.83	0.67	0.97	0.93	0.30						
Well 3	-0.10	0.87	0.74	0.61	0.93	0.94	0.20	0.95					
Well 5	0.44	0.83	0.83	0.54	0.88	0.65	0.62	0.81	0.71				
Well 6	0.01	0.90	0.91	0.75	0.92	0.88	0.34	0.92	0.84	0.82			
Well 8	0.08	0.95	0.92	0.74	0.96	0.87	0.39	0.93	0.87	0.88	0.95		
Yakima	-0.10	0.96	0.89	0.68	0.94	0.92	0.28	0.94	0.92	0.78	0.91	0.94	
Well 4	0.25	0.69	0.69		0.73	0.41	0.28	0.77	0.71	0.58	0.78	0.84	0.67
Well 14	0.22	0.81	0.72		0.81	0.60	0.29	0.82	0.81	0.65	0.78	0.77	0.86

Table 14. Pearson coefficients of relationships between water elevation sites in summer.

Site	AGPND	CSC1	DP	DSC1	Well 11	Well 12	Well 13	Well 2	Well 3	Well 5	Well 6	Well 8	Yakima
CSC1	-0.26												
DP	-0.24	0.39											
DSC1	0.01	-0.35	0.64										
Well 11	-0.25	0.45	0.74	0.40									
Well 12	-0.08	0.06	0.81	0.67	0.29								
Well 13	0.32	-0.31	0.49	0.79	0.14	0.65							
Well 2	-0.22	0.44	0.94	0.61	0.88	0.65	0.42						
Well 3	-0.17	0.22	0.94	0.71	0.53	0.95	0.61	0.83					
Well 5	-0.06	-0.01	0.86	0.90	0.67	0.79	0.73	0.86	0.87				
Well 6	-0.08	0.09	0.91	0.86	0.68	0.81	0.70	0.89	0.91	0.98			
Well 8	-0.21	0.26	0.96	0.68	0.65	0.91	0.54	0.89	0.98	0.89	0.92		
Yakima	-0.15	0.34	0.96	0.72	0.68	0.83	0.61	0.92	0.94	0.91	0.94	0.94	
Well 4	-0.09	0.18	0.86	0.81	0.76	0.66	0.62	0.90	0.81	0.93	0.94	0.83	0.91
Well 14	-0.25	0.44	0.98	0.64	0.94	0.97	0.50	0.98	0.98	0.88	0.91	0.97	0.96

The strongest relationships in winter were generally found between the stage recorders and wells closest to the Yakima River, ranging between 0.68 and 0.96, with the most distant and disconnected sites showing the weakest correlations (Well 13, AgPond) ranging from -0.10 to 0.28. AgPond had the weakest correlations of any site in winter, with only Wells 13 and 5 having significant positive relationships, and a Well 12 showing a negative correlation. The strongest correlations in summer were generally found between well sites, with lower correlation found between most sites and the Yakima than in winter. Much higher correlations were found between Well 13 and most sites in the summer, although CSC1 water levels dropping below the sensor in the summer give it some of the weakest correlations after AgPond, from -0.35 to 0.45.

Several maps of statistically significant ($p < 0.05$) Pearson correlation coefficients calculated from water level elevations are shown below in intervals of weak (0.01-0.40), moderate (0.41-0.60), moderately strong (0.61-0.80) and strong (0.81-1.00). The main channel Yakima River and Well 13 were used to represent relationships between different water sources, with Yakima River representing relationships to surface water movement and Well 13 representing relationships to groundwater movement. Well 13 was chosen to represent groundwater because it is the well furthest from surface water and least likely to be influenced by Yakima River discharge. Summer and winter relationships were used to represent relationships at different seasonal levels of Yakima River discharge (Figure 43).

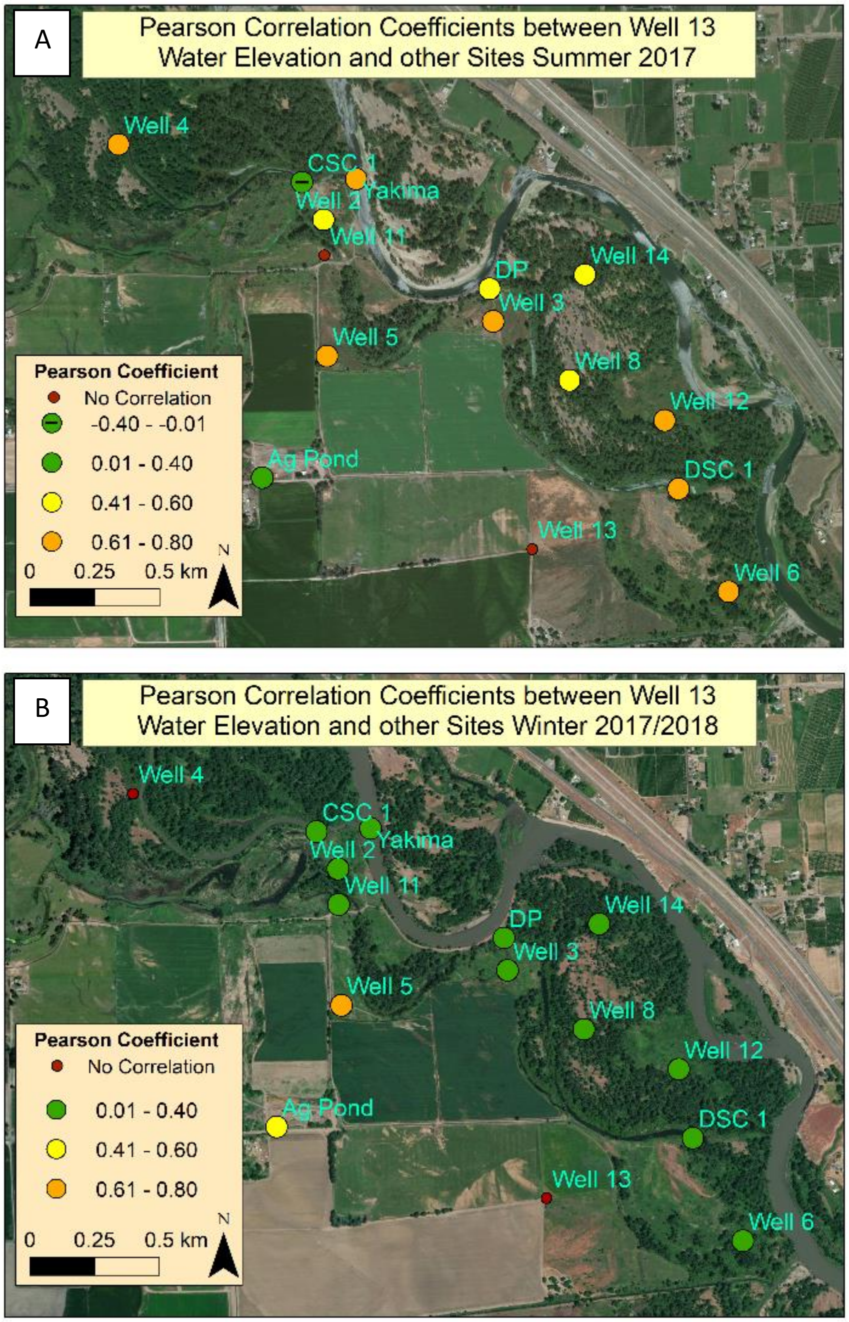

Figure 43. Pearson correlation coefficients between Well 13 water elevations and other water elevation sites in summer (A), and winter (B).

Moderate (0.41 - 0.60) to moderately-strong (0.61 - 0.80) coefficients were found between Well 13 and 11 out of 14 water elevation sites in the summer, during lowest Yakima River flows. CSC 1 showed a weak negative (-0.01 - -0.40) correlation, Well 11 showed no significant correlation, and Ag Pond showed a weak (0.01 - 0.40) correlation with Well 13 during this time period. Weak (0.01 - 0.40) correlations were found between Well 13 and 11 out of 14 other sites in winter, during highest flows. Almost all water elevation locations showed moderately-strong (0.61 – 0.80) to strong (0.81 – 1.00) relationships to Yakima River stage in the summer, and in the winter; the only exceptions were Ag Pond and Well 13 (Figure 44).

Ground Penetrating Radar

Radargrams of GPR transects vary by site, showing a mixture of water table indicators. Some radargrams show horizontal lines of stronger reflectance, which are possible indicators of the water table, although changes in other substrate characteristics (e.g. grain size or density) can also cause this feature. Attenuation in reflected signals can also indicate the presence of groundwater, as radar waves are absorbed by water instead of reflected to the antennae. The radargram of Well 5 shows a pattern of strong linear reflectance near the measured average daily water table depth, possibly indicating the water table (Figure 45). Well 5 is located in a substrate of relatively homogenous gravel that has been disturbed twice by well installation, so this pattern is more likely to result from the presence of water than from a stratigraphic layer of material.

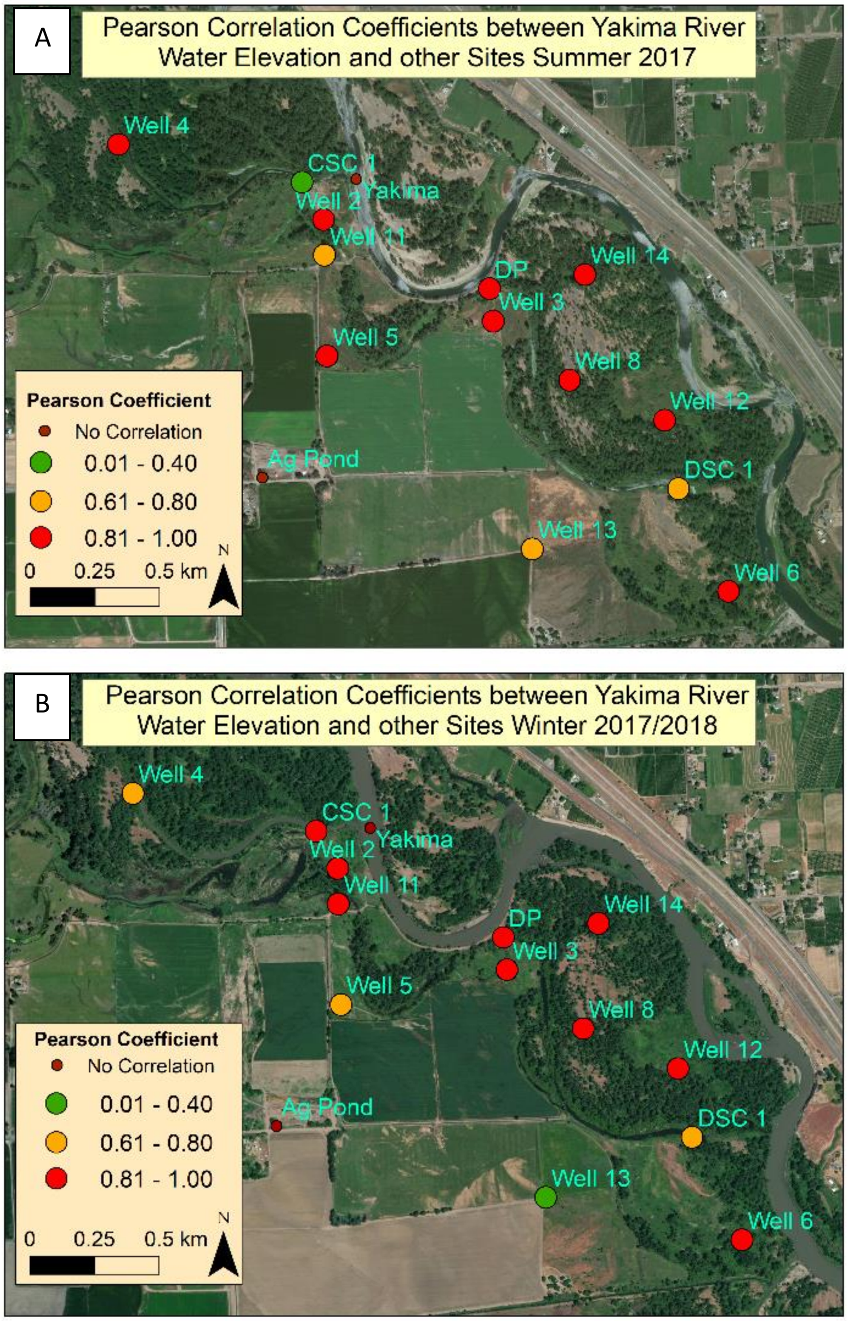

Figure 44. Pearson correlation coefficients between Yakima River water elevations and other water elevation sites in summer (A), and winter (B).

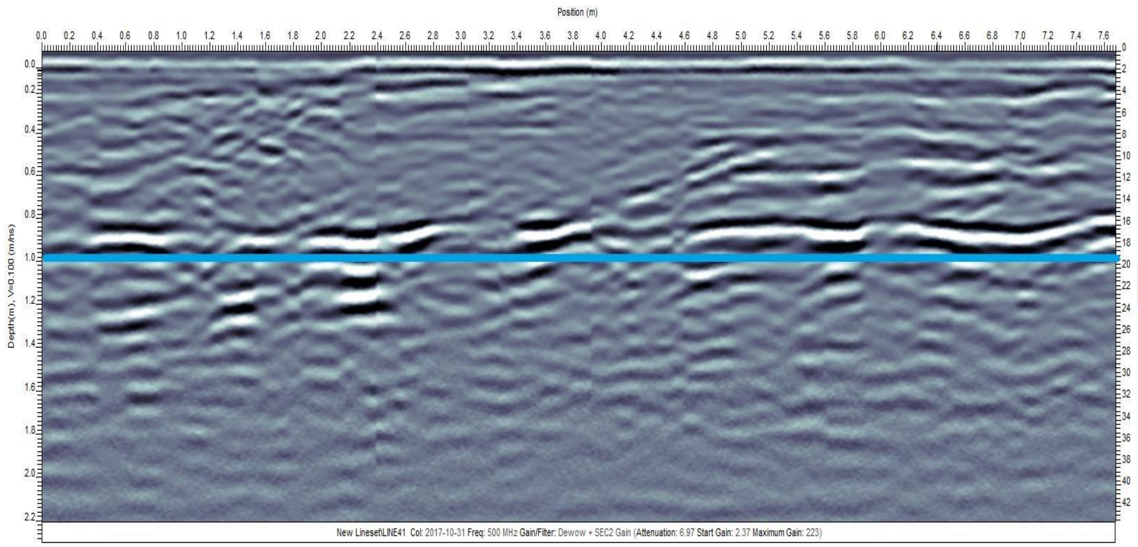

Figure 45. Radargram of the GPR transect at Well 5. The blue line represents the measured average daily water table depth.

The radargram of Well 12 shows a pattern of attenuated reflectance starting near and continuing below the average daily water table depth (Figure 46). Attenuation of the radar waves can be seen in the lower contrast and smoother texture of the reflected signals below the measured water table. Well 12 is located in an area where there is a meter of soil on top of gravel, so this pattern may also be indicative of a change in material, and a coincidental position of the water table. The radargram of Well 13 shows both of the patterns described, with lines of high reflectance and an area of attenuated reflectance below the measured water table (Figure 47). It is not clear whether the water table can be discerned from this radargram, since the measured water table depth is in an area of attenuated reflectance, and is well below features of strong linear reflectance.

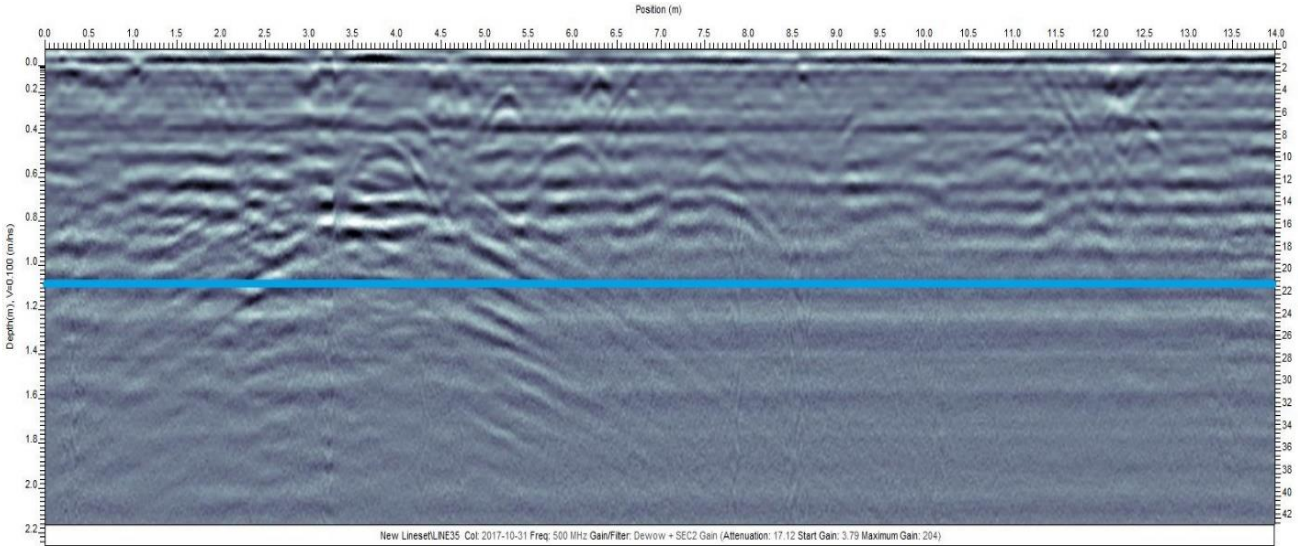

Figure 46. Radargram of the GPR transect at Well 12. The blue line represents the measured average daily water table depth.

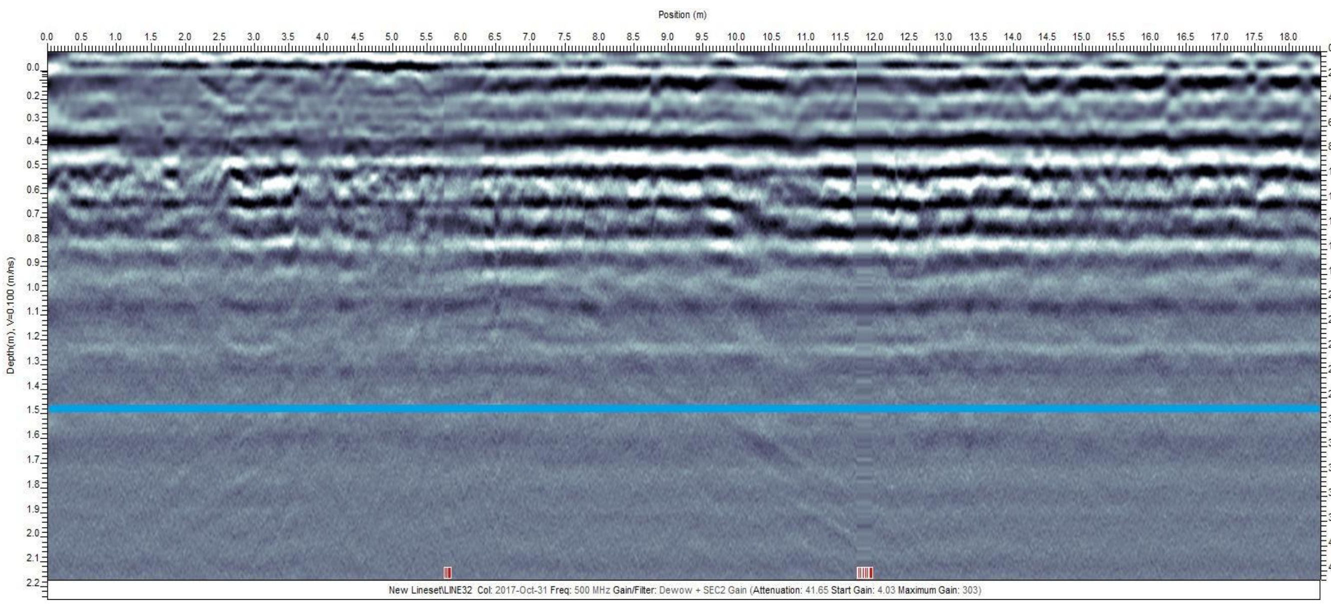

Figure 47. Radargram of the GPR transect at Well 13. The blue line represents the measured average daily water table depth.

CHAPTER VI

DISCUSSION AND CONCLUSIONS

Water Quality

Significant temperature differences between seasons followed an expected pattern at all sites, where summer temperatures were significantly higher than spring or fall due to lower water levels, increased air temperatures, and more direct sunlight on the water over a longer day. Specific conductance drops in the spring as high flows in the Yakima River bring recent rain and snowmelt through the floodplain in rarely activated side channels and hyporheic flow. Recent snowmelt and precipitation have much lower amounts of dissolved solids than hyporheic or groundwater, and so have a lower specific conductance. Some of this water manages to reach disconnected side channels, overcoming the influences of evaporation and possible groundwater inputs, decreasing specific conductance. Specific conductance generally increases in the summer and fall because of increased groundwater influence on surface water, and because of evaporation in disconnected locations. Turbidity was significantly higher at most CSC sites and the Yakima due to high flows carrying higher suspended sediment loads. While fluctuations in DO can be seen over the study period, no statistically significant differences were found between seasons at any of the sites. Variation in DO occurred partially because data were collected sometimes in the morning, and sometimes in the afternoon. Water quality data are missing from late-November through mid-March due to snow and ice covered collection sites.

Significant temperature differences between site pairs also followed an expected trend, where disconnected side-channels sites had higher temperature over the study period than connected sites. Spring temperatures also tended to be higher at disconnected sites, made warmer by still water stagnating in the sun, while Yakima River and connected side-channel water remained well mixed due to higher currents. While DP was separated from the Yakima by only 20 m (width of the levee) and is very responsive to changes in the main-channel stage, its temperatures were significantly higher over the study period and in the spring, probably due to its small and shallow nature, and lack of surface connectivity most of the year. The mid-point of the disconnected channel also had a significantly higher temperature over the study period and in the spring than the mid-point of the connected channel. Increasing the ability of spring and fall high flows to reach these disconnected locations can help moderate temperatures and enhance habitat connectivity.

Specific conductance in surface water is higher in disconnected sites because of groundwater inputs and evaporation. As water moves through soil it dissolves salts which allows it to better conduct an electrical current, so a considerable difference can be seen in groundwater and surface water specific conductance (Lee et al. 1997). This difference can also be seen between surface waters, such as the connected and disconnect side-channels. The effect of evaporation can be seen in the significant differences in specific conductance between DP and MC over the study period and seasons, as evaporation reduces the amount of water and increases the concentration of dissolved solids.

The water in DP is likely water from the Yakima River given the high correlation between DP and MC stages, and their close proximity. Values are much higher in DP than MC, but not as high as at DSC1, indicating less groundwater input and mostly evaporation effects in DP. While there was little difference in specific conductance between MC and CSC2, DSC2 is significantly higher than both of them, and higher than DP, indicating a different mixture of water sources (surface vs groundwater).

Significantly higher conductance at CSC0 than CSC3 during the summer and fall while water is relatively low may also indicate ground water inputs along the length of the connected side-channel, or could be due to evaporation. As Yakima River flow drops, so does the amount of surface water entering the connected side-channel, increasing the likelihood that some locations be fed by hyporheic flow, increasing the amount of dissolved solids in the water. There are also small side-channels in the connected side-channel, which could be groundwater springs and contribute small amounts of flow to CSC. The higher specific conductance in summer and fall can also be linked to irrigation inputs, as irrigation water carries fertilizers that increase conductance, and could be the focus of future research. Significantly higher conductance at DSC1 than DSC3 over the entire period and in each season show a similar pattern but to a higher degree. DSC3 is located near the Yakima River, receiving hyporheic flow that keeps specific conductance moderated and generally lower at that site. Conductance is significantly higher down-channel, especially beginning at DSC2, but with little difference between DSC2 and DSC3. This pattern is seen in the longitudinal profiles of DSC in winter and summer, when readings spike around the site. Temperature differences corroborate this conclusion. These results show changing sources of water with varying distance from and degree of connection to the Yakima River.

Further evidence for groundwater inputs in the side-channels was provided by longitudinal profiles of temperature and specific conductance. Longitudinal profiles have been an established method of investigating groundwater/surface water interactions, using both temperature and specific conductance (Torgersen and Ebersol 2012). Significant differences in summer and fall conductance at CSC0 and CSC3 are illustrated with increasing conductance along the length of the connected side-channel in late summer. More uniform specific conductance can be seen in the winter, when flows are higher and dominated by surface water. Significant differences in conductance along the disconnected side-channel are also illustrated with longitudinal profiles. Conductance is higher in the late summer than the winter with higher evaporation and groundwater influence, but both seasons show the same trend of increasing conductance along the side-channel. This trend is notable in the February profile, as surface water influences were at their peak and water levels were essentially as high as they get before water spills over the beaver dam below DSC1.

The uniformity of temperature in the connected side-channel is seen in the longitudinal profiles for late summer and winter. Temperatures increase slightly near the end of the profiles, but the differences are insignificant and the water is well mixed and likely has little if any groundwater influence. While significant temperature differences were not found between DSC1 and DSC3, clear trends can be seen in the temperature profiles of the disconnected side-channel. Water temperatures in the late summer vary throughout the profile, where temperatures drastically increase in areas of open water and decrease in areas of shade. The first jump in temperature was seen at the beginning of the profile where there is little shade over the water, before the temperature quickly drops entering a shaded area. The second increase in water temperatures occurs in the second half of the profile, where there is little to no shade along the rest of the side-channel. This second increase is much more gradual than the first increase in temperature, and may be moderated by groundwater inputs. These results are similar to other studies conducting profiles, where large variability can be seen over relatively short distances (Vaccero and Maloy 2006; Rosenberry and LaBaugh 2008).

A similar yet inverted pattern occurs in temperature during the winter in the disconnected side-channel, where water temperatures are lowest in the first area of open water and increase in areas covered by trees. Leaving the trees the temperature begins to decrease again, before spiking and gradually decreasing. This spike near the middle of the profile occurs near the same place where the temperature drops off after beginning to increase after coming out of the trees in the late summer profile. Temperature changes down-stream from this spot are more gradual than changes above it, likely indicating groundwater inputs moderating temperature in the second half of the disconnect side-channel.

The differences between temperatures along the length of the side channels can also be seen over the study period. Temperatures along the length of the connected side-channel track each other over almost the entire the study period. The differences in temperatures along the disconnected side-channel occur throughout the year. Temperatures at DSC3 are substantially higher in summer and lower in winter than DSC2, where temperatures appear to be moderated with groundwater inputs throughout the year. DSC3 and DSC2 begin to track each other as high flows in the Yakima during the fall and early winter send water along flood flow paths and through subsurface flow to the disconnected side-channel.

Acceptable ranges of water quality measures for salmonids have been estimated by many authors and agencies, with specific ranges varying across species and life stages, with varying impacts if exceeded (Bell-McKinnon 2011; Carter 2005). Single readings do not give enough information about water quality, and multi-day averages of water quality parameters maybe be needed for assessment. Areas of water temperatures exceeding 21-24 ^{o}C during migration will generally act like a wall, with the fish avoiding the warmer areas, and temperatures above 18 ^{o}C are not acceptable, and may be lethal for some fish. These temperatures were frequently exceeded during the summer in both connected and disconnected sites. While that is the case at specific sites at specific times, the channels provide varying temperatures with changing depth, shade, and groundwater influences that provide opportunities for fish to escape hazardous conditions. In fact, summer temperatures in the disconnected side-channel are more ideal than the connected side-channel because of the large variation along the length of the channel, while the connected side-channel has little variation and is above 18 ^{o}C along its length. Daily average temperatures at DSC2 are notably lower during the summer (consistently <18 ^{o}C) compared to CSC sites that regularly exceeded 20 ^{o}C.

Dissolved oxygen at CSC sites were generally in the acceptable range for salmonids (>7 mg/L), while DSC sites were generally below this threshold, except for DSC1. Mixing in the connected side-channel from turbulence keeps DO replenished along its length, while photosynthesis is the primary source of DO in the disconnected side-channel so it varies notably through the day, sometimes reaching < 2 mg/L in the early morning. These low levels at DSC sites would stress and potentially kill salmonids, which would need to leave the channel before water levels become too low for them to escape low DO in the summer and fall. Increased connection to the Yakima River could help improve these conditions with more oxygen-rich water.

Isotopic analysis is primarily useful for comparing isotope ratios before and after the project as a snapshot of seasonal isotopic ratios does not provide enough information to make definitive statements about water sources. Comparisons with the LMWL at Ellensburg and well and surface waters from the study area indicate that the water in the study area is generally less evaporated (newer) than Yakima River water at Ellensburg, except for fall surface water, which is more evaporated (Figure 34). Seasonal variation can be seen between surface waters, but well samples were only collected in winter. Some loose grouping can be observed in the fall (September) surface water where evaporation has increased isotope concentrations; winter (February) surface water concentrations are less evaporated as higher flows bring newer water through the area; summer (June) surface water concentrations are more in between fall and winter, appearing to be in transition from newer to more evaporated water. An extensive investigation of changes in isotopic ratios was outside the scope of this study. Future investigations may provide more insight into the usefulness of this measure.

Water Elevations

Comparisons between the surface water elevation graph and the well water elevation graph display varying degrees of responsiveness of sites to changes in Yakima River discharge and groundwater levels. Water elevation responses to changes in Yakima River stage generally diminish with distance from the river, with the exception of Well 4 where water levels were moderated by a beaver dammed channel adjacent to it. This beaver dam kept water levels relatively constant throughout the year leaving Well 4 levels largely unaffected by large fluctuations in connected side-channel stage. Changes in surface and ground water elevations completely unrelated to changes in Yakima River stage were observed during the summer and fall, likely due to irrigation. AgPond displayed variation over weeks during the summer, culminating in a large increase in stage at the end of the growing season that is likely responsible for the large pulse of groundwater in September that can be seen in multiple wells and DSC1, where levels increase and decrease by up to a meter over about two weeks. This large increase in DSC1 stage unrelated to changes in the Yakima River further indicates groundwater influences on the disconnected side-channel. Water levels at DSC1 do not change very much after December because water levels reached the top of a beaver dam and spill over into a small channel that flows back into the Yakima River. Since the water spills over the top of the dam, the water level stays constant, even during high Yakima River flows, such as the 318 m^3/s (11,229 cfs) event on February 5, 2018. This moderated water level can be beneficial for fish that may be over wintering in the disconnected side-channel by providing opportunities to reach the main channel well into spring.

Interpolated water elevation contours display lines of likely equal water table elevations, which can be used to tell where water is coming from and going to through the floodplain. The water table slopes west to east in the summer, almost parallel to Yakima River flow, indicating that groundwater is the dominant driver of water movement through the floodplain. This pattern changes as high flows start occurring on the Yakima, such as those mapped on October 23 and November 25, 2017, and surface water begins dominating water movement through the floodplain. Water elevations mapped on January 07, 2018 represent water movement with surface waters at their highest stages between high flow events, with contour elevations perpendicular to the Yakima River flow, indicating surface water from the Yakima River and reactivated side-channels are driving water movement through the floodplain.

Well 13 was chosen to represent water levels least affected by Yakima River flows because it is the furthest from the river, and because it consistently had the highest specific conductance values. Moderate to moderately-strong correlations between water levels in Well 13 and most other sites in the summer indicates that they share the same source of water, and that changes in water levels in the floodplain are driven by groundwater flow. Correlations between Well 13 and most other sites become weak in the winter suggesting Yakima River discharge becomes the dominant factor in water movement through the floodplain and Well 13 is relatively unaffected by it. Correlations between the Yakima River and other sites during the summer also indicate a common source of water with Well 13, as the Yakima had a moderately-strong correlation to it and strong correlations at most other sites in the floodplain. High flows in the Yakima River during winter were moderately-strong to strongly correlated with increases in water levels at most surface and well sites, with AgPond and Well 13 being exceptions. These two sites were relatively unaffected by flows in the Yakima River, indicating little hydrologic connection between the Yakima and its floodplain over the winter while surface flows are highest. These moderately-strong to strong correlations further indicate that Yakima River discharge is the dominant factor of water movement through the floodplain during the winter, but that influence does not extend far from the main channel (Well 13 is about 870 meters from the main channel at its closest).

GPR radargrams were not always useful for identifying the water table around wells with certainty. Some transects showed signs of an easily identifiable water table when compared with the measured water table depth at the well, while others did not show easily identifiable features. There are many reasons why clear features corresponding to the water table were not found, including differences in substrate material, signal attenuation from the capillary fringe, and the use of average daily water table depth when the water table can fluctuate hourly. Radargrams also went through minimal processing and interpretation, as a more thorough investigation of the water table in the study area with GPR was beyond the scope of this study. Results indicate that a more robust analysis of GPR data would be useful for identifying and investigating changes in the water table in the study area. These results may also be useful for future substrate and water table depth comparisons.

Changes with Reconnection

Two-dimensional surface hydrology models of water levels after the floodplain reconnection project predict that the disconnected side-channel will be reconnected with the main channel at Yakima River discharges as low as 85 m^3/s (3000 cfs). This level of discharge occurs an average of 86 days out of the year, based on the last 35 years of discharge data for the Yakima River near Parker, WA, and generally during the late fall, winter, and spring. If the disconnected side-channel is reconnected during flows >85 m^3/s, it will likely receive flow during the coldest period of the year—December and January. This could reduce the likelihood of ice forming over the disconnected side-channel, as it currently does, which can cut off atmospheric/water oxygen exchange and inhibit photosynthesis, limiting DO for over-wintering fish. Future monitoring would benefit from investigating changes in ice cover on disconnected surface water. More surface flow during the winter could also affect DO by reducing water temperatures in the disconnected channel and increasing the capacity of water to hold DO. Specific conductance would decrease as the influences of groundwater become reduced with higher surface water inputs, and the extent to which groundwater is still able to moderate winter temperatures is uncertain. Turbidity would likely increase as flowing water disturbs sediments that have been accumulating with little disturbance for years.

Providing habitat for fish to reside during the winter without being stranded will be a benefit of reconnecting disconnected side-channels in this project. As flows in the Yakima increase over fall and winter, fish will be looking for calmer areas to occupy. The combination of less energetic flows and warmer, more consistent water temperatures make the disconnected side-channel possible over-wintering habitat for young fish. The disconnected side-channel also allows fish to leave the channel during spring as high flows fill it to the top of its impounding beaver dam. Winter temperatures are moderated by apparent groundwater inputs in the lower portion of the disconnected side-channel near DSC2, but they are not remarkably higher. This groundwater generally keeps the water near DSC2 a couple degrees warmer than DSC3, CSC2, CSC3, and DP throughout the winter. Although the water temperature is slightly higher in this area, low air temperatures can still cause ice to form over the entire disconnected side-channel. It is unknown how the input of surface water to the disconnected side-channel from the Yakima River will impact the influence of groundwater on temperature.

Allowing disconnected side-channels in the study area to be connected to the Yakima River at modest flows will allow for disturbance during every season, except summer when flows do not reach >28.3 m^3/s (>1000 cfs). Floodplain and riparian ecosystems are dynamic ecosystems that require disturbance for proper functioning. Alterations in flow and connectivity in the floodplain will likely add to habitat complexity, with new and enhanced connections to side-channels and ponds, more frequent seed, soil, and nutrient deposition on the floodplain, and geomorphic changes. These disturbances will not only benefit fish by providing and improving habitat, but can also benefit riparian species by raising the water table and dispersing seeds, as well increasing habitat for avian species. An enhanced riparian zone around the disconnected side-channel would benefit water quality by shading areas that are currently exposed on the south end, reducing daytime temperatures and increasing the ability of the water to hold DO.

Abiotic and biotic processes will likely affect disturbance in the floodplain. Given the current level of beaver activity on the disconnected side-channel, increased flows could stimulate new dam construction or raising of existing dams. Water levels in the disconnected side-channel are currently limited to a certain stage by an existing beaver dam. If beavers build on to the existing dam, water could be diverted to new channels and/or contribute to water storage in the floodplain (Westbrook et al. 2006). Maximum water levels in the disconnected side-channel are currently less than 0.5 meter from the top of the bank, and stay at that level for weeks during the winter; raising water levels further could significantly alter surface water flow in and around the disconnected side-channel. There is also the possibility of beaver dams being washed out by high flows after reconnection, drastically altering the hydrology and geomorphology of the channel. Observing changes in the size and abundance of beaver dams should be considered in future monitoring to account for possible storage and flow changes.

Management Recommendations

It is generally accepted that increasing connection of rivers to their floodplains will increase the residence time of water. A longer residence time should allow water to infiltrate and percolate to groundwater, as previously discussed. However, it is uncertain exactly how long the water is stored in the subsurface before returning to the Yakima River or flowing downstream. While drastic changes in the water table can be seen in wells and stage recorders due to high flows on the Yakima, these pulses of water pass through the area on the order of weeks (Figures 35 and 36). The observed speed with which the water moves through the floodplain will not allow water to be stored long enough to be useful for aquifer recharge, or water temperature moderation when it is needed in summer. Projects should take observed residence times into account when planning strategies to increase aquifer recharge or summer baseflows. Strategies that move water during winter and spring high flows much further away from the river might increase the time it takes for water to reach the Yakima River or allow for more aquifer recharge. Of course, further modification of the Yakima's flow presents the possibility of unintended or unwanted changes in its hydrology.

As discussed before, project monitoring is vital to learning how to make projects more effective at reaching their goals, and to adapt future projects to lessons learned. Researchers have suggested the need for at least two years of pre-project monitoring to gain an understanding of baseline biological and physical conditions for floodplain enhancement projects in the Pacific Northwest (O'Neal et al. 2016). Given that a year of pre-project monitoring has been already been collected and analyzed, only another year of monitoring would be required to gain a better understanding of baseline conditions in the study area over time. Pre-project monitoring should also be expanded to include fish counts or something similar, to evaluate changes in side-channel use by fish. O'Neil et al.

also recommended post-project monitoring lasting at least 10 years, as changes take time to occur before conditions begin to improve. This may seem excessive but understanding the long-term effects of projects is the only way to improve the effectiveness of future projects. Considering the immense social and financial investments that have been made to restore and increase habitat quality and quantity for salmonids in the Yakima basin, it would be prudent to learn as much as possible from every project, as we cannot fix what we do not know is broken.

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