AN ABSTRACT OF THE THESIS OF

Jessica Serin Pierson for the degree of Master of Science in Geography presented on June 8, 2018.

Title: Flow From Flexibility: Identifying Opportunities For Streamflow Restoration in a Transboundary Municipal Watershed Through Water Budgeting

Abstract approved:

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Municipal watersheds attempt to balance growing and conflicting demands for water for human use and for ecosystems. The Mill Creek basin, a 295 km^2 basin in southeast Washington, exemplifies these conflicts. Since the late 1800s, the City of Walla Walla has withdrawn water from Mill Creek for municipal use. However, current streamflow levels in Mill Creek do not meet minimum instream flow recommendations developed in part to protect federally listed threatened species, including bull trout and middle-Columbia steelhead. This study addressed the physical potential for changes in water withdrawals by the City to contribute to a Pilot Local Water Management Program Strategy focused on “flow from flexibility”, a set of innovative strategies adopted in 2009 to reduce conflict and improve instream flows in the greater Walla Walla Basin (RCW 90.92). Using records of water withdrawals by the City for 2001 to 2016, as well as climate and streamflow data, this study quantified the timing and magnitude of water withdrawals, their effect on streamflow in the basin, and other factors, such as climate and vegetation change, that might contribute to water conflicts.

On an annual basis over the period from 2001 to 2016, water withdrawals ranged from 16 to 25% of the annual discharge at the City Intake, and 11 to 19% of

annual streamflow at USGS 14013000 (Kooskooskie), the point where compliance with instream flow recommendations is assessed. On a monthly basis, withdrawals ranged from 15 to 54% of streamflow at the intake gage, and 10 to 40% of streamflow at the USGS gage. In years with high discharge, more water has been withdrawn. Starting in 2010, water withdrawals have increased in the winter, but summer water withdrawals have not decreased, and even increased slightly. When the water withdrawn by the City in July through October is added back to the stream at the intake, and projected to the Kooskooskie gage, median daily streamflow in July through October would meet or exceed the minimum instream flow recommendations. Annual precipitation has not declined significantly since 1950. Over the period from 1940 to 2017, annual water yield declined by less than 0.01%, but August streamflow declined by 17% over the same period. Declining streamflow also may be due to increasing evapotranspiration. However, visual analysis of aerial photography from 1939, 1959, and 2015 reveals relatively little vegetation change in the watershed. Increased withdrawals from groundwater and surface water by private land owners along Mill Creek may also account for declining streamflow. The results of this study provide some insights into the available options for the City to contribute to "flow from flexibility." This study indicates that "flow from flexibility" and other water-sharing or water conservation measures have potential to mitigate conflicts among alternative uses of water in the Upper Mill Creek Basin.

Flow From Flexibility: Identifying Opportunities For Streamflow Restoration in a Transboundary Municipal Watershed Through Water Budgeting

by
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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented June 8, 2018
Commencement June, 2019

Master of Science thesis of Jessica Serin Pierson presented on June 8, 2018.

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

Jessica Serin Pierson, Author

ACKNOWLEDGEMENTS

The author expresses sincere appreciation to her dear family, friends, and mentors for their support along this journey.

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Flow From Flexibility: Identifying Opportunities For Streamflow Restoration in a Transboundary Municipal Watershed Through Water Budgeting

CHAPTER 1 -- INTRODUCTION

Municipal watersheds attempt to balance growing and conflicting demands for water for human use and for ecosystems. Many cities in the western United States rely for their water on forested headwaters, which have been protected in part as National Forests since the early 1900s. Water scarcity is a growing concern, especially in the western United States, because even though water is abundant in headwaters and during wet seasons, it may be scarce downstream and during dry seasons (Jaeger et al., 2017). Many factors may exacerbate conflicts for water.

Globally, water withdrawals for municipal and agricultural use represent a substantial fraction of streamflow (Alcamo et al., 2003). Water withdrawals have especially large effects on streamflow in semi-arid and arid regions and during dry seasons (e.g., (Schindler & Donahue, 2006). At the same time, water withdrawals from groundwater have drastically depleted groundwater tables globally (Famiglietti, 2014), with particularly severe effects in dry portions of the western US (Scanlon et al., 2012). Conjunctive use strategies – use of groundwater and surface water – are of increasing importance for water resource management (Singh, 2014). Aquifer storage and recovery (ASR)—i.e., the placing of water into an aquifer for later retrieval— is increasingly implemented throughout the world to mitigate groundwater reductions (Pyne 1995, 2002, Maliva and Missimer 2010). In particular, storage of storm-water (streamflow during peak flow events) in groundwater may provide groundwater sources that can replace dry-season withdrawals from surface water sources (Page et al., 2017).

Changing climate and vegetation also may alter the water balance, affecting water availability. Climate change may alter precipitation and affect streamflow (Hamlet et al., 2007). Harvest of forest, which typically occurs in the headwaters of municipal watersheds, increases water yield, and reforestation or afforestation decreases water yield (e.g., (Bosch & Hewlett, 1982; Brown et al., 2005). Rapidly growing young forest may use more water than old forest during the dry season (Jones & Post, 2004; Perry & Jones, 2017).

The Mill Creek basin, a 295 km^2 basin in southeast Washington, exemplifies these conflicts. The physical geography and political geography of this basin are tightly interconnected. Like many cities in the western US, Walla Walla depends on water from a mountain watershed which is on public land. Since 1918, a portion of the headwaters of the catchment has been co-managed with the US Forest Service as the municipal watershed for the City of Walla Walla (U.S. Forest Service, 1990). Although wet winters provide relatively abundant water, dry summers produce low streamflow. Resident and anadromous fish species, including federally endangered bull trout and Middle-C steelhead, occur in the basin. The vegetation of the basin is adapted to dry summers, but agriculture and possibly fire suppression have altered vegetation cover in the basin.

The political geography of water in the Mill Creek Basin is fragmented among many institutions, laws, and regulations. Governance institutions range from local to federal. The City of Walla Walla (hereafter, "the City") has one of the most senior water rights in the basin, which dates to 1866. Water withdrawals from the Mill Creek basin supply 80 to 90% of the annual water used by the City (City of Walla Walla Public Utilities, 2018). The Mill Creek basin is a transboundary basin, spanning the states of Washington and Oregon. The Washington Department of Ecology enforces streamflow recommendations and manages groundwater in the basin (groundwater is jointly managed with the Oregon Department of Water Resources). The Confederated Tribes of the Umatilla Indian Reservation (CTUIR) have "usual and accustomed" treaty rights to fish and other traditional resources in the basin. Mill Creek Basin fisheries are co-managed by the Washington Department of Fish and Wildlife (WDFW) and the Oregon Department of Fish and Wildlife (ODFW). The land upstream of the City's water intake is the Umatilla National Forest, managed by the US Forest Service (USFS).

The US Fish and Wildlife Service (USFWS) filed lawsuits against several irrigation districts in the WW basin in 2001, citing violation of the Endangered Species Act (ESA). The middle-Columbia-River segment of winter-steelhead (*Oncorhynchus mykiss)* has been ESA listed as threatened since 1999, and bull trout listed as threatened since 1998 (*Salvelinus confluentus*) (Schaller et al., 2014). In response to litigation and other regional conflicts, minimum instream flow recommendations for the Walla Walla Basin were updated via Washington Administrative Code (WAC 173-532-030, 2007). Although minimum instream flow recommendations have existed for the Walla Walla basin since 1977, these water-rights are often junior in priority date to existing upstream claims. Therefore, minimum streamflow recommendations are often left unfulfilled in the summer months, where peak demand coincides with low-natural streamflow availability.

Current streamflow levels in much of the state of Washington do not meet instream flow recommendations. In 1999, a report by Washington Joint Natural Resource Committee, identified 16 watersheds which "over-appropriated", a condition where more water is legally allocated in water rights than is naturally available (State of Washington, Governor's Salmon Recovery Office, 1999). These basins were identified as fish critical, where significantly lowered instream-flows alter the distribution of water in a way where behaviors such migration, spawning are inhibited (Lovrich & Siemann, 2004).

Litigation over endangered species and emerging awareness of groundwater depletion and surface water overallocation led to the establishment of innovative water governance structures in the Walla Walla Basin. In 2009, Washington Legislature approved a pilot program to transfer water resource management decisions over from to local control, with enhanced water rights flexibilities unavailable within the confines of traditional water law (RCW 90.92, 2009). The Walla Walla Watershed

Management Partnership (WWWMP) was authorized by the Washington Department of Ecology to manage certain aspects of water regulation in the greater Walla Walla basin. The WWWMP works closely with the Walla Walla Watershed Council, an Oregon-based agency, to coordinate with transboundary stakeholders to improve water management conditions in this historically overallocated basin.

The Washington Department of Ecology supports this 10 year pilot program embracing the concept of "flow from flexibility". This conceptual goal for water management embraces a suite of voluntary actions to augment streamflow without jeopardizing the water rights of participating stakeholders (Ecology, 2008). Examples of "flexibility" in this context include changes to point of diversion, place of use, time of use, or source of water without the burden of administrative oversight by the Washington Department of Ecology. Feasibility of the "flow from flexibility" approach depends on accurate knowledge of the volume, timing, and trends in streamflow in various portions of the Mill Creek basin. Understanding spatial and temporal trends in water-use is also essential to coordinating strategic actions to augment sufficient in-streamflow during fish-critical time periods.

Prior to this study, the volume of water withdrawn by the City from upper Mill Creek has not been readily publicly available. Moreover, it is not known how vegetation, land use, and streamflow has changed in the watershed in the past half century. In addition, the Mill Creek basin is one of only two basins in the state of Washington that is involved in an aquifer storage and recovery (ASR) (Scherberg et al. 2014, Pitre, 2017). As the City improves conjunctive management of their municipal supply, the ability for the city to participate as an actor in "flow from flexibility" approach may be shifting. This study obtained records of water withdrawals by the City and observations of streamflow at the Intake Structure for the time period from 2001 to 2016.

Based on analysis of these data, as well as historical streamflow and vegetation records dating back to the mid 1900s, this study addressed the following research questions:

1. What is the physical potential for the City to adjust patterns of water withdrawals to contribute to basin efforts to restore "flow from flexibility"?
2. What is the timing and magnitude of water withdrawals by the City from upper Mill Creek?
3. How have these water withdrawals affected streamflow in the upper Mill Creek basin?
4. How have other factors, including the aquifer storage and recovery program and historical vegetation change, affected water withdrawals and streamflow?

CHAPTER 2 – SITE DESCRIPTION

2.1. Location

Mill Creek is a trans-boundary watershed (295 km^2) straddling the Eastern Oregon and Washington border (Figure 1). The study site is the upper Mill Creek basin, a 152 km^2 basin in Washington and Oregon, area upstream of USGS Gage 14013000 (Figure 2). The municipal watershed for the City occupies the uppermost 89 km^2 of upper Mill Creek, or 59% of the contributing catchment for USGS Gauge 14013000. The City owns 5.8 km^2 (1,440 acres) at the downstream end of this protected basin, where an impoundment dam, and intake structure are operated to withdraw water permitted for municipal use (U.S. Forest Service, 2014). An additional 143 km^2 of the Mill Creek basin lies between the KK gauge and the Walla Walla river.

2.2.Physical geography.

Elevation ranges from 180 m at the confluence with the Walla Walla river to 1907m in the headwaters in the Blue Mountains. USGS Gage 14013000 is located at 608m. The study basin is underlain by the 17-m yr Columbia River Basalt Group.

The upper watershed is characterized by deeply incised canyons. Upper Mill Creek is high gradient, with a complex channel (Schaller et al., 2014). Downstream of the Kooskooskie gage, the Mill Creek basin joins the eastern Columbia plateau province, and the channel historically split into a network of distributary channels. Between the intake structure and the City, upper Mill Creek maintains a natural character with a sinuous channel confined in a valley with relatively intact riparian vegetation [Howell et al., 2016]. The stream channel and riparian floodplain are relatively free of anthropogenic modifications.

2.3. Climate and streamflow

Daily air temperature in the headwaters of the Mill Creek basin ranges from a low of -5 °C in Dec to a high of 15 °C in July (Figure C). Daily air temperature at Walla Walla is on average 7 °C warmer than in the headwaters of the Mill Creek basin (Figure 3). Average annual precipitation ranges from 114 cm in the forested headwaters of the Blue Mountains to as little as 25 cm on the semi-arid Umatilla Plateau (Ecology, 2012). Mean annual precipitation is 1500 to 2000 mm at the top of the basin, but only 300 to 500 mm at the Walla Walla Airport (Figure 2, 4). Monthly precipitation is highest in December through April and lowest in July (Figure 4).

Average annual streamflow is approximately 500 mm at the Kooskooskie gage (Figure 5). Monthly streamflow is highest during the snowmelt period in March, and lowest in August to November. Over the period of record (1940 to 2016), March median streamflow has increased, while August Median Streamflow has decreased (Figure 6).

2.4. Water Supply Systems

Mill Creek is the primary source of municipal water for the City, Washington. Water withdrawals for the City occur at the City's Intake structure (45°59'23.0"N, -118°02'52.0"W) (Figure 2). Water from the intake structure is diverted 22 km through a 30-inch diameter transmission pipeline, passing through a gravity fed power generation station, before reaching the Walla Walla water treatment plant (Figure 2). After treatment, water is pumped into two 7-million-gallon finished water storage tanks, which feed into supply network delivering drinking water to the City. The Mill Creek Watershed supplies 88-90% of the water distributed for municipal supply (City of Walla Walla Public Utilities, 2018).

The City's water supply is supplemented by seven deep (800-1400') wells drilled into the underlying basalt aquifer, which were developed between 1940's and 1960's (City of Walla Walla Public Utilities, 2018). The City has been actively developing Aquifer Storage and Recovery operations with several adapted wells since 1999.

2.5. Vegetation

The land cover of the USGS14013000 catchment is classified as predominantly evergreen forest (79.9%), herbaceous (11.7%), shrub/scrub (7.3%), and some developed property (1%) (NLCD, 2011). Above the City's water intake, upper Mill Creek is public forest land, dominated by Douglas-fir (*Pseudotsuga menziesii)* and grand fir (*Abies grandis*), which are primarily found on north and east-facing slopes. South and west-facing slopes are dominated by grassland and shrubs. Riparian zones are forested (Hulbert, 2006). Downstream of the USGS14013000 gauge pre-dominant land use types as listed in the 2011 National Land Cover Database are: cultivated crops (35%), vegetative contribution (predominantly evergreen forest, shrub/scrub) (44%), and developed land (29% of high, med, and low intensity) (Homer et al., 2015).

There have been no major vegetative disturbances in the upper catchment since the establishment of the Municipal Watershed in 1918. To protect the City's Water Supply, fire suppression has a component of forest management in Municipal Watershed since the early century. No form of prescribed fire or other mechanical manipulation of forest fuels have occurred in the Municipal Watershed since its establishment out of concern for water quality (Hulbert, 2006). As a result, heavy fuel loads in the catchment place the Municipal Forest at elevated risk for a large wildfire. Recent modeling of Fire Regime Condition Class of the Municipal forest classifies 60% of the catchment to be of moderate departure for normal conditions (class 2), and 10% of the catchment as high departure condition (class 3) (Walla Walla County, 2017).

While small wildfires have occurred in the municipal watershed during this period, they have been quickly extinguished by Forest Service fire suppression crews

(Hulbert, 2006). The 2015 Blue Creek fire burned 24 sq km adjacent to western boundary of the Municipal Watershed (Walla Walla County, 2017). The Washington state drought declaration of 2015, and near catastrophic damage to the city's Municipal Water supply increased local concern of high fuel loads within the catchment. Awareness of fire fisk to the catchment has led the Community Wildfire Protection Plan Steering Committee to reassess potential projects such as: biomass removal, thinning, mechanical mastication, prescribed fire, or development of defensible spaces around the City Intake Structure and watershed boundaries (Walla Walla County, 2017).

2.6.History and Land Use

The area was historically occupied by the Walla Walla Indians, who in 1855 were combined into the Confederated Tribes of the Umatilla Indian Reservation (CTUIR), based in the town of Umatilla. The area has a long history of native peoples, reflected in local names. The USGS Gage 14013000 is known locally as Kooskooskie, derived from the Nez Perce (Sahaptian) word kōōs kōōs' kē ə meaning "clear water" (Bright, 2004). The name "Walla Walla" is also derived from the first nations word for "many waters". The area was settled by Europeans in the 1800s with the establishment of the Whitman Mission, which grew into the City. In 2015, the US Census population estimate for City was 31,772 (U.S. Census Bureau, 2015). The population of Walla Walla has increased by 7% from 2001 to 2015 (Figure 7). Regional population is expected to increase by 24% from 2000 to 2020 (Pickett, 2011). Over 300 residences have been developed along the Mill Creek Road, which is the primary access to the Municipal Watershed (Walla Walla County, 2017)

2.7.Water Governance

The study site is a transboundary basin spanning Oregon (31%) and Washington (69%). Fifty-five percent of the basin is located within Walla Walla County (WA) (Figure 2). In the 20th Century, several reaches of lower Mill Creek and the Walla Walla River have been documented as periodically dewatered. Overallocation of streamflow has reduced the availability of suitable habitat and inhibit passage for aquatic species (Sierra and Martin, 2007).

Downstream of the study area, there have been various barriers that have inhibited passage of fish into the headwater catchment. The Kooskooskie Dam blocked passage to all life stages of basin species of concern, until its removal in August 2005 overseen by the Tri-State Steelheader branch of Trout Unlimited.

The Mill Creek Diversion Dam for Bennington Lake, an off-channel flood control reservoir marks the start of Army Corps of Engineers (ACOE) Mill Creek Flood Control District which began construction in 1930's. (Figure 2). Below the diversion Dam, the natural character of the stream channel is significantly altered by a series of flood control dams, levees, and weirs. The Mill Creek channel is lined and armored with cement for 11 kilometers through the City (ACOE, 2015; Schaller et al., 2014). The flood control infrastructure has historically inhibited passage of fish into the reach of Mill Creek above Walla Walla (Figure 2). Fish passage was added to several features of the Flood Control District in the 1980's.

The USFWS has designated the reach of Mill Creek upstream of Bennington dam (Figure 2) to City's water intake as critical habitat in the endangered species recovery plans for middle-Columbia-River winter steelhead (Oncorhynchus mykiss) and bull trout (Salvelinus confluentus) (Schaller et al., 2014). Instream flow recommendations for fish in this portion of Mill Creek are measured at the Kooskooskie gage USGS:14013000 (Table 1).

Periods of critically low-flow in the spring have potential to impact out migration of smolts (salmon and steelhead) to the ocean, as well as upstream migration of adult spring chinook into regions where they have been historically extirpated. Periods of critically low flow in the fall impact steelhead migration (adults migrating upstream) and bull trout (adults and sub adults moving downstream) (WWWMP, 2012). Through the Critical Low Flow Planning process, the WWWMP works collaboratively with stakeholders to augment streamflow during the spring (April 1-June 15) and in the fall (October 1- November 30).

The City has three primary water rights (Table 2) issued by the state of Oregon with priority date of 1866, shortly after the to the incorporation of Walla Walla in 1862. The CTUIR retains ancestral treaty rights to fish in the Mill Creek basin. Since 1918, almost 30% (88 km2) of the upper Mill Creek basin has been co-managed by the U.S. Forest Service and the City “to provide water at a level of quality and quantity” for the City’s municipal supply (OWRD, 2009). They City’s water rights have been amended to accommodate various forms of development, including Aquifer Storage and recovery operations and the Federal Energy Regulatory Committee relicensing of the City’s hydropower facility. The City has agreed to reduce the maximum water amount exercised of its 1866 priority water right to 25.5 cfs during summer months as a condition of the FERC and ASR licensing process.

CHAPTER 3 – METHODS

This study determined the magnitude of water withdrawals by the City relative to the overall water balance for the upper Mill Creek basin. The water balance is defined as

$$Q = P - ET - GW - \Delta S - W \qquad [1]$$

where Q = discharge, P = precipitation, ET = evapotranspiration, GW = groundwater recharge, ΔS = soil water storage, and W = water withdrawals. For the purposes of this study, we assumed that there were no long-term trends in precipitation (Figure 6), groundwater recharge, or soil water storage.

This analysis focused on quantifying withdrawals (W) and discharge (Q) at two points in the Mill Creek basin: the intake, where the City withdraws water, and the Kooskooskie gage, where instream flow recommendations for fish habitat are assessed (Figure 8). In addition, this analysis attempted to determine whether there has been any long-term change in vegetation cover, which might have affected evapotranspiration.

3.1. Data Sources

Climate data were obtained from Snow Telemetry (SNOTEL) Data Collection Network (National Water and Climate Center, 2017) and the U.S. Historical Climatology Network (Menne et al., 2015) (Figure 2). Mean daily precipitation (P) and temperature (T) data since 2007 were obtained from the "MilkShakes" SNOTEL site located within the Mill Creek Municipal Watershed, via the National Water and Climate Center Report Generator (NRCS, 2017) (Table 3). Climate data also were obtained from the Walla Walla Regional Airport, WA for the period starting in 1948 (Table 3). Data were obtained using the R package 'rnoaa', developed by the National Oceanic and Atmospheric Administration (NOAA) (Chamberlain, 2017). The function ‘ghcnd’ was used to download mean daily precipitation and minimum, maximum, and average daily temperature records for the full period or record stored in the U.S. Historical Climatology Network (USHCN).

Mean daily streamflow data for Mill Creek were obtained from the USGS gage 14013000 (KK) (Table 4, Figure 2) for the period 1947 (or, with gaps, 1914) to present. This gage serves as Management Point 1 (MP1) for instream flow recommendations in the Walla Walla Water Resource Inventory Area (WRIA-32). Data were obtained from the National Water Information System (NWIS using the R: package ‘waterData’ developed by the US Geological Survey (USGS) to distribute daily time series data (Vecchia & Ryberg, 2017). The function ‘importDVS’ was used to download the entire available period of record.

Data on water withdrawals from the upper Mill Creek basin were obtained from the City for the period 2001 through 2015 (Table 4). Water withdrawals in this study are defined as water removed from the stream channel of upper Mill Creek for beneficial Municipal Use and distribution by the City, WA, consistent with the City’s water rights (Table HM-3). A public request for information was filed with the City’s Public Utilities Department in 2015, to obtain observations of water withdrawn at the Intake Structure and discharge downstream of the intake Structure. The mean daily rate of water withdrawn from Mill Creek (in cfs) is measured using a SCADA flow meter installed at the headworks of the 30-inch transmission pipeline at the dam.

The daily discharge rate (Q) of upper Mill Creek is recorded downstream of the intake structure, using a radio-telemetry staff gauge. An exponential relationship was fitted to stage and discharge values to determine the rating curve used by the City to calculate the mean daily discharge (in cfs) relative to the observed daily river stage height (in feet/inches). The rating curve is:

$$y = 0.1053e^{0.2445x} \ (r^2 = 0.8) \qquad [2]$$

This rating curve is limited to a stage height of <27.6 inches, or discharge values < ~100cfs. Discharge values >100 cfs were estimated from a relationship with flow at the USGS Kooskooskie gage (described below).

No record of the natural flow regime of Mill Creek exists that is unaffected by the consumptive withdrawals at the City Intake Structure. Therefore, the flow above the intake structure was estimated for the period 6/1/2001-12/31/2015 in a three-stage process. First, for stream discharge values that were <100 cfs below the intake (eq. 1), stream discharge upstream of the Intake structure was calculated as

$$Q_{intake1} = Q_{below} + W_{intake} \qquad [3]$$

where $Q_{intake1}$ = flow above the intake (cfs), Q_{below} = flow below the intake (eq. 2, <100 cfs), and W_{intake} = withdrawals at the intake (cfs). Second, a linear regression was fitted to predict stream discharge upstream of the Intake structure as a function of streamflow at the Kooskooskie gage (Figure 9). Streamflow values were log-transformed prior to fitting the regression, and outliers (streamflow values >300 cfs at Kooskooskie) were removed from the analysis. The resulting equation was

$$Q_{intake2} = 0.547*Q_{KK} + 20.637 \qquad (r^2 = 0.654) \qquad [4]$$

Where $Q_{intake2}$ = estimated flow above the intake (cfs) and Q_{KK} = flow at USGS 14013000 (cfs). Third, this equation was used to estimate stream discharge values below the intake that were >100 cfs (Figure 10).

3.2. Analysis of streamflow and water withdrawals

The rate and volume of withdrawals by the City for the provided period of record (2001-2015 WY) was displayed using raster-hydrographs and box and whisker plots. Raster-graphics are widely used in hydrology for exploratory analysis of long-term time-series datasets (D. A. Keim & Kriegel, 1996; Daniel A. Keim, 2000; Koehler, 2004). Raster hydrographs were constructed using Surfer v 15 software by Golder and Associates following (Koehler, 2004). Raster plots display day of water year (1-366) on the x axis, individual water years (2001-2015) on the y axis, and the magnitude of data values as a color gradient on the z axis.

Daily mean withdrawal rates (in cfs) were converted to a daily volume (million gallons per day), and summed to determine the total water withdrawn by the City over an individual month, or water year, and as a proportion of total withdrawals.

Streamflow (in cfs) was characterized at daily, monthly, and annual resolutions based on median, max, min, and interquartile values. The seven-day minimum flow was calculated for each year. Percentiles of observed daily mean discharge values where characterized in monthly intervals using the Indicators of Hydrologic Alteration (IHA) software developed by the Nature Conservancy (Richter et al., 1996).

Daily deviations from instream flow recommendations established by WAC-173-532-030, (2007) were calculated as:

$$D = Q_{KK} - Q_{instream} \quad [5]$$

where D = deviation (cfs), Q_{KK} = mean daily discharge at USGS14013000 (cfs), and $Q_{instream}$ = daily instream flow recommendation (cfs). The number of days per month on which instream flow recommendations were not met was calculated by month and year. Instream flow recommendations were compared to monthly percentiles of observed daily mean discharge over the Full Period of Record, as caulcated by the IHA software.

Discharge at the intake structure and the Kooskooskie gage were converted to unit area discharge (in mm/day):

$$Q\left(\frac{mm}{d}\right) = Q(cfs) * \frac{1}{Drainage\ Area\ (km^2)} * 2.446476 \qquad [6]$$

Withdrawals were estimated as a percent of flow at the Kooskooskie gage, where flow at Kooskooskie includes the withdrawals at the intake (eq. 7) and as a percent of the estimated flow above the intake (eq. 8).

% of Q at Kooskooskie:

$$= \left(\frac{Withdrawal\ (cfs)}{Withdrawal(cfs) + Q\ (cfs)\ at\ USGS\ 14013000}\right) * 100 \qquad [7]$$

% of Q above Intake

$$= \left(\frac{Withdrawal\ (cfs)}{Interpolated\ Q\ (cfs)\ Above\ Intake\ Structure}\right) * 100 \qquad [8]$$

3.3. Vegetation change detection

Long-term vegetation change was assessed using remote sensing and historical aerial photography to determine whether trends in vegetation change might have altered evapotranspiration, affecting the water balance of upper Mill Creek.

Seasonal vegetation change in the upper Mill Creek basin was determined from the change in normalized difference vegetation index (NDVI) between early and late summer images for a subset of available images within the Landsat TM/ETM period of record (1984-2011). NDVI products were downloaded and masked, pairs of images were selected based on the absence of cloud cover and atmospheric distortion in the Mill Creek basin, and then these pairs of NDVI images were differenced. A total of ten years over this period had available pairs of imagery suitable for calculating seasonal vegetation change. Average seasonal vegetation change was determined as the average of seasonal change in these years (Appendix A).

Historical vegetation change was determined through comparison of historical aerial photography (1939/1969), and digital ortho quarter quad tiles from the National Agriculture Imagery Program (NAIP) (composite imagery from 2010-2015). Historical aerial photographs were obtained from the Map and Aerial Photography Library at the University of Oregon. NAIP imagery was downloaded from the National Resources Conservation Service (NRCS) Geospatial Data Portal. Landscape composites of aerial photographs were created using ArcMap 10.5. Aerial photo composites were visually compared side by side. Selected sub-areas were extracted to show examples of types of vegetation change.

CHAPTER 4 – RESULTS

4.1. Streamflow

Daily discharge from upper Mill Creek (estimated streamflow above the intake, water years 2002 to 2016) is highest in late March/April and lowest in the late summer (July through October) (Figure 12). Median march streamflow was a median of 122 cfs from 1940-1976, and 154 cfs from 1980-2016 (Figure 6).

Historical stream discharge shows the expected climate change trend of increasing flows during the early snowmelt period (March) and decreasing flows in late summer (August) (Figure 6). While Annual water yield declined by less than 0.01 percent over the period from 1940-2017. Over the same period, August streamflow declined by 17% (Figure 6). The Median August streamflow was 32 cfs from 1940-1976, and 27 cfs from 1980-2016 (Figure 6). The lowest observed 7-day average flow in the late summer was 32 cfs in October, but flow is relatively stable at this level over the late summer and fall months. Seven-day average flow below 50 cfs occurs in all months except April (Figure 12).

Daily discharge at the USGS 14013000 Gauge was highest in late February to late March over the period 2002 to 2016, but peaked in late March and April in the full period of record (1940 to 2017, Figure 13). The lowest 7-day average flow observed over the period 2002 to 2016 was 21 cfs in October. The 7-day average minimum flows were below 30 cfs for July through October over the full period of record. However, the lowest 7-day flow has been as low as 10 cfs in December (Figure 13). The 7-day minimum average flows were equal or higher over the period 2002 to 2016 compared to the full period of record for all months (compare dotted red line to solid red line, Figure 13).

4.2.Withdrawals

Rates of withdrawal by the city ranged between 4 and 28 cfs per day (Figure 14). The volume of withdrawals varied across months. The highest monthly rates of withdrawal occur in June, July, and August, and the lowest rates occur in winter (Figure 15). Median daily withdrawals were 20 to 21 cfs/day in June and July and 14 cfs from November through February (Figure 16).

The volume of water withdrawals also changed over the years. Starting in 2011, the total water withdrawals increased (Figure 14). However, withdrawals decreased again during the 2015 water year, due to the state-wide drought brought on by record low snowpack (Anderson et al., 2016). Median daily withdrawals were 14 to 18 cfs/day before 2011, but were consistently at 18 cfs starting in 2011(Figure 16). In 2015, median daily withdrawals decreased to 15 cfs, likely in response to drought conditions (Figure 17).

Beginning in water year 2011, daily withdrawals increased in winter, intermittently approaching the maximum permitted value of 28 cfs/day (Figure 14). Beginning in water year 2008, daily withdrawal rates in the months of July, August, and September increased relative to water years before 2008 (Figure 14).

Before 2011, median daily withdrawals were 14 cfs/day in November through March. Starting in 2011, the median withdrawal in March increased to 17 cfs/day, and occasional high withdrawals increased the variability of withdrawals from December through March, relative to water years before 2011 (Figure 17). Starting in 2011, median daily withdrawals decreased from 18 to 16 cfs in May, and from 21 to 19 cfs in June, relative to water years before 2011. Starting in 2011, median withdrawals increased from 20 to 23 cfs in July, from 16 to 20 cfs in August, and from 16 to 19 cfs in September, relative to water years before 2011 (Figure 17).

4.3. Withdrawals relative to Streamflow

Water withdrawals ranged from 11 to 18.8% of annual streamflow at USGS 14013000, and 16 to 25% of the annual discharge at the City Intake (Figure 18). The highest relative withdrawals occurred in 2005 and the lowest in 2011. Annual withdrawals were weakly positively related to annual streamflow at the Kooskooskie gage ($r^2 = 0.28$), and the estimated discharge above the intake ($r^2 = 0.26$) (Figure 19).

Median monthly withdrawals ranged from 15 to 54% of streamflow at the intake gage, but only 10 to 40% of streamflow at the Kooskooskie gage over the period of water years 2002 to 2016 (Figure 20). Median daily withdrawals ranged from 25 to 32% of streamflow at the intake gage, and 15 to 28% of streamflow at the Kooskooskie gage over water years 2002 to 2016 (Figure 21, 22, 23). Daily withdrawals have been as high as 60% of daily flow at the intake and 50% of daily flow at the Kooskooskie gage (Figure 22, 23). The smaller percentages at the Kooskooskie relative to the intake gage are due to the fact that water is lost to groundwater recharge along the reach from the intake gage to the Kooskooskie gage, especially in the winter months (Figure 24).

4.4. Ability to meet instream flow requirements

The median daily deviation from streamflow recommendations ranged from -10 to -20 cfs for the months of July through October (Figure 25, Figure 29). However, if the City did not withdraw any water during these months (all other factors being equal), the median daily streamflow would meet or exceed the instream flow recommendation in the months of June through October (Figure 26, Figure 27).

Currently daily streamflow falls below the instream flow recommendation on an average of 28 to 30 days of the month in July through October, and 15 to 22 days of the month in mid-winter (November through April) (Figure 28). However, if the City did not withdraw any water during these months (all other factors being equal), the instream flow recommendations could be met on almost all days of the month for August and September, and about 15 days of the month for July and October (Figure

28). In contrast, if the City were to cease water withdrawals entirely during the winter, it would still not beneficially affect the numbers of days of the month on which instream flow recommendations are met during winter months (Figure 28).

When the water withdrawn by the City is added back to the stream at the intake, and projected to the Kooskooskie gage based on the relationship between discharge at the intake and the Kooskooskie gage (eq. 4), median daily streamflow in July through October would meet or exceed the minimum instream flow recommendations (Figure 29). However, during the winter months (especially in Feb and March) of low flow years (e.g., 2005, 2010, 2015) winter flows would still fall below the instream flow recommendations for periods of weeks to months (Figure 25, 26).

The 2007 Instream Flow Recommendations (ISF) established through WAC 173-532-030 were compared to the relative observed probability of flows at USGS 14013000 during two time periods, 1940-1976 and 1980-2016 (Figure 30). During the early hydrologic record from 1940-1976 all ISF targets except April and May occur <50% of the time; ISF targets for November occurred <10% of the time; and ISF targets for June-October occur <25% of the time (Figure 30 a.). In the later hydrologic record all ISF targets except March occur <50% of the time; ISF targets for July-November occur <10% of the time; and ISF targets for December and June occur <25% of the time (Figure 30 b). Comparing 1980-2016 (period 2) to 1940-1976 (period 2), the ISF targets have become less obtainable.

4.5. Long-term trends in vegetation

Over the course of the dry season, vegetation Normalized Differential Vegetative Index (NDVI) declined over the watershed (Appendix A: Figures A1-A4) average seasonal vegetation change). The seasonal NDVI decline is smallest in the riparian areas and upper slopes, and greatest in the S- and W-facing hillslopes.

Over the period of available historical aerial photography (1939 or 1969 to present) relatively little vegetation change is apparent in the watershed (Figures 31-36). Timber harvest has occurred in some of the private land, below the City's intake, but above the Kooskooskie gage (Figure 35, Figure 36). In some riparian zones the canopy cover of trees and shrubs has increased (Figures 37-40). Also, in some hillslopes shrub cover has expanded, and scattered trees have increased in size (Figures 37-40). Most of the changes appear to involve increases in vegetation density rather than expansion of vegetation cover.

CHAPTER 5 – DISCUSSION

5.1. Long-term trends in hydrology and vegetation

The objective of this study was to determine how the water withdrawals from upper Mill Creek by the City of Walla Walla affect streamflow in the upper reaches of Mill Creek upstream of the City. Since 1866, the City has had a water right to withdraw up to 28 cfs/day from upper Mill Creek (Table 2). However, prior to this study, the actual amounts of water withdrawals were not publicly available. We obtained a record of water withdrawals from upper Mill Creek by the City over the period 2001-2015, and analyzed the patterns of withdrawals relative to discharge at the downstream Kooskooskie gage, where instream flows, recommended by WAC (2007), are monitored. Summer instream flow requirements are designed to protect the endangered bull trout, which are in residence in the upper reaches of Mill Creek in summer, when the rest of the river network is too hot and dry for fish. Winter instream flow requirements are designed, in part, to help improve fish migration and connectivity for winter run steelhead to the middle Columbia River.

This study showed that instream flow recommendations are not being met at the point (Kooskooskie gage) where instream flows are monitored. This study also shows that if the City were to stop all withdrawals from July to October, then the instream flows during this period would be met at the Kooskooksie gage. However, even if the City were to stop all withdrawals in some winter months, instream flow requirements would still not be met during some winter base flow periods. This study shows that the Instream Flow Recommendations established for USGS 1401300 may not be realistic pertinent to observations of probability in the long term streamflow at the USGS14013000 gauge (Figure 30).

The study also shows that the timing and magnitude of water withdrawals has varied over the past 15 years. In years with high discharge, more water has been withdrawn. Starting in 2010, water withdrawals have increased in the winter, but summer water withdrawals have not decreased, and even increased slightly. The increased winter withdrawals appear to be the result of the Aquifer Storage and Recovery project.

5.2. Water budget and uncertainties affecting this analysis

This study assumed that the water balance in the study area is stationary. August streamflow at the Kooskooskie gage has declined by 17% since the 1940s. Therefore, it is possible that some other elements of the water balance along Mill Creek have changed. Historical stream discharge records shows a trend expected with climate change predictions of increasing flows during the early snowmelt period (March) and decreasing flows in late summer (August) (Figure 6). The slight decline in August streamflow at the Kooskooskie gage may be attributable to a number of long-term trends, including declining P, earlier snowmelt, increased ET, increased GW withdrawals from wells, and other withdrawals besides those from the City of Walla Walla.

Declining streamflow may be attributable to earlier snowmelt and/or declining precipitation. Many studies indicate that snowmelt is occurring earlier (Mote, 2003; Stewart et al., 2005), especially at low and mid elevation mountain sites (Stewart, 2009). However, in much of the Pacific Northwest, summer streamflow may be more sensitive to precipitation amount than to the timing of snowmelt (Kormos et al., 2016). (Charles H. Luce & Holden, 2009) asserted that precipitation has declined in southeast Washington and southern Idaho. (C H Luce et al., 2013) argued that weakening westerly winds account for the decline in precipitation. In this study, analysis of long-term precipitation records at the City airport indicate that annual precipitation has not declined significantly since 1950. Hence there is little support for the hypothesis that declining precipitation has contributed to the observed decline in August streamflow at the Kooskooskie gage.

Declining streamflow also may be due to increasing evapotranspiration. Some forms of change in vegetation cover may increase summer evapotranspiration, reducing summer streamflow (e.g., (Perry & Jones, 2017)). However, in this study, analysis of long-term vegetation change demonstrated that although riparian and hillslope vegetation appears to have become denser in some limited areas, there has been relatively little change in vegetation cover patterns in upper Mill Creek since 1939 or 1969. Hence, there is little support for the hypothesis that increasing ET has contributed to the observed decline in August streamflow at the Kooskooskie gage.

Increased withdrawals from groundwater and surface water by private land owners along Mill Creek may also account for declining streamflow. Downstream of the CWW intake gage and upstream of the Kooskooskie gage, Mill Creek passes through private land consisting of farms and residences. In much of the dry summer, this reach is a losing reach, meaning that flow is lower at the Kooskooskie gage compared to the upstream intake gage (Figure 24). It is possible that groundwater withdrawals from private wells and other withdrawals along the reach from the intake to the Kooskooskie gage may have increased over the period of record (since the 1940s).

The development of residential wells in the upper catchment following the adaptation of the City's Intake Pipeline for hydropower in the 1980's may contribute to this change. Community Wildfire Protection Plan documentation estimates that there are ~300 residential developments which exist within the upper Mill Creek Catchment ((Walla Walla County, 2017). However, The lack of a long record at the City's intake gage makes it impossible to determine whether these withdrawals have increased over time. Nevertheless, historical groundwater withdrawals from the alluvial aquifer have lowered the regional water table, limiting its contribution to base-flow in the lower Mill Creek Basin (Baldwin et al., 2008). In other parts of the Walla Walla basin, decreased surface groundwater connectivity has reduced the amount of groundwater contribution to summer base flows (Ecology, 2007).

5.3. Management Implications

The results of this study provide some insights into the available options for the City to contribute to "flow from flexibility" – voluntary adjustments in water withdrawals. This study provides some insights into the potential feasibility of several options to improve water allocation in the Mill Creek basin.

Options intended to increase or restore stream flows can be "hard" or "soft" (Gleick, 2003). In the Walla Wala Basin, the hard options include: infrastructure replacement, aquifer storage and recovery, changes in the point of diversion, or other engineered storage mechanisms. "Soft" options include: conservation, water banking, and other legal mechanisms for acquisition of water rights into trust.

Option 1: leasing water right to create an instream flow protected water use

As a transboundary catchment, the geography of Upper Mill Creek introduces inherent complexities in the regulation of water rights and allocations. The city of Walla Walla's water rights were originally regulated by the State of Oregon, until their transfer to the state of Washington. By Oregon state law, unless there is drought declaration by the Oregon Governor, Oregon water law does not provide the same flexibility as Washington to use innovative flow enhancement tools in the Walla Walla basin (RCW 90.92)(WWWMP, 2012).

Washington Water Trust Water Rights Legislation (90.42 RCW) language which allowed the transfer of allocated water rights into trust as instream flow, with water rights maintaining their original seniority date (Washington State Legislature, 1991) introduced. Options for acquiring other water rights into trust within the Upper Mill Creek Basin include: purchase (transfer); lease (temporary acquisition, during a given time period); split-season lease (returning water during period of need for fish); dry-year lease (no irrigation during drought); or donation. The Washington state Water Acquisition Program relies on partnerships with the Washington water trust (nonprofit), the Columbia river basin (governmental), the Walla-Walla watershed plan, and Walla-Walla basin watershed council (National Research Council, 2004).

The City's water right is protected, even if it is not "perfected" (if the water is not withdrawn). Under current law, water that is not used by the City, but is part of their water right, can be used by a junior water user, unless this water is established as an instream flow protected water use with its own priority date. In the future, if the City reduces summer surface water withdrawals, it could lease the water that is not used as an instream flow protected water use. This study shows that reductions of City summer withdrawals from upper Mill Creek could increase the chance of meeting summer instream flow requirements.

Option 2: Aquifer storage and recovery

Increased water withdrawals in the winter are part of a new policy of aquifer storage and recharge (ASR) in the Walla Walla basin. The objective of ASR is to store water as groundwater during the winter, when it is relatively abundant, and withdraw the water in the summer. Thus, ASR may provide opportunities to improve instream flow conditions during low flow periods while continuing to meet existing and projected demands for out-of-stream uses of water. This study shows, however, that the increased winter withdrawals for the ASR policy may diminish the capacity to meet instream flow requirements for winter steelhead. According to the City's website (Walla Walla Department of Public Works, 2018) the City has a 10 year supply of water from deep wells, which should be sufficient to meet July to October water demands by the City, if it foregoes water withdrawals from upper Mill Creek during summer months.

Option 3: Increasing supply by reducing losses: improvements in water infrastructure

Nearly 30% of the metered water from the municipal treatment is lost in leaking pipes before it reaches source consumers. One billion of the 3.4 billion gallons of water produced each year by the Public Works Division are lost. Nearly 50% of the City's water distribution pipe length (146 of 307 km) were reported to be facing failure (City of Walla Walla, 2016). The Water Use Efficiency guidelines enacted by the State Legislature (WAC 246-290-810, 2006) strive for efficiency standards of only 10% water loss via pipe leakage. Currently, the City is undergoing a long-term effort to repair and replace water lines, sewer-lines, and street lines. However, because losses from the water supply system are currently contributing to groundwater storage, the proposed repairs may be neutral relative to the flow from flexibility issues considered in this study.

CHAPTER 6 -- CONCLUSION

The Mill Creek basin is typical of many small river basins in the western US, where water is over-allocated among competing demands. The Walla Walla watershed management partnership is pursuing a policy of “flow from flexibility”, which involves voluntary adjustments in water use to restore natural flow regimes in rivers. Cooperating river scientists, resource managers, and appropriate stakeholders require accurate quantitative information about the water balance, water withdrawals, and trends in water balance components in order to discriminate among possible alternative water policy actions.

This study quantified the potential for the City to contribute to “flow from flexibility” by assessing how water withdrawals by the City affect streamflow, which currently does not meet instream flow requirements for endangered fish in the basin. Results indicate that instream flow requirements in summer could be met if the City stopped summer water withdrawals, which would require the City to shift to alternative sources (groundwater wells) during the summer. However the inability to meet ISF recommendations may also be due to unrealistic flow probabilities relative to recommended minimum flows. However, even so this approach might complement ongoing efforts for aquifer storage and recovery in the basin.

Long-term increases in human water use are increasing pressure on water supply in the western US. This study found no evidence of long-term trends in annual streamflow, however there was evidence increasing March flows an decreasing August baseflows over the full record. The study also found no evidence that vegetation trends in the upper Mill Creek basin might have reduced long-term streamflow. This study indicates that “flow from flexibility” and other water-sharing or water conservation measures have potential to mitigate conflicts among alternative uses of water in the Walla Walla basin.

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FIGURES

Figure 1: Location of Mill Creek

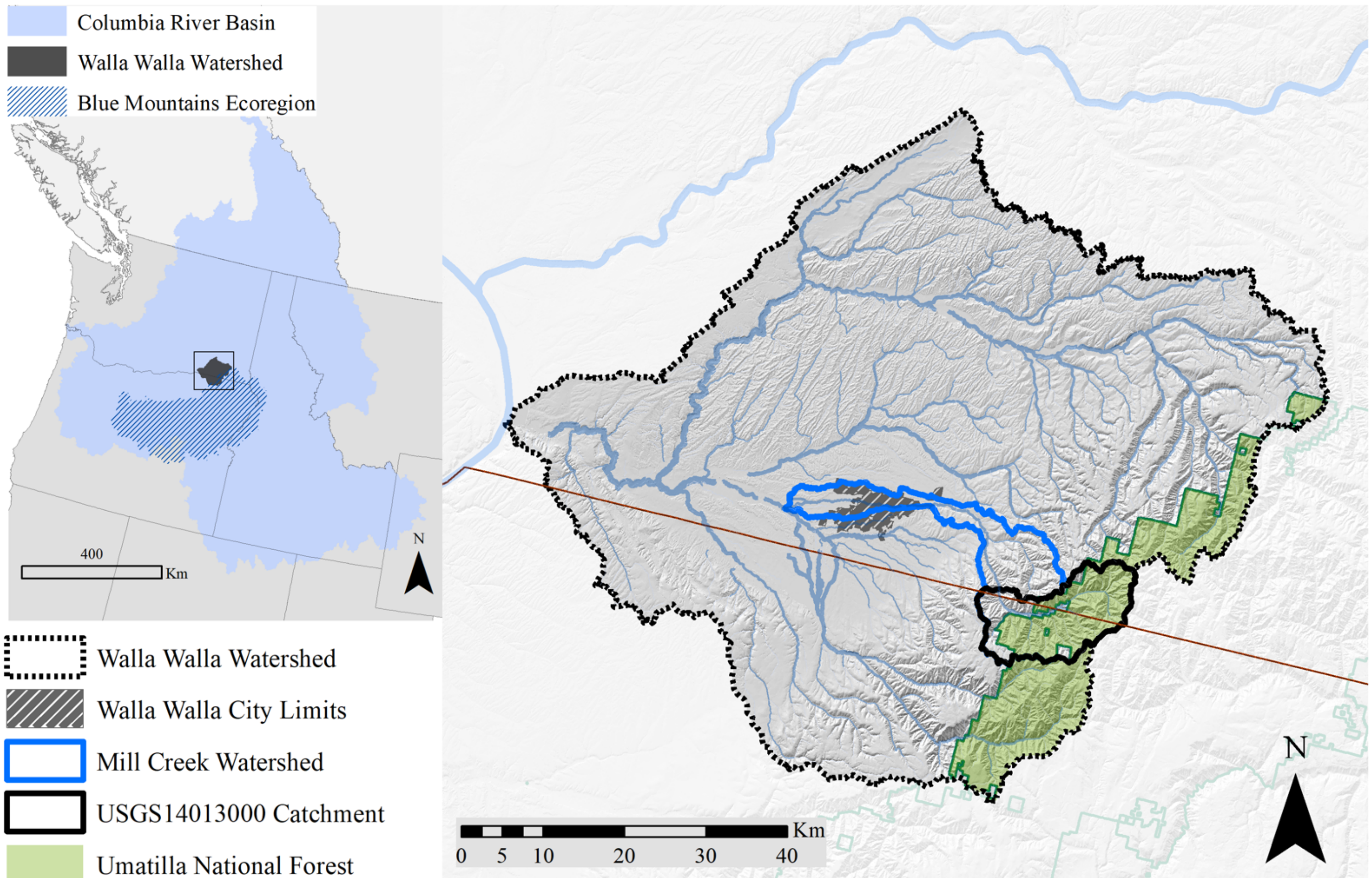


Figure 2: Study Area: Mill Creek Basin, with location of municipal water frastructure (Δ) and gages used in data analysis (•, □)

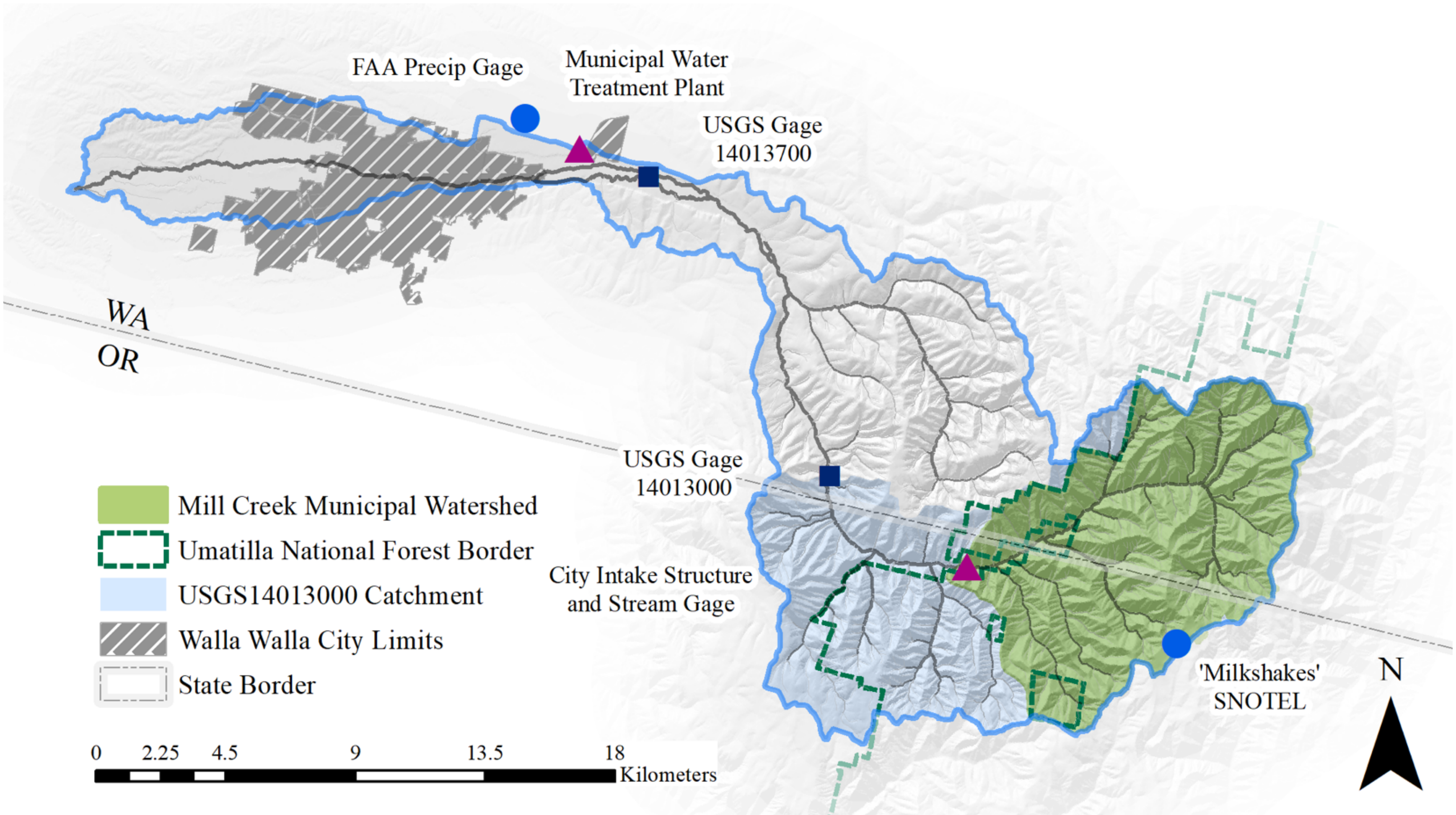


Figure 3: Precip/Climate Norms by Month of Water Year. Period of Record Walla Walla FAA (369m) is 1948-2016). Period of Record for "Milkshakes" SnoTEL (1701 m) is 2008-2016.

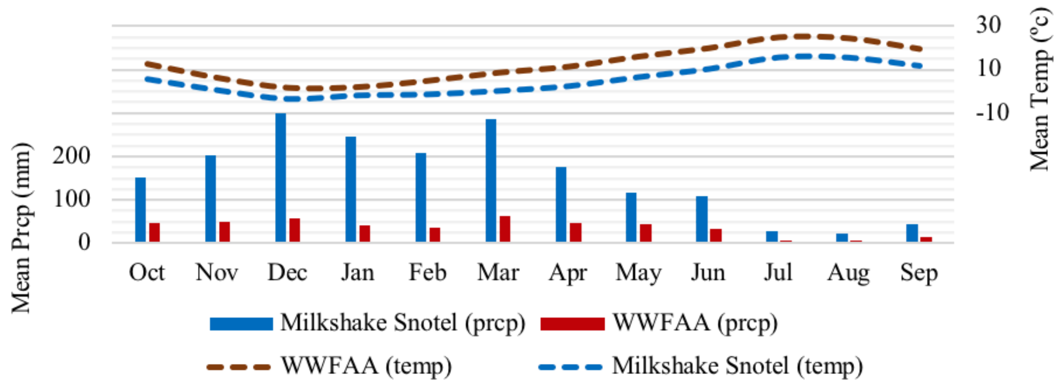


Figure 4. Annual Precipitation Observations at Milkshake Snotel (1701m), and Walla Walla FAA (369m) for available period of overlapping record (2008-2017).

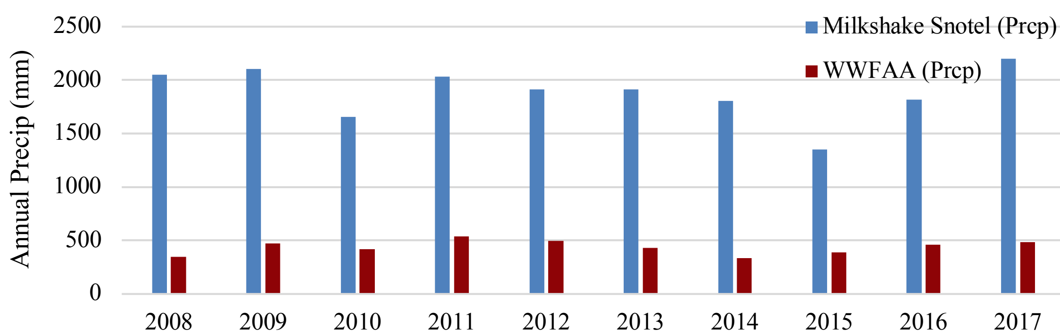
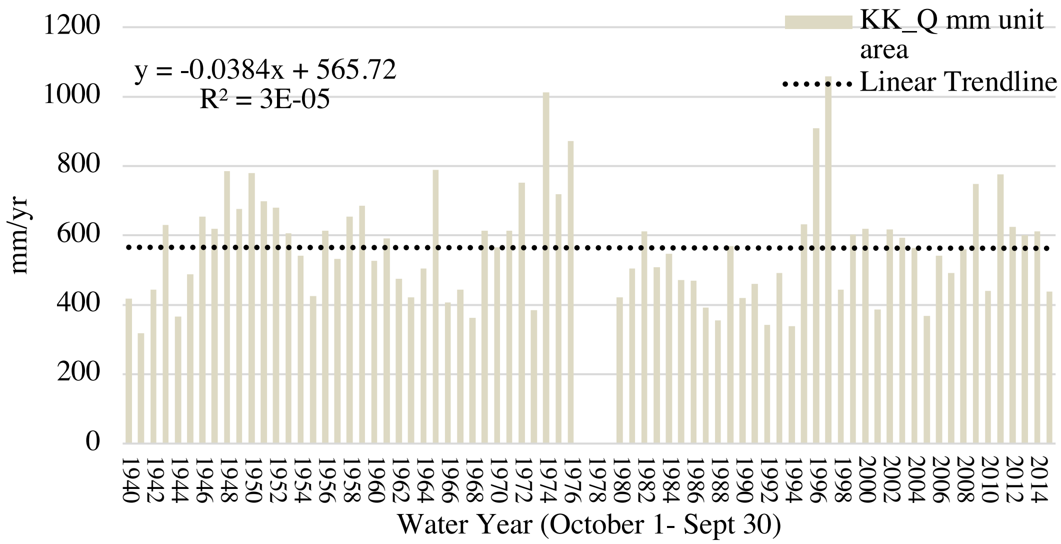


Figure 5. a.) Annual streamflow (mm/unit area) observed at USGS 14013000, and b.) Precipitation observed at Walla Walla FAA (1940-2014).

a.



b.

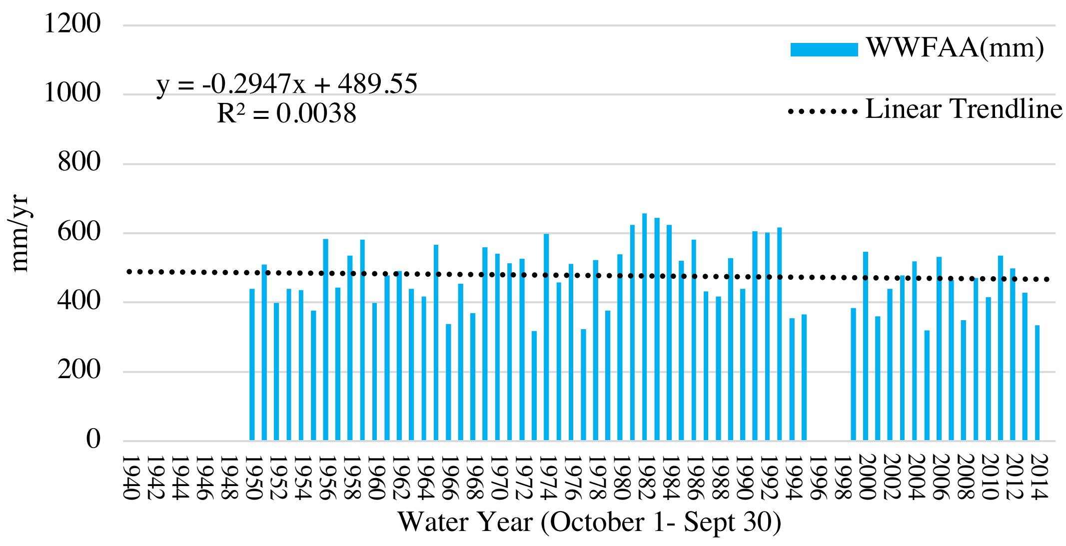
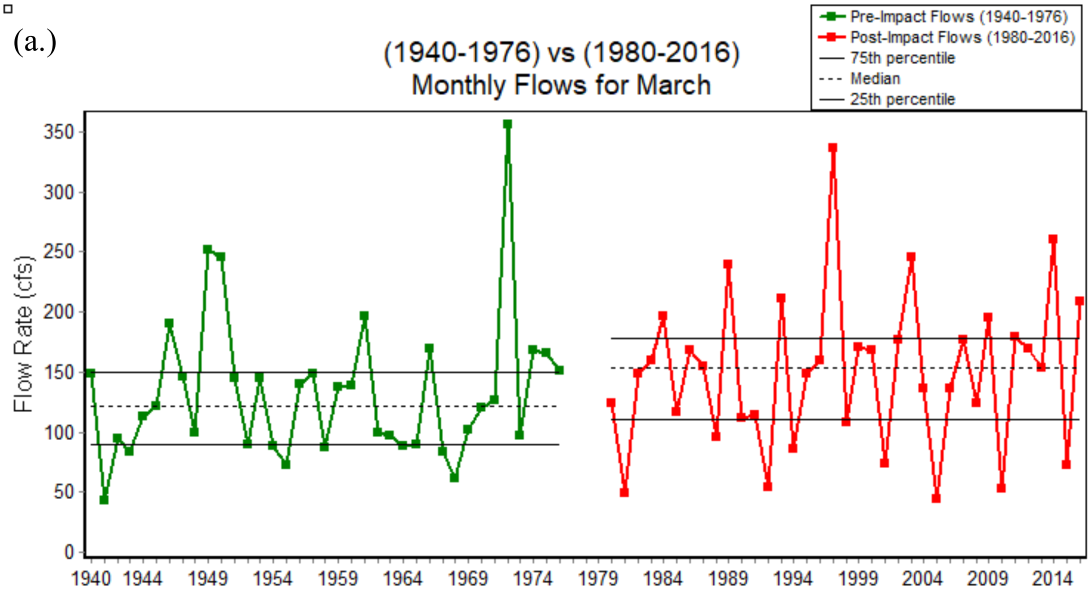


Figure 6. Median daily flow rate (cfs) observed at USGS14013000 (152 km^2) in (a.) March (b.) August, for period of available record (1940-2016). Pre/Post Impact flows refer to the gap in hydrologic record 1977-1979. Several changes have occure din the upper catchment following the gap in the record, most notably the adaption the City Municipal Water Intake pipeline for hydropower which shifted the water supply of rural residencies along Mill Creek Road to well use.

(a.)



(b.)

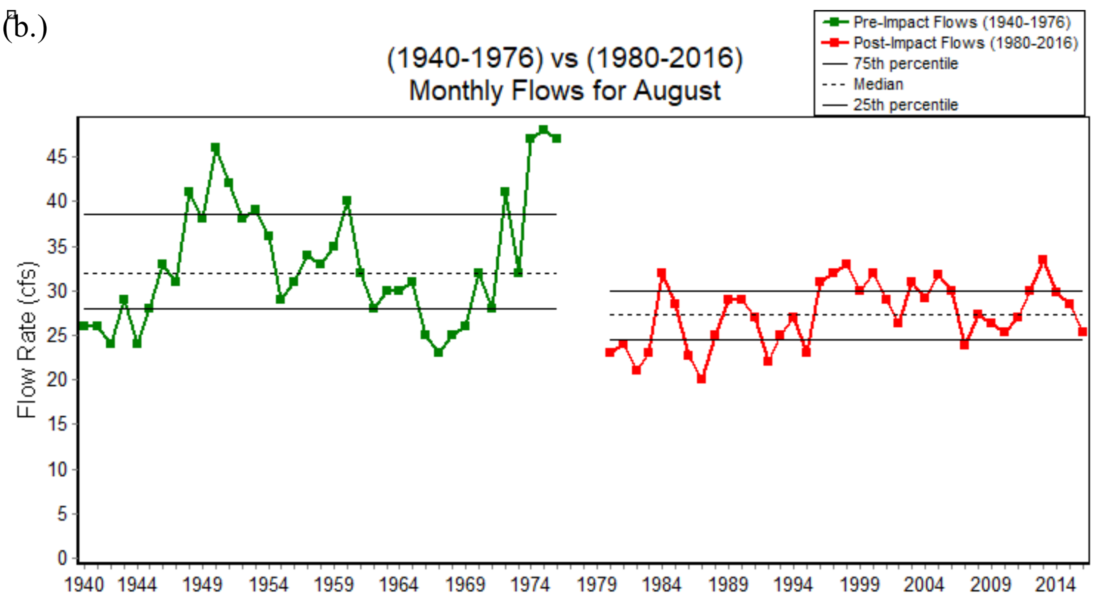


Figure 7. Population Change in City of Walla Walla, Washington (1870-2015) (US Decennial Census). *American Community Survey 5-yr estimates.*

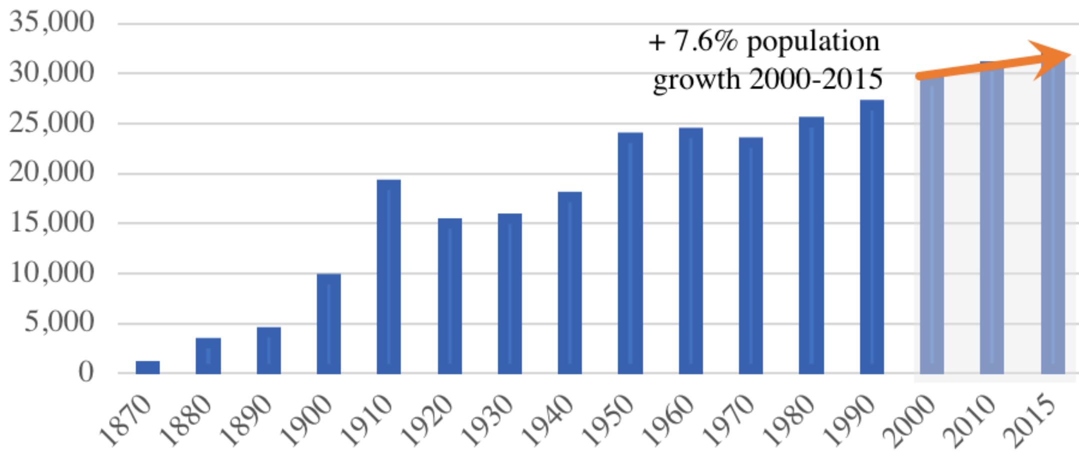


Figure 8. Conceptual Water Budget Model for Upper Mill Creek Catchment. precipitation (P), evapotranspiration (ET), soil water storage (S), discharge (Q), and surface water, groundwater withdrawals (WD_Q, WD_{GW}).

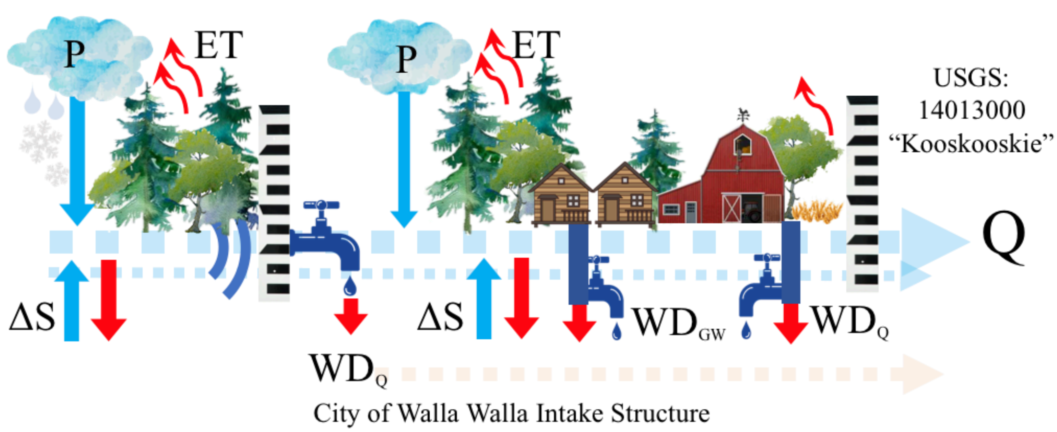


Figure 9. Linear relationship between USGS Gauge 14013000 and interpolated streamflow above City of Walla Walla Intake Structure. daily mean discharge at the Stage Gauge is added to the known withdrawal values. For this interpolation, all discharge values above 300 cfs at Kooskooskie were removed . This improves the goodness of fit from an R^2 0.5189 in the unaltered linear regression to an R^2 of 0.65396.

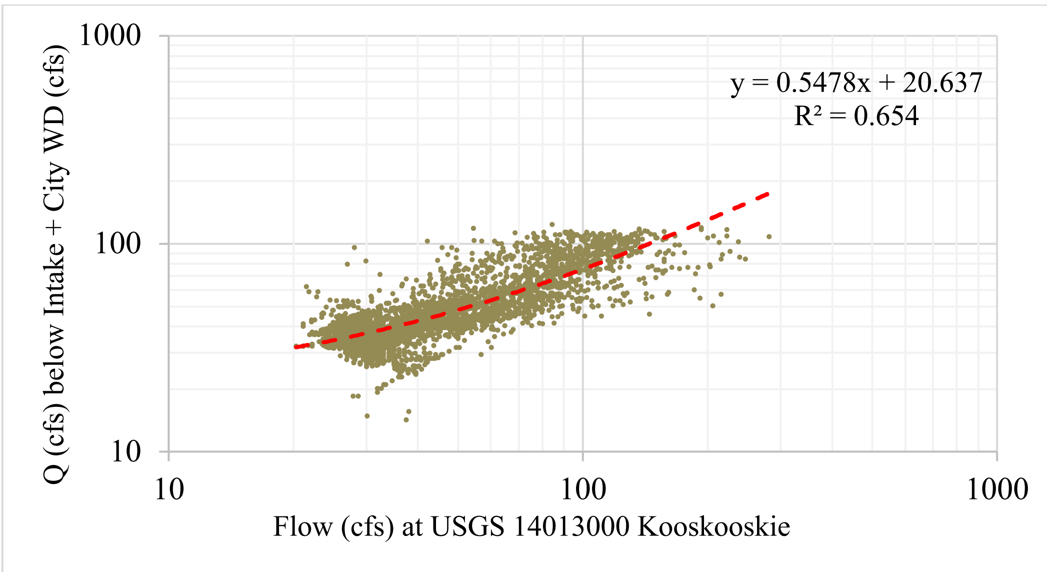


Figure 10. Reconstruction of Estimated Flow above the City of Walla Walla Intake Gauge (2001-2016) Estimated flows above 100 cfs were determined by extrapolating between flows at the Intake and the 14013000 gauge for the period 2001 to 2016. (See Figure 9).

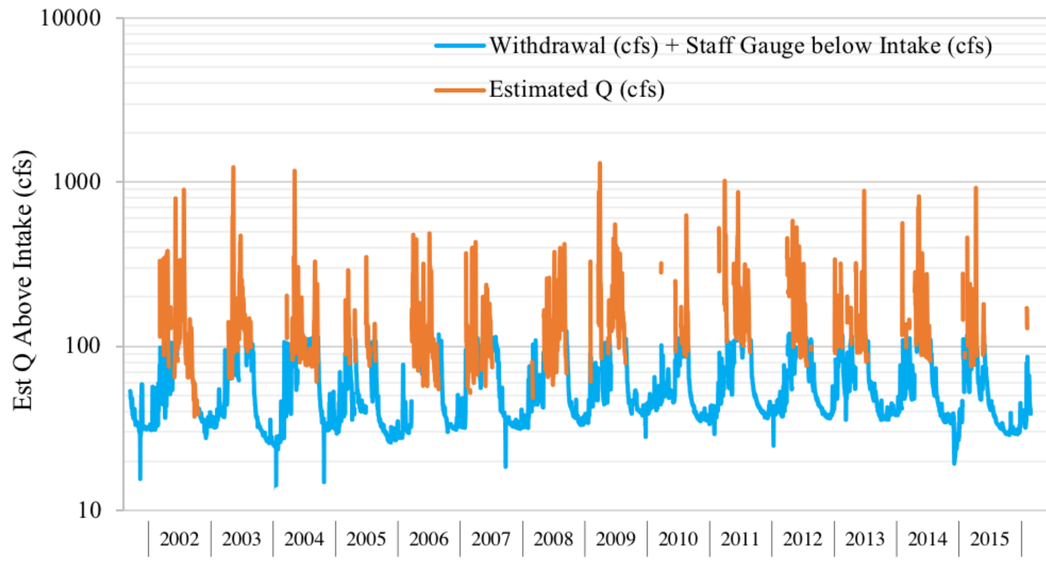


Figure 11. Negative Deviations in discharge (cfs) from 2007 Instream Flow Recommendations for full period of record. Full Period of Record. For the years 1977-2007, a prior set of instream flow (ISF) values were followed, as recommended by WAC 173-532-030. No regulation of ISF occurred in years prior to 1977.

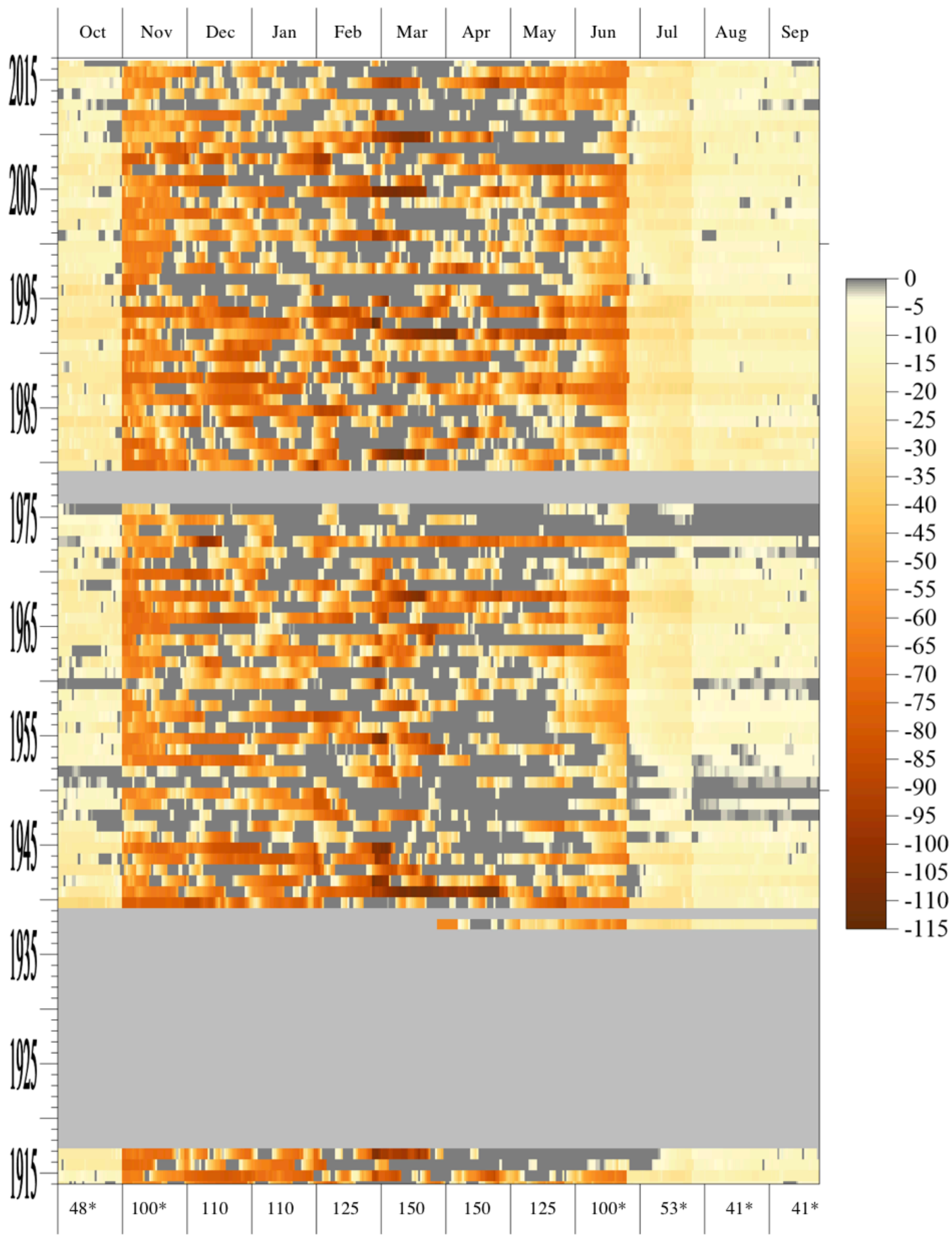


Figure 12. Daily estimated streamflow above City of Walla Walla Intake gage (2002-2016 WY). Median Estimated Daily Discharge, positive standard deviation (grey shading), and 7 day average minimum observed values for 2002-2016 water years above the City of Walla Walla intake gage. Flows >100 cfs were estimated from Figure 9. The 2007 monthly ISF recommendations for the downstream gage USGS 14013000 (Management Point 1 for the Walla Walla Watershed) have been superimposed for context.

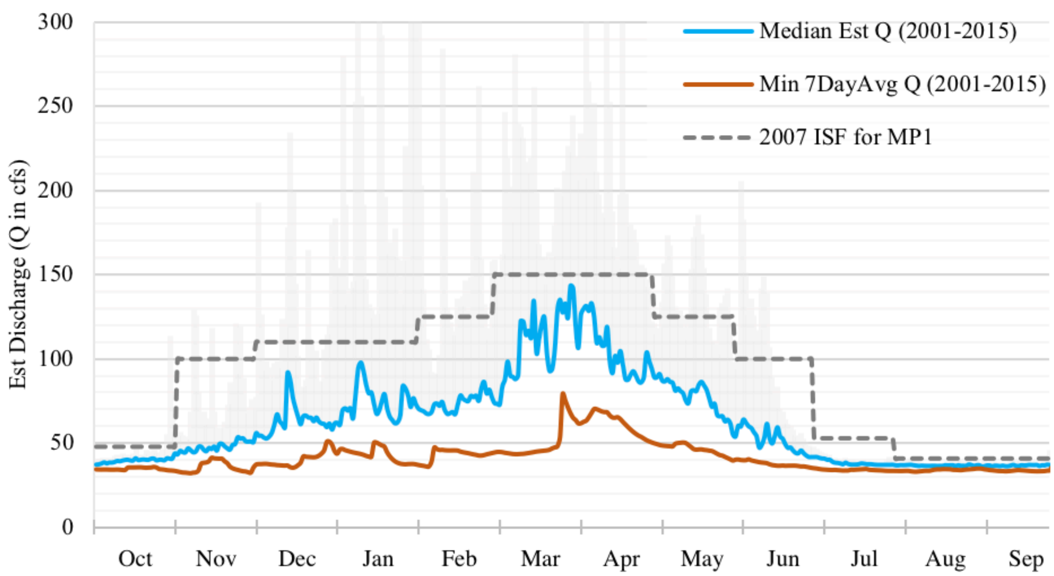


Figure 13. Daily Streamflow Statistics for USGS 14013000 (2002-2017 WY.) Median Estimated Daily Discharge, positive standard deviation (in grey), and 7 day average minimum observed discharge values for 2001-2015 are compared to their values for the full period of available record (1940-2017). The 2007 monthly ISF recommendations for the downstream gage USGS 14013000 (Management Point 1 for the Walla Walla Watershed) have been superimposed for context.

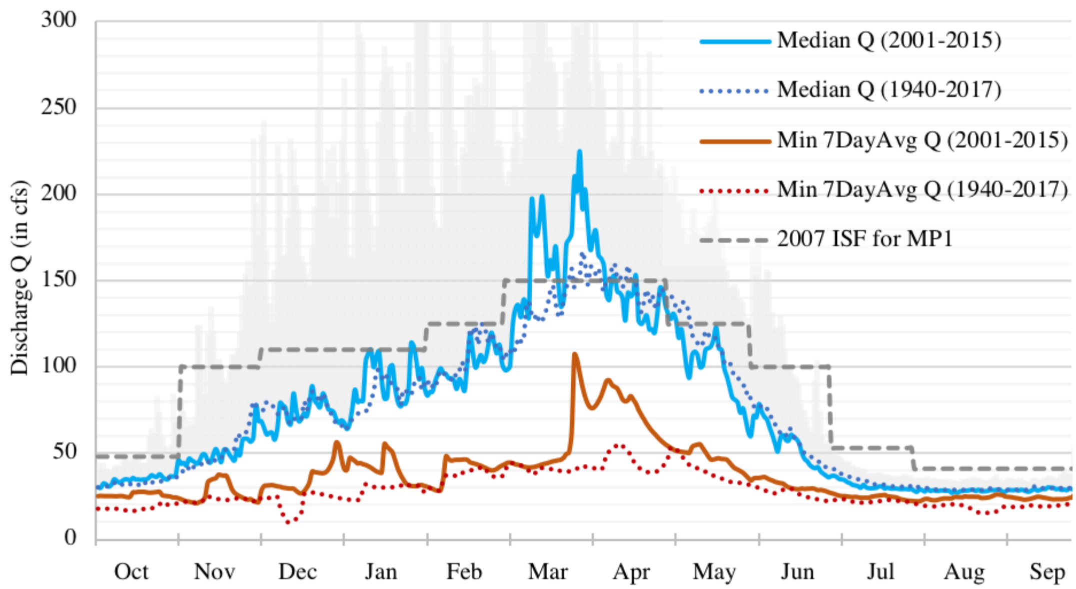


Figure 14. Raster Hydrograph of Daily Mean Withdrawal rate (cfs) at City of Walla Walla Intake (June 2001- December 2016). Withdrawals of zero are represented as white, and periods of no data are represented as grey. Withdrawal data is recorded at head of intake pipeline with SCADA flow meter, provided by City of Walla Walla Public Utilities. Periods of No Data are represented as grey.

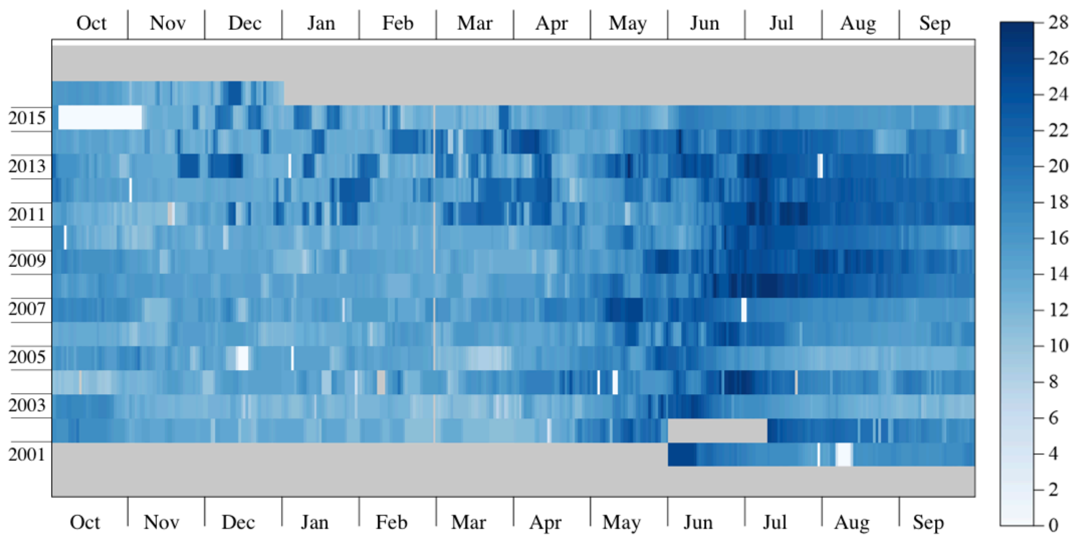


Figure 15. Monthly and annual withdrawal volumes (million gallons) reported by City of Walla Walla at intake structure. Some data gaps occur, as described in Table 3.

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual WD
2016	308	251	308										
2015	null	215	312	312	239	276	277	290	344	332	316	297	3242.6
2014	291	265	291	297	315	351	364	350	399	443	361	339	4066.3
2013	304	315	354	295	269	329	306	405	430	455	435	352	4248.0
2012	319	259	281	349	301	350	348	358	383	458	450	411	4267.8
2011	265	221	318	345	261	400	353	305	377	515	454	430	4243.0
2010	267	251	272	267	246	275	304	345	371	471	407	324	3799.9
2009	340	274	283	266	259	270	273	375	436	482	474	395	4129.3
2008	316	297	289	291	257	286	300	379	432	521	448	362	4177.9
2007	353	273	294	292	269	316	344	445	405	356	341	306	3994.5
2006	268	263	278	264	260	294	284	370	412	382	322	319	3716.3
2005	321	288	234	275	264	209	300	372	375	286	249	255	3426.5
2004	211	261	285	267	245	304	362	325	432	408	338	342	3778.3
2003	336	245	240	239	214	216	252	358	413	307	263	229	3312.7
2002	336	274	262	263	228	239	258	393	null	316	388	338	3295.6
2001									424	324	267	333	

Figure 16. Daily Mean Rate of Withdrawals by Water Year (2002-2015). Data was provided by City of Walla Walla Public Utilities, recorded at head of Intake Pipeline with SCADA Flow Meter. Periods of Zero Intake, and No Data intermittently exist (and are documented in table 3). Annual box and whisker plots display mean (X), Median (-), interquartile range (Box of 25th and 75th percentile), and local max/min values (whiskers) with threshold for outliers established by Tukey industry standard (distance from box = 1.5 times the length of the interquartile range).

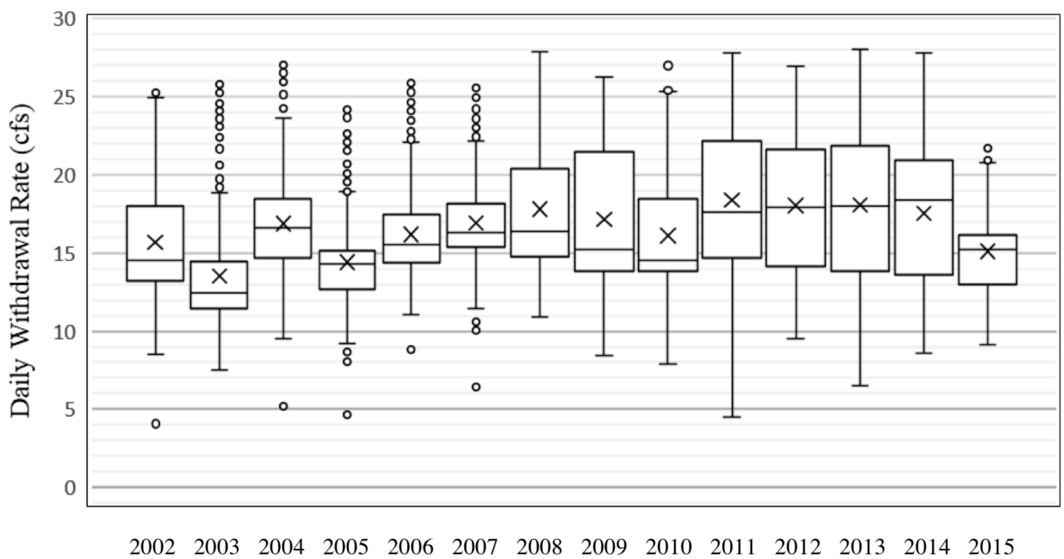


Figure 17: Daily Mean Rate of Withdrawal by Month of Water Year (2002-2015) before and after ASR implmentation (2001-2010, 2011-2016). Data recorded at head of intake pipeline with SCADA flow meter, provided by City of Walla Walla Public Utilities. Incomplete Water Years, and periods of No Data were removed for statistical analysis. Annual box and whisker plots displaying mean (X), Median (-), interquartile range (Box of 25th and 75th percentile), and local max/min values (whiskers) with threshold for outliers established by Tukey industry standard (distance from box = 1.5 times the length of the interquartile range).

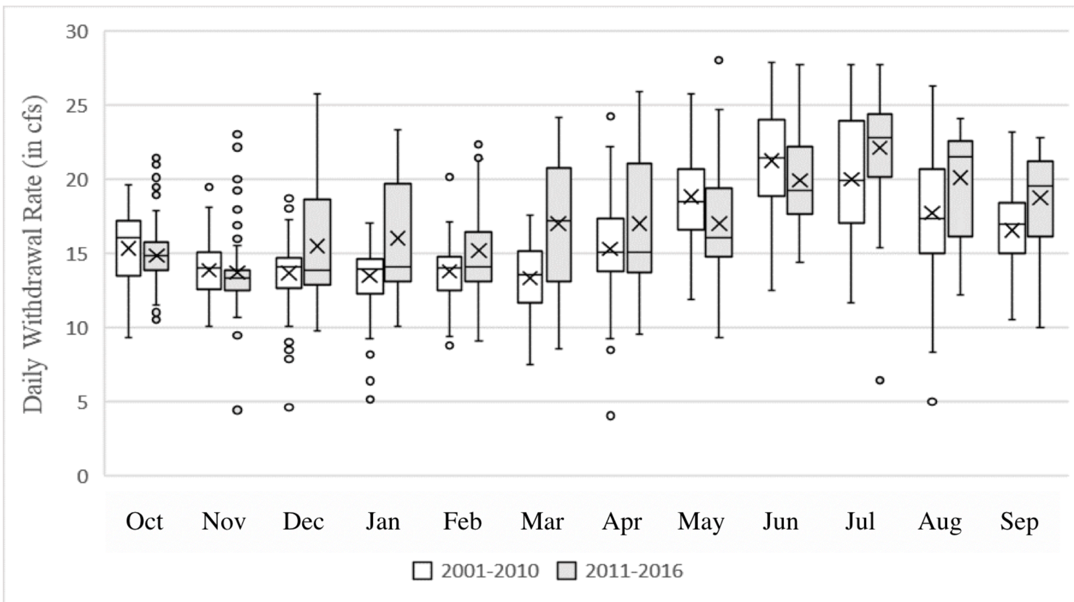


Figure 18. Annual Withdrawal as a percent of Annual Discharge at USGS14013000, and Interpolated Discharge above City of Walla Walla Intake (2002-2015)

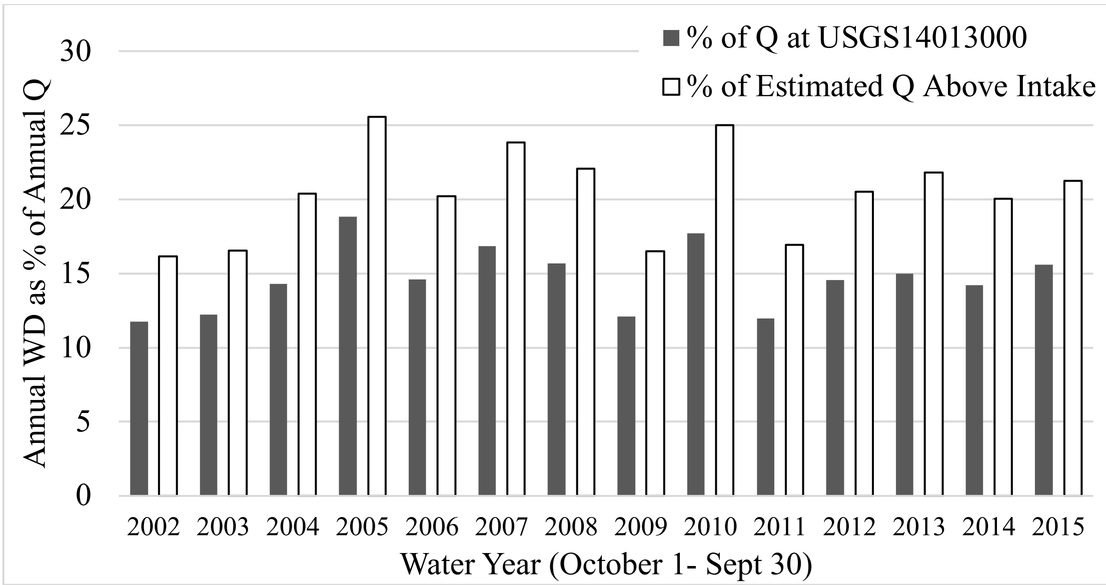


Figure 19. Scatter plot of annual withdrawal volume (in million gallons) relative to annual discharge at a. Above City of Walla Walla Intake, and b. USGS 14013000 in absence of withdrawals.

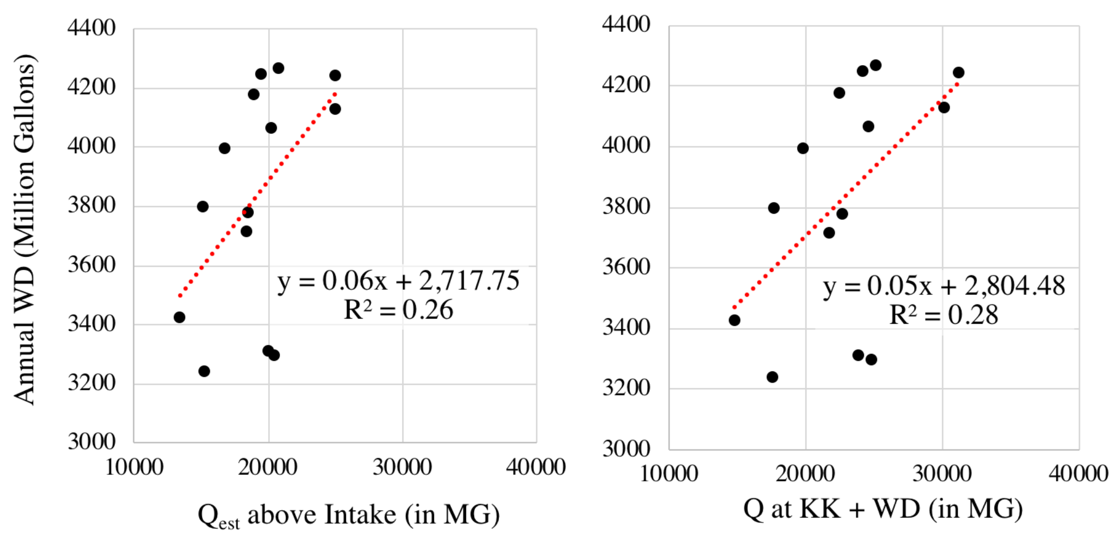


Figure 20: Withdrawals as a proportion of monthly discharge above City Intake, and USGS Gauge 14013000. Monthly box and whisker plots display mean (X), median (-), interquartile range (Box of 25th and 75th percentile), and local max/min values (whiskers) for withdrawal percentages. The threshold for outliers (○) was established by Tukey industry standard (distance from box = 1.5 times the length of the interquartile range).

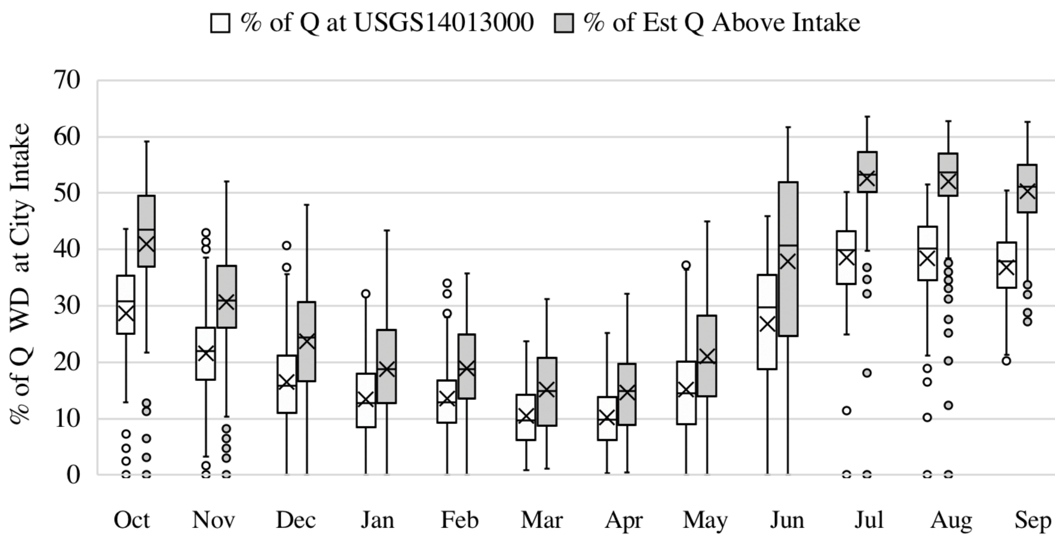


Figure 21: Annual Pattern (2002-2015 WY) for daily withdrawal rates as percent of median daily estimated flow above City of Walla Walla Intake, and USGS 14013000. Annual box and whisker plots display mean (X), median (-), interquartile range (box denotes 25th and 75th percentile), and local max/min values (whiskers) for withdrawal percentages. Threshold for outliers established by Tukey Industry standard (distance from box = 1.5 times the length of the interquartile range).

Figure 22: Raster Hydrograph depicting mean daily withdrawal rates (cfs) as a percent of median daily streamflow (cfs) at USGS 14013000. Withdrawals range from 0 – 55% of discharge. Missing values are depicted in grey.

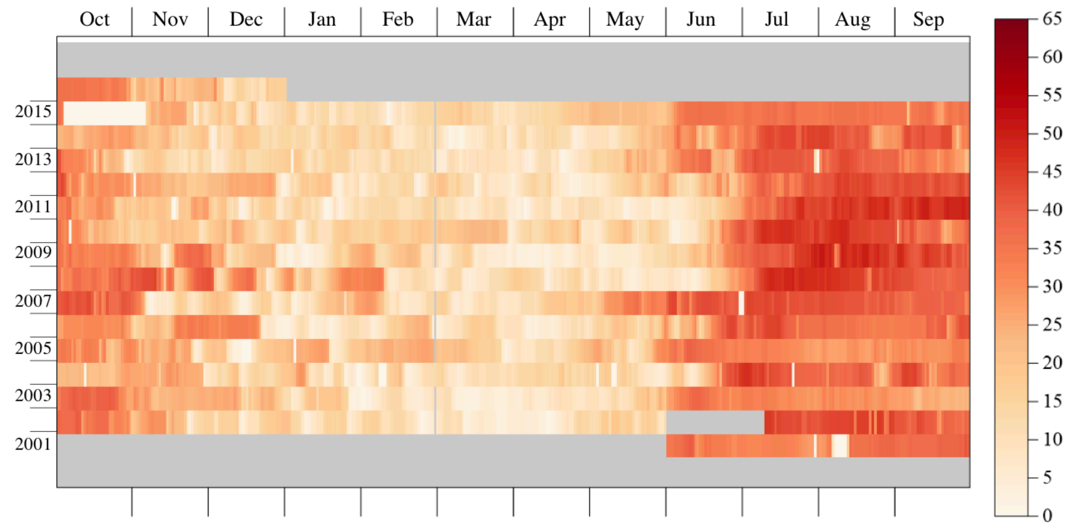


Figure 23: Raster Hydrograph depicting mean daily withdrawal rates (cfs) as a percent of median daily streamflow (cfs) estimated above intake. Withdrawals range from 0 – 65% of discharge. Missing values are depicted in grey.

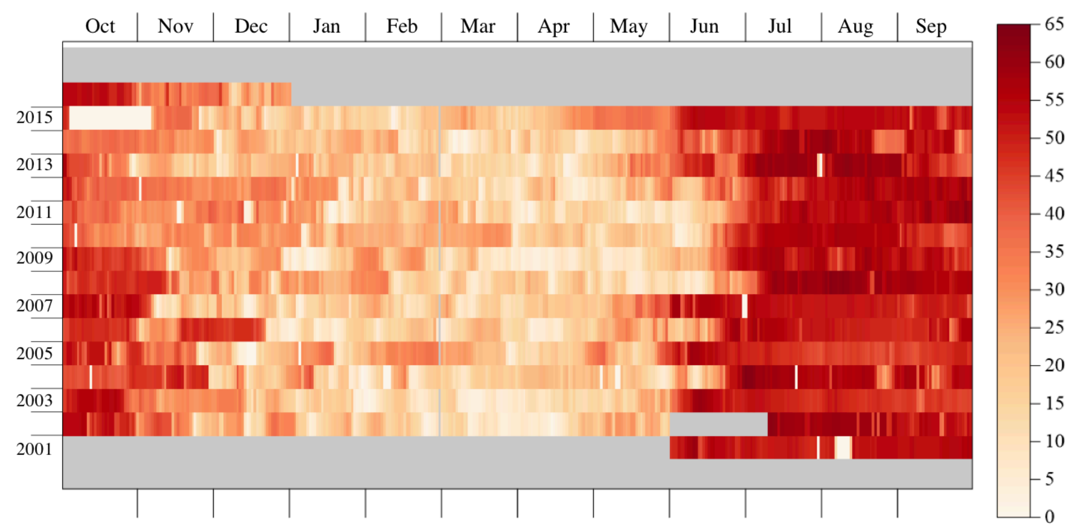


Figure 24. Difference in mean daily flow (+/-cfs) at the Kookskooskie gage vs. flow estimated at the upstream Intake gage, over the period 2001 to 2016. Upper= magnitude of losses of flow between the intake and the Kooskooskie gage, indicating days with "losing" conditions in the reach. Lower= increases of flow, indicating days with "gaining" conditions.

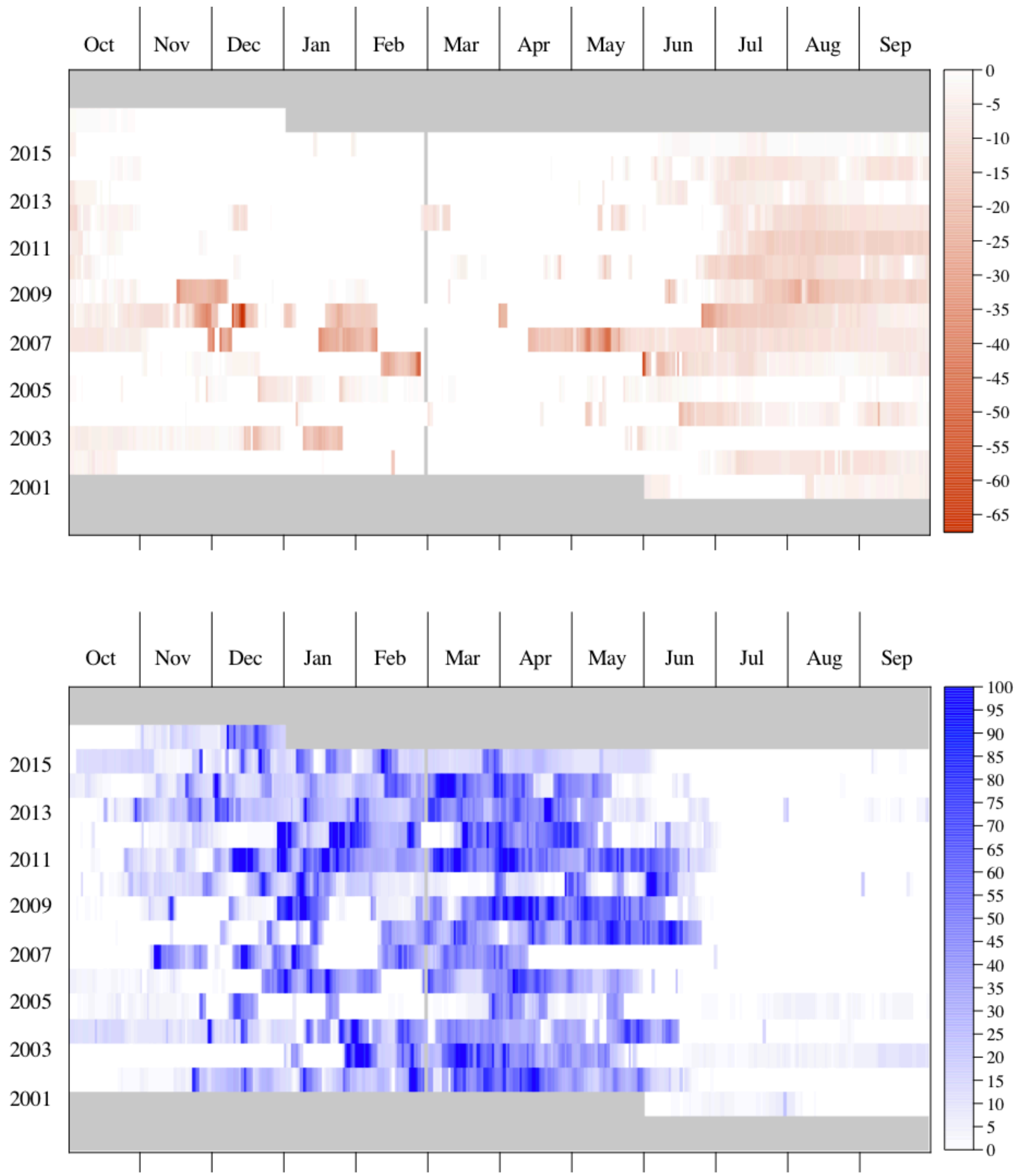


Figure 25: Raster Hydrograph depicting negative deviations in observed discharge (in cfs) from 2007 Monthly Instream Flow Recommendations issued for USGS Gage 140130000. Flows equaling or exceeding recommendations appear dark grey.

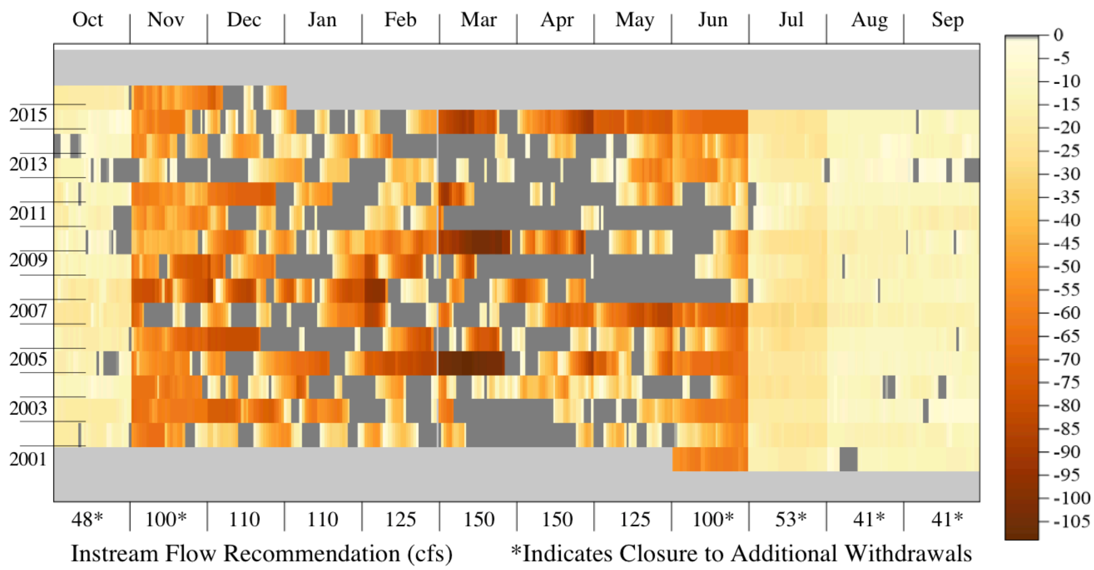


Figure 26: Raster Hydrograph depicting negative deviations (in cfs) from 2007 Monthly ISF Recommendations at USGS14013000 if the city hypothetically ceased all withdrawals. Flows equaling or exceeding recommendations appear dark grey.

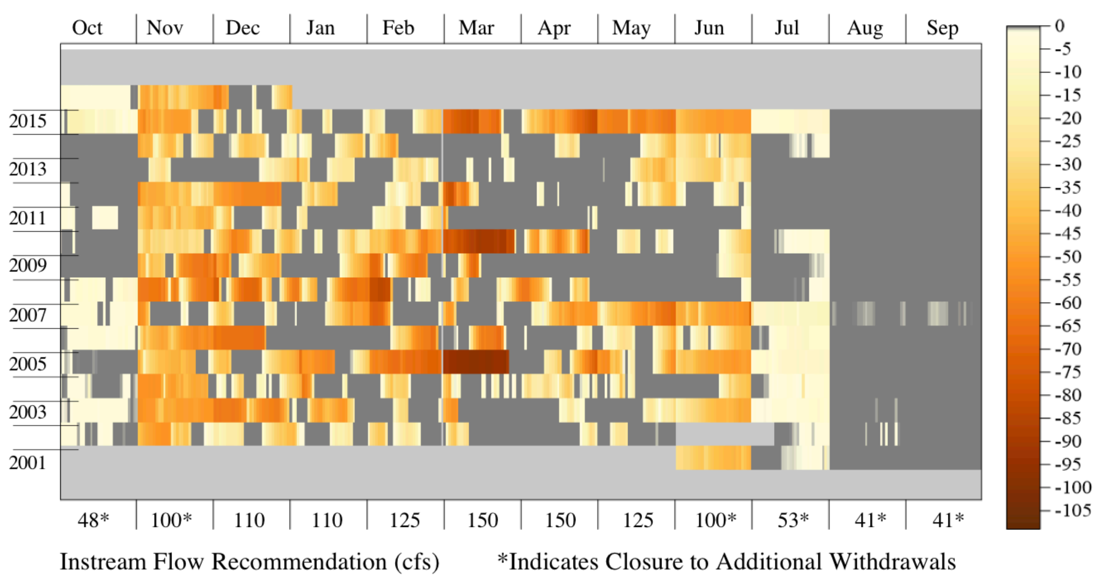


Figure 27: Daily Deviations (in cfs) from 2007 Instream Flow recommendations issued for USGS 14013000, summarized by month. Instream flow deviations are compared to hypothetical flows if the city ceased all withdrawals at the Intake Structure.

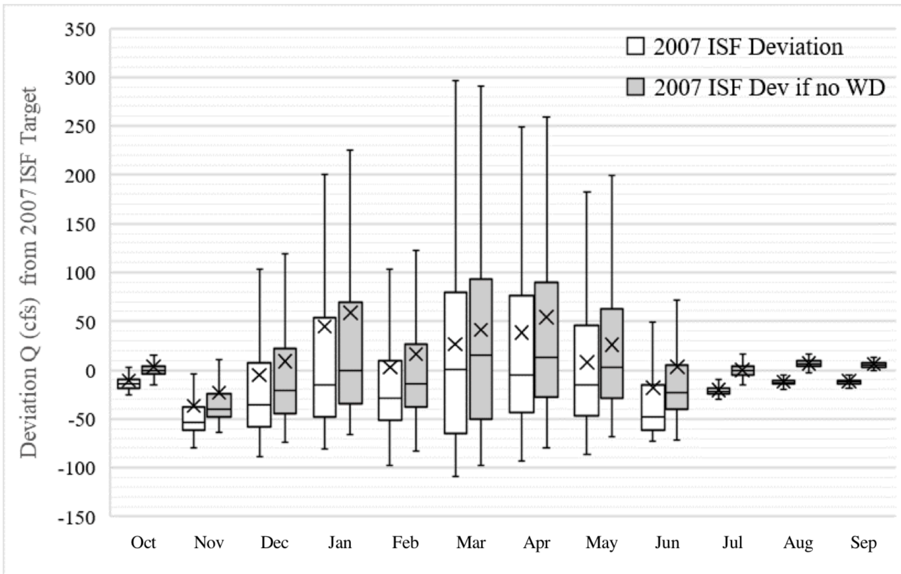


Figure 28: Monthly statistics for the number of days per month ISF recommendations are not met at USGS 14013000. Grey bars depict the number of days per month ISF recommendations would have been met if the city did not withdraw water at the intake.

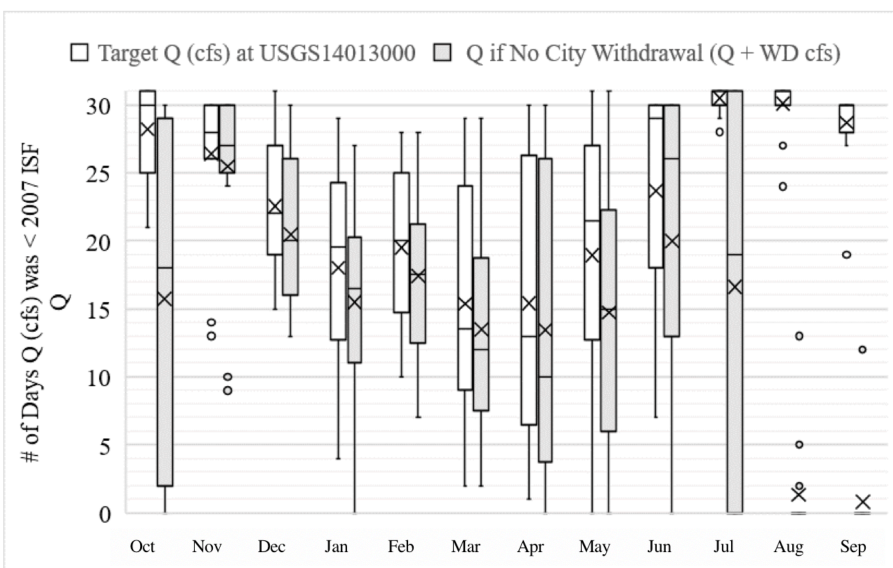


Figure 29: Instream Flow Deviations (in cfs) at USGS14013000 for the months of (a.) July, (b.) August, (c.) September, (d) October for 2001-2017 water years. Box and whisker plots displaying mean (X), Median (-), interquartile range (Box of 25th and 75th percentile), and local max/min values (whiskers) with threshold for outliers established by Tukey industry standard (distance from box = 1.5 times the length of the interquartile range).

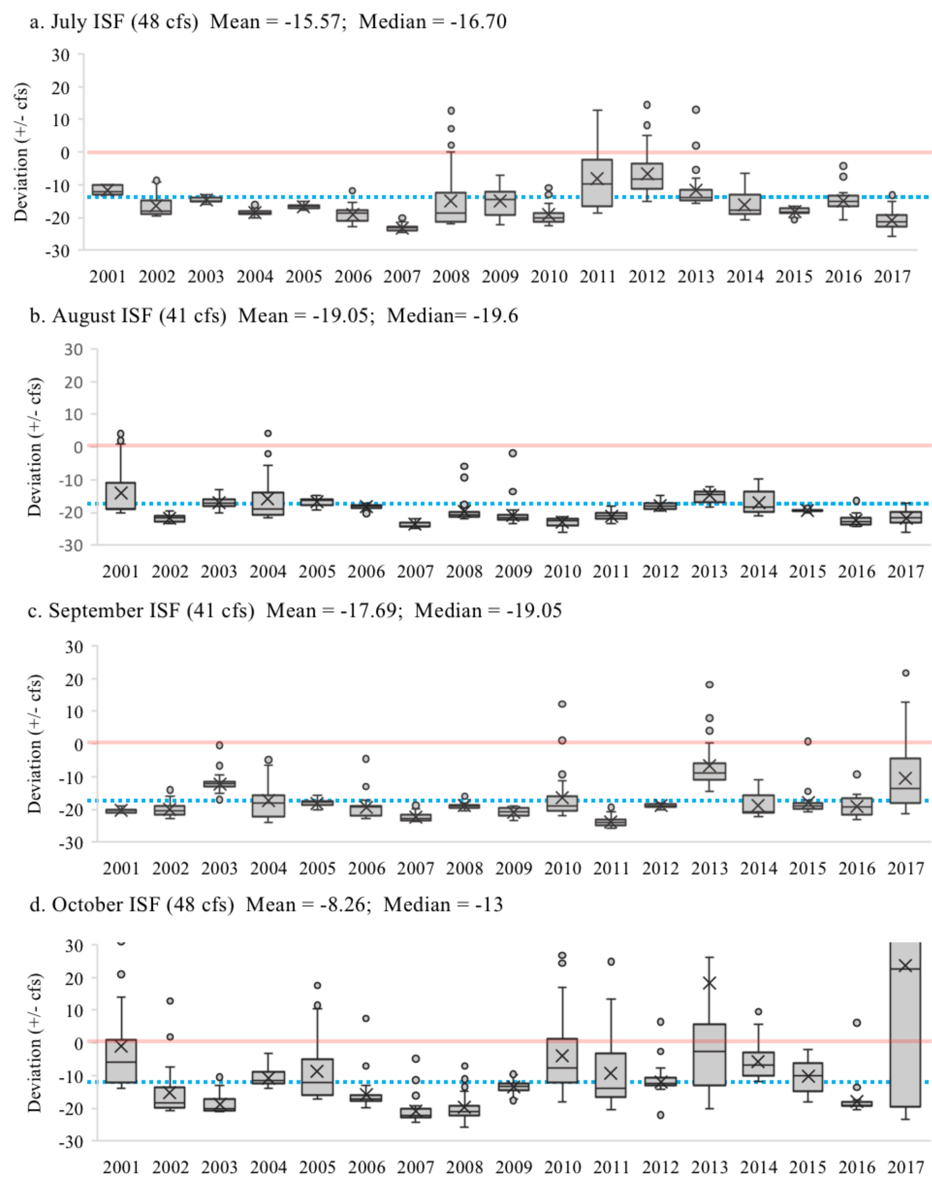
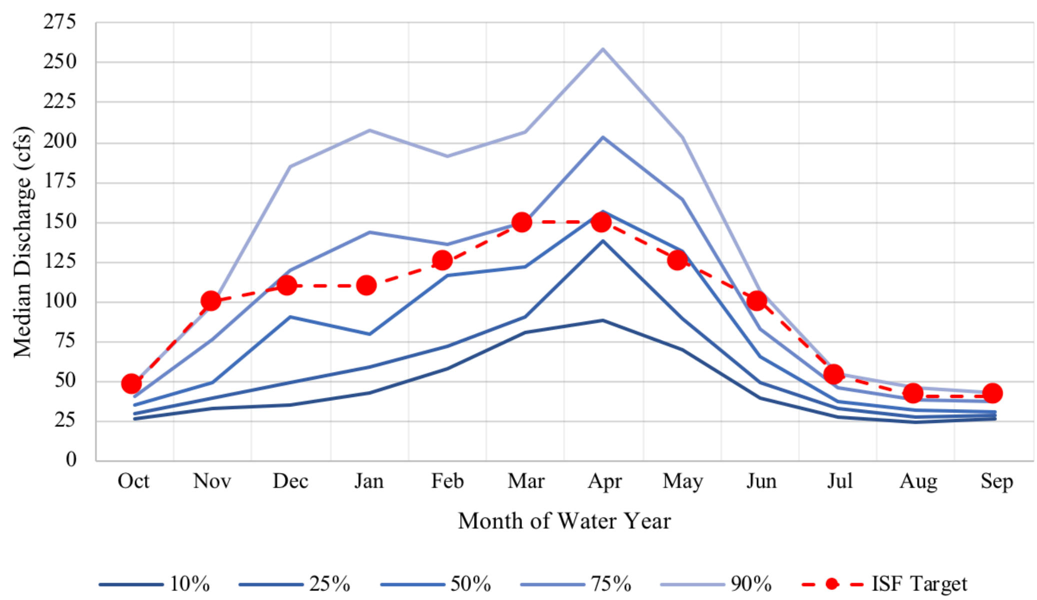


Figure 30. Median daily discharge (cfs) probabilty percentiles for USGS 14013000, data was assessed with a Two Period non-parametric analysis comparing median discharge percentials by month of year for a.) 1940-1976 WY, and b.) 1980-2016 WY. Data was summarized using the Indicators of Hydrologic Alteration (IHA) Software (Richter et al, 1996). This data is presented relative to 2007 Instream Flow Recommendations established by WAC are shown in red.

a.) 1940-1976 WY



b.) 1980-2016 WY

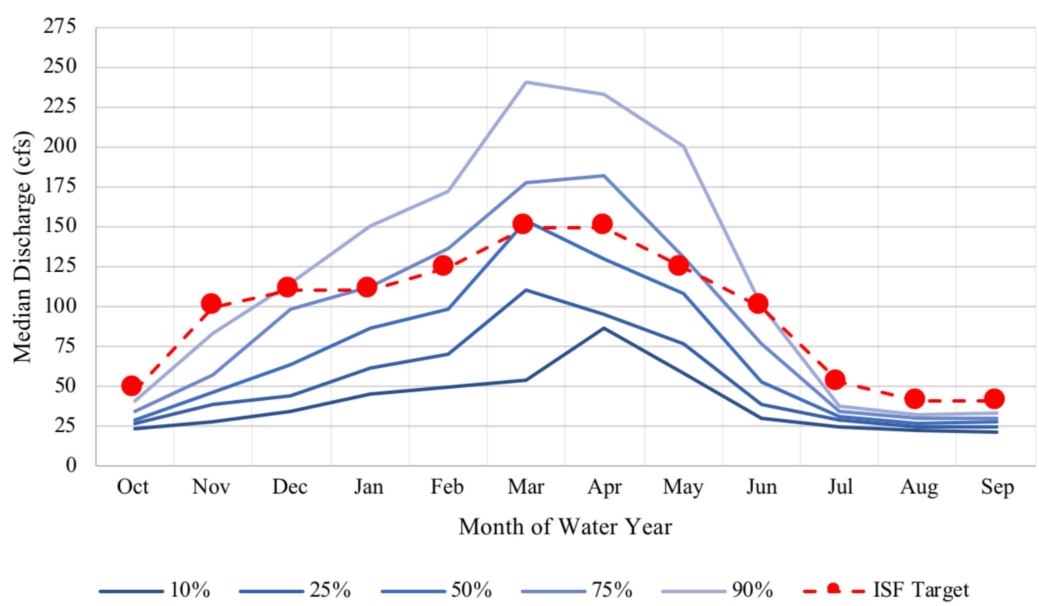


Figure 31: Location overview of aerial photo comparisons

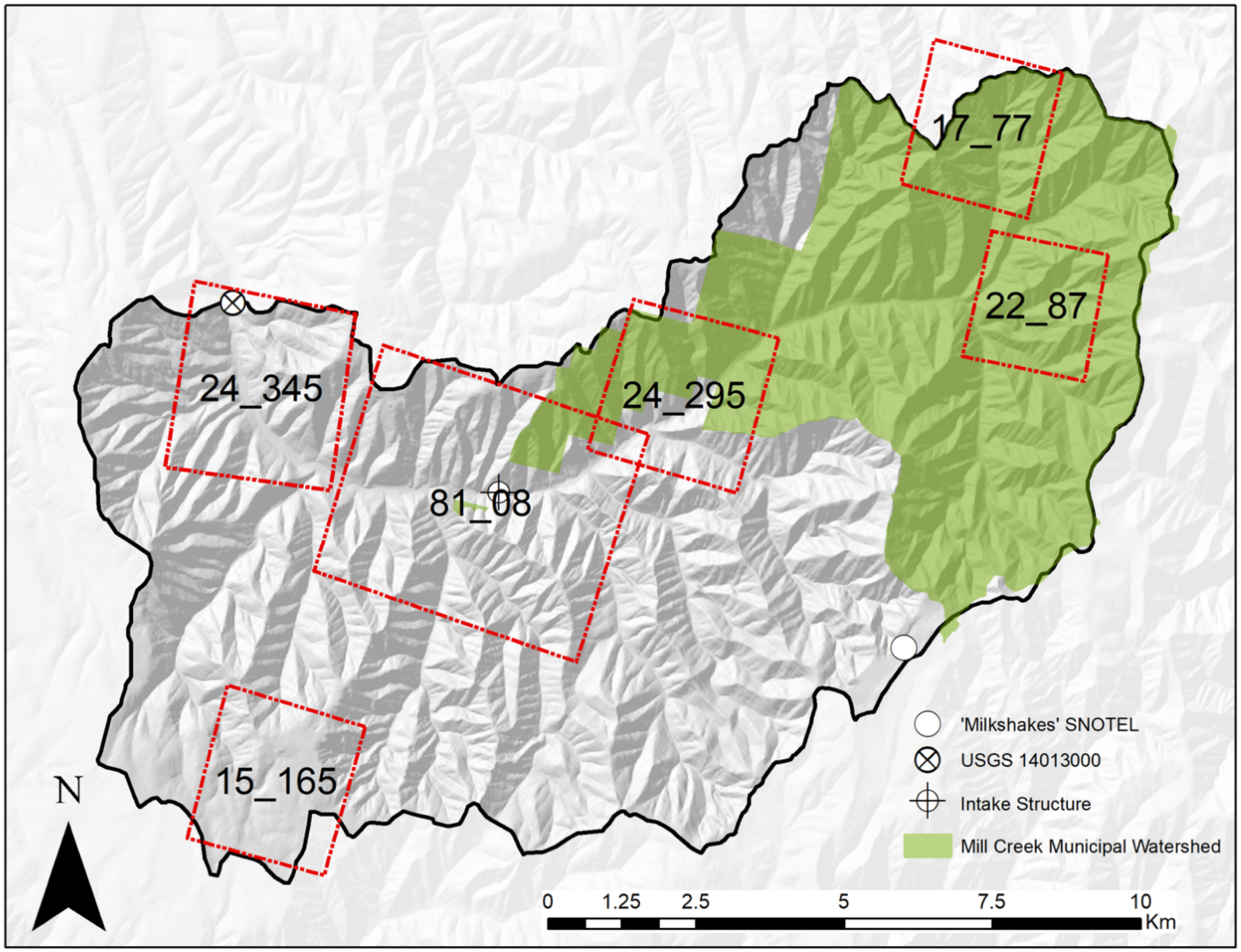
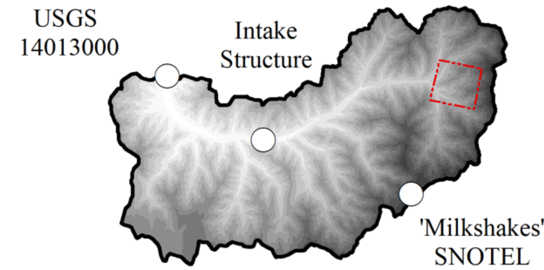


Figure 32: Aerial Photo 1



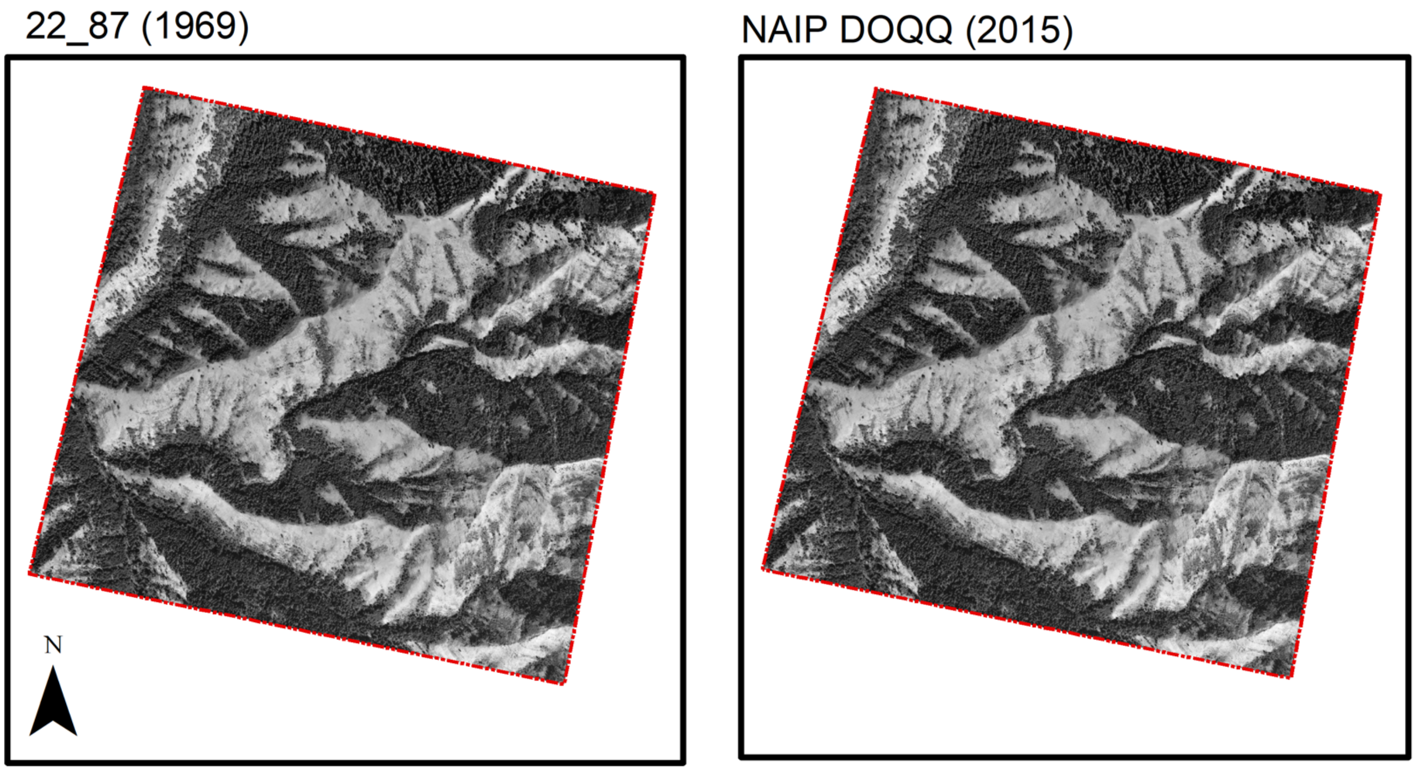


Figure 33: Aerial Photo 2

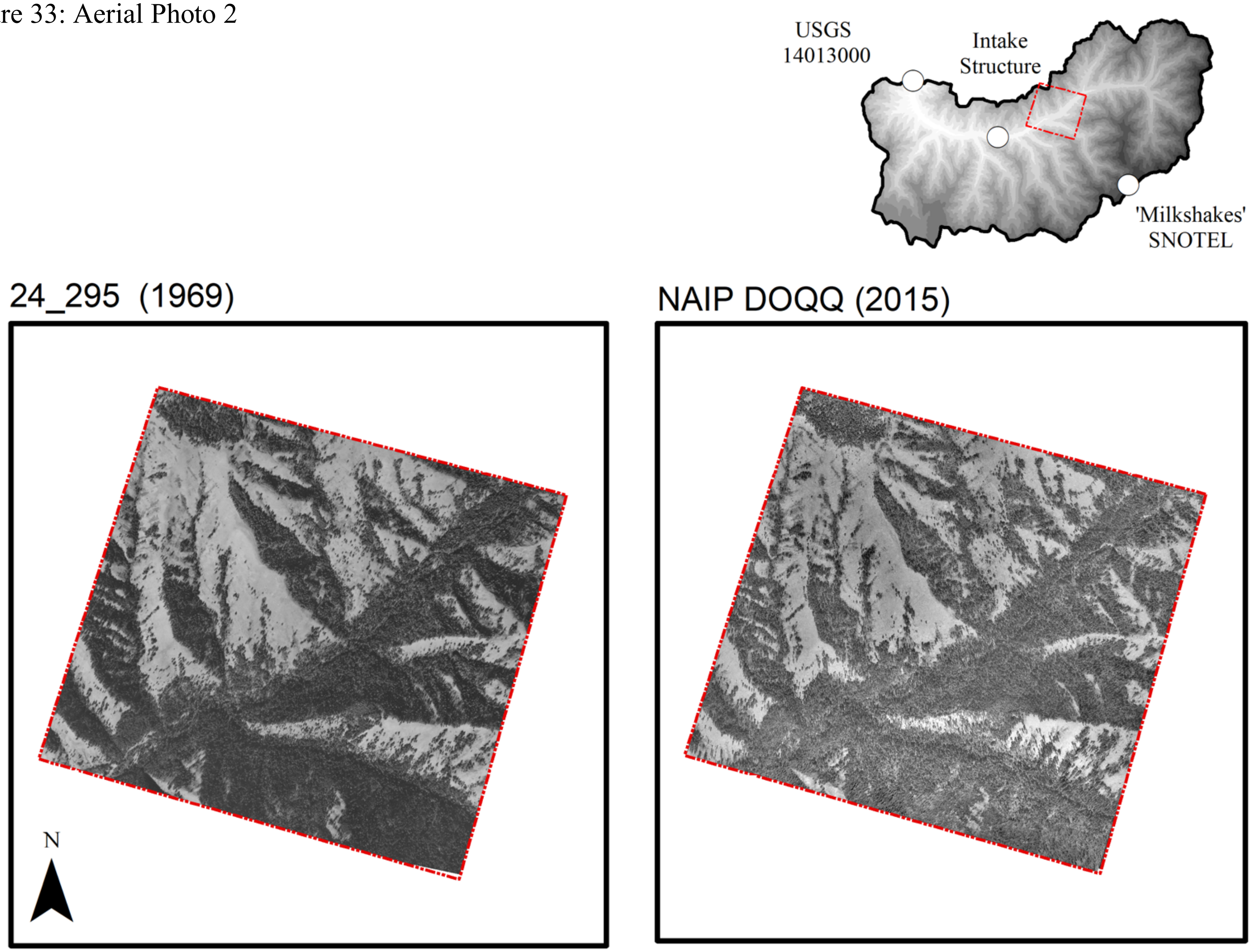
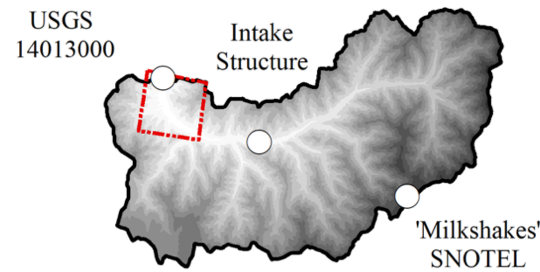


Figure 34: Aerial Photo 3



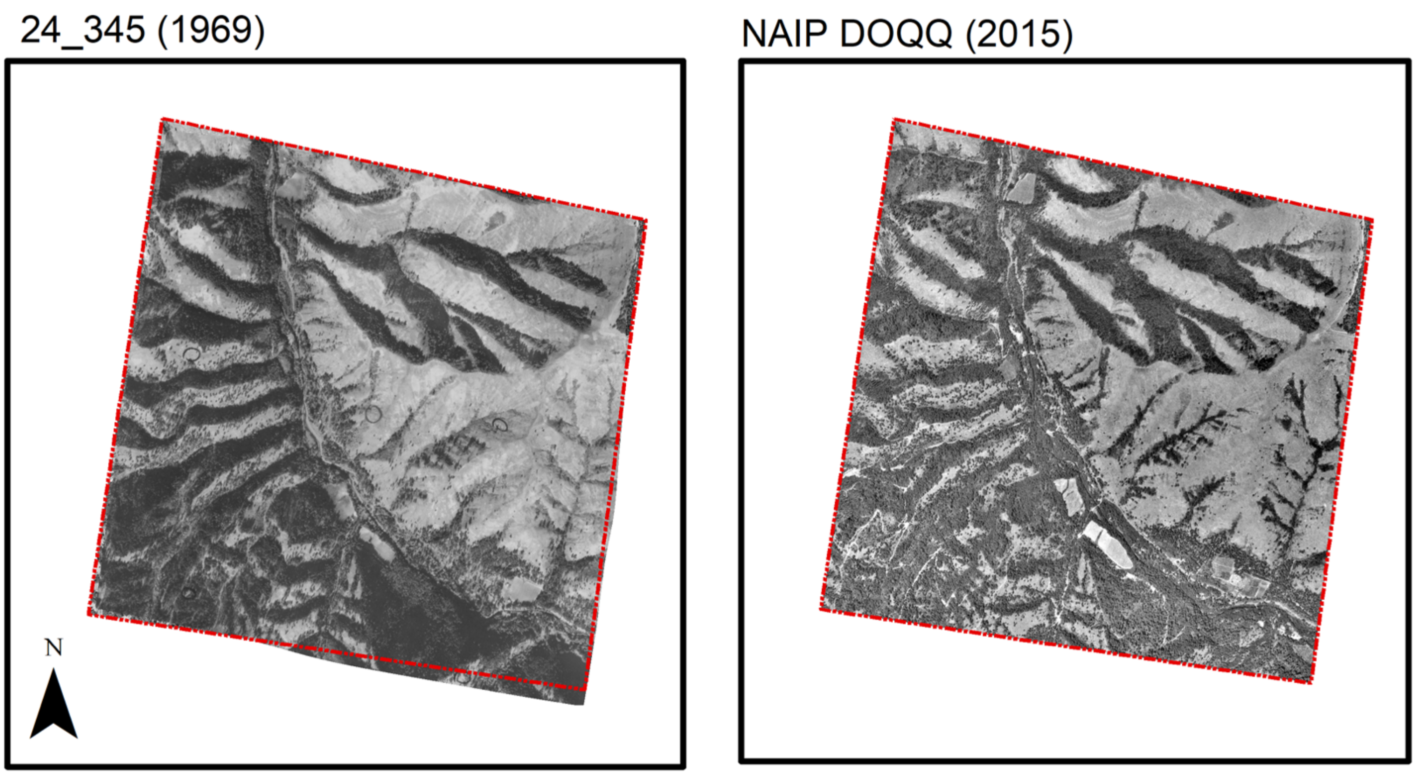
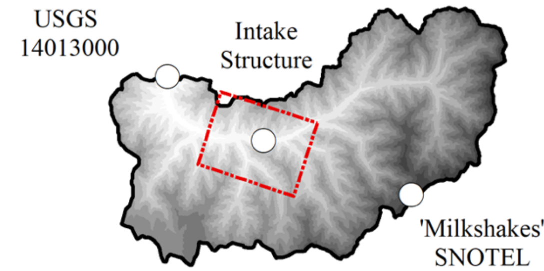


Figure 35: Aerial Photo 4:



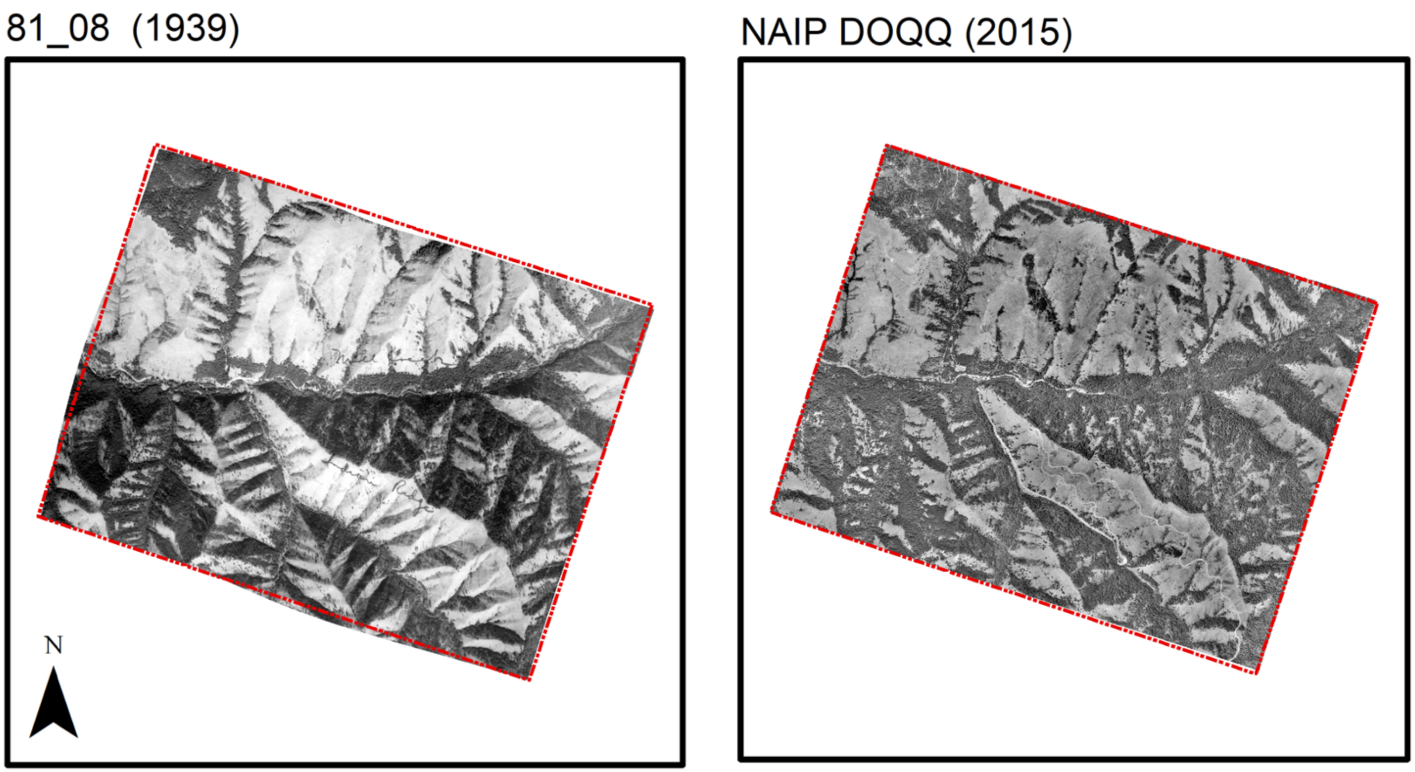


Figure 36: Aerial Photo 5:

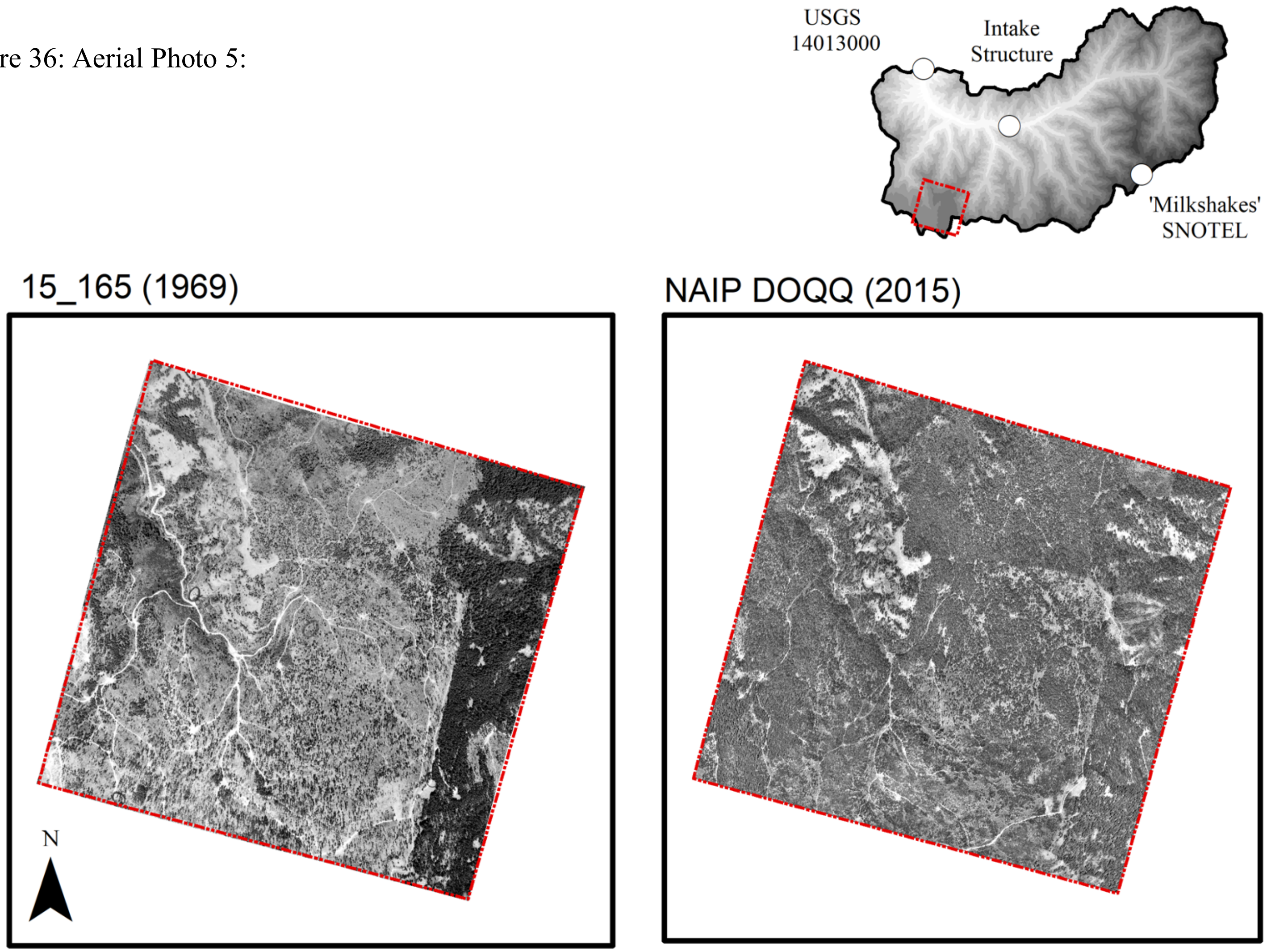


Figure 37: Aerial Photo Detail 1

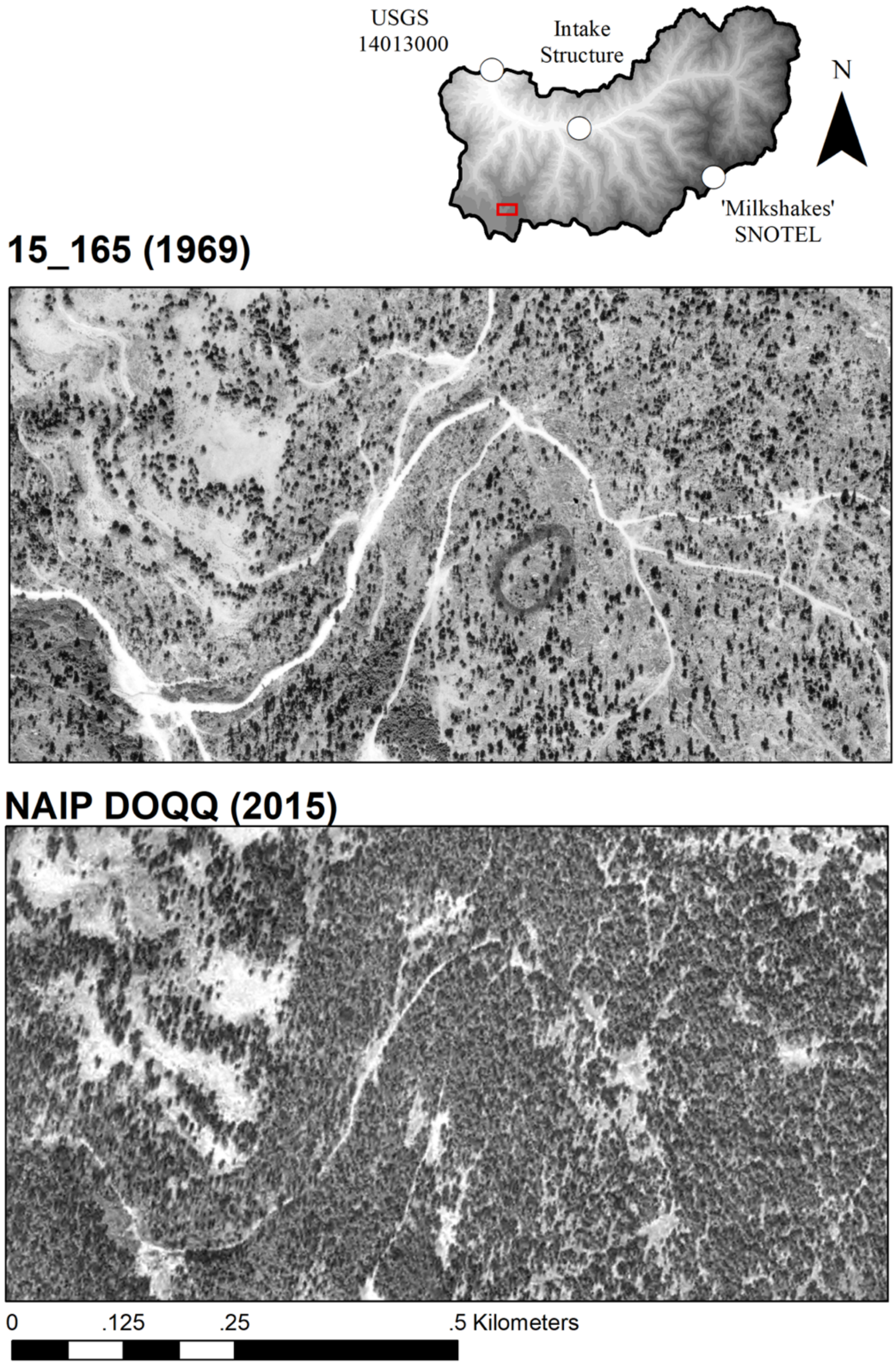


Figure 38: Aerial Photo Detail 2

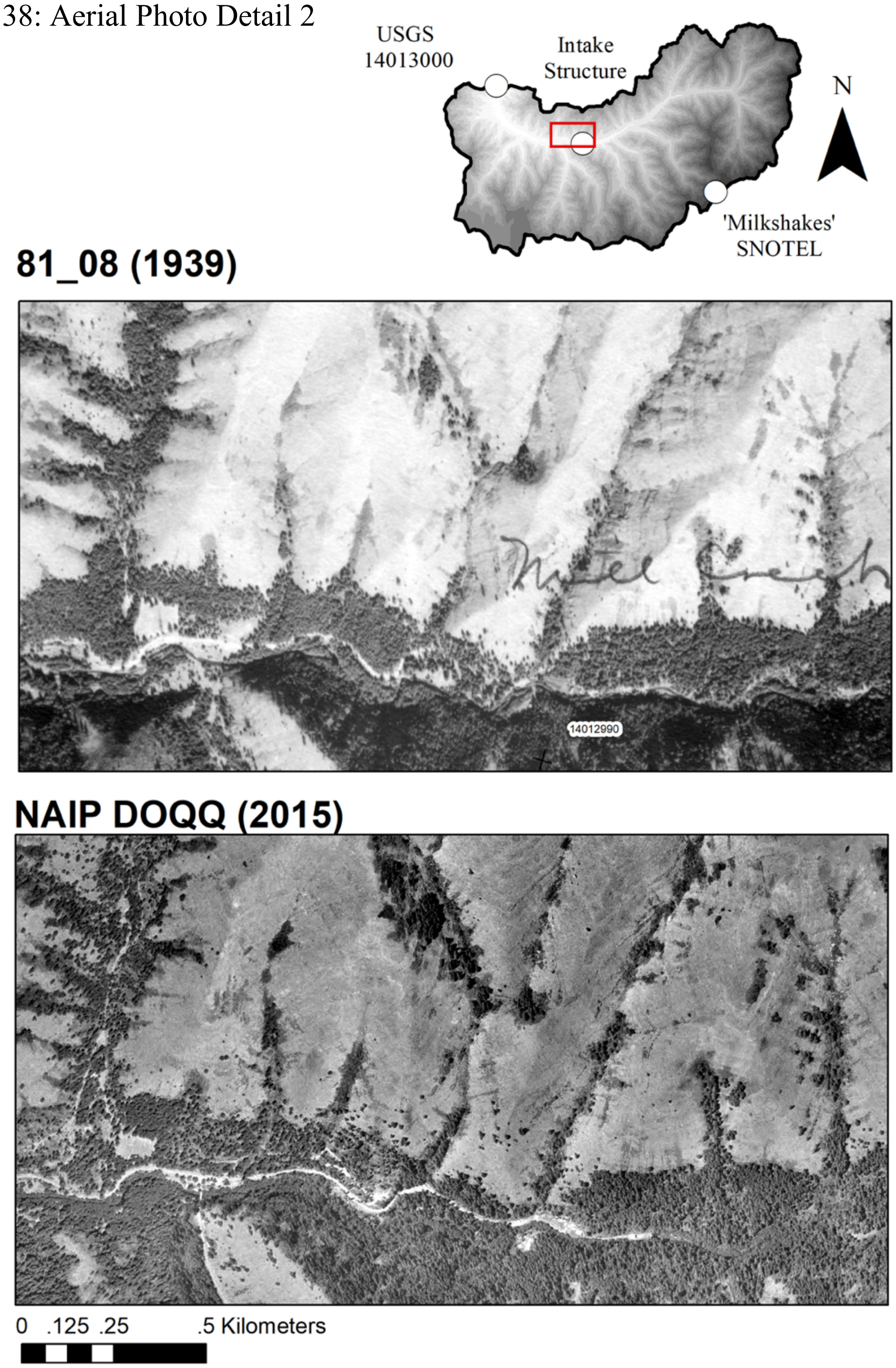


Figure 39: Aerial Photo Detail 3

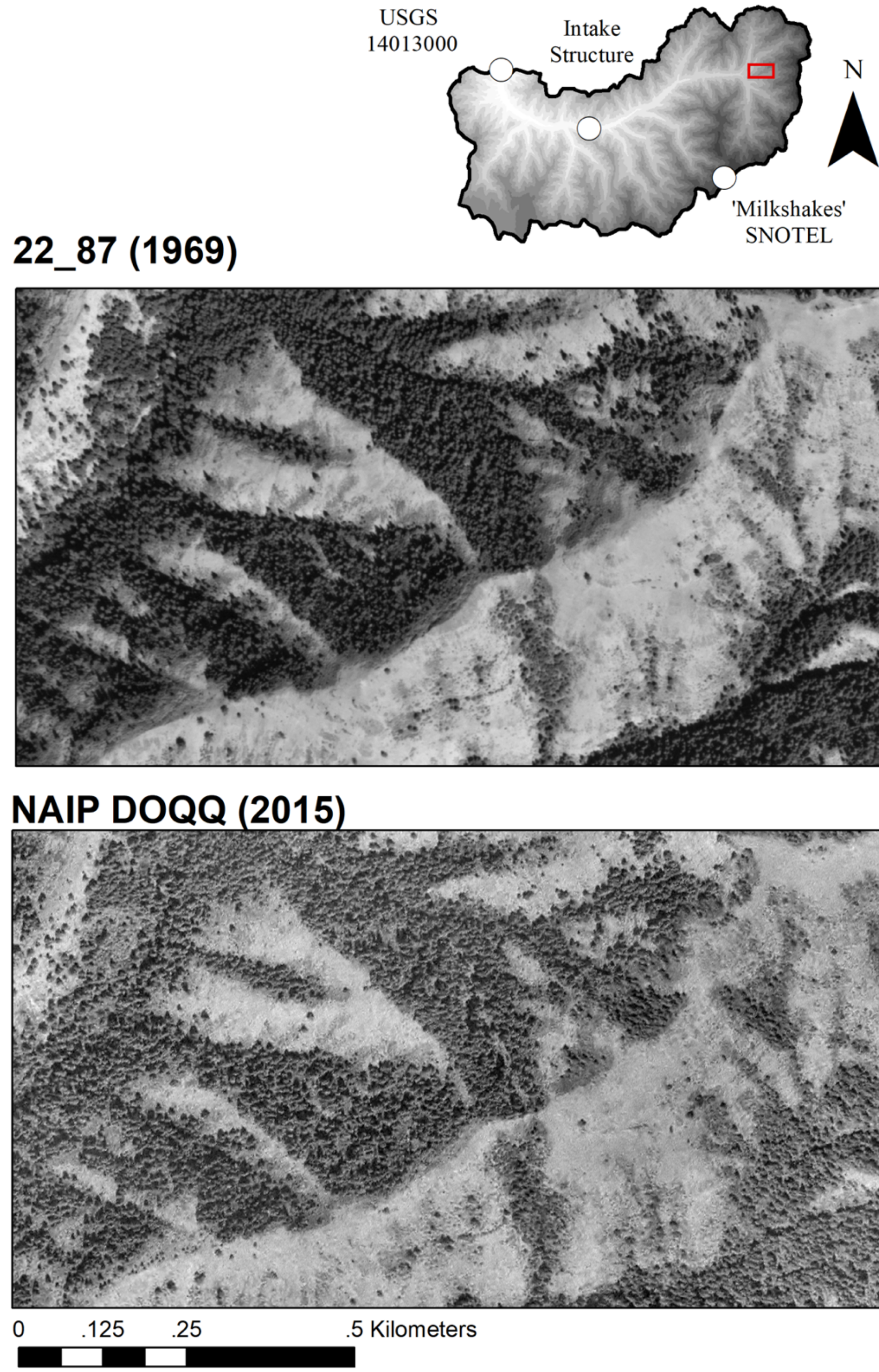
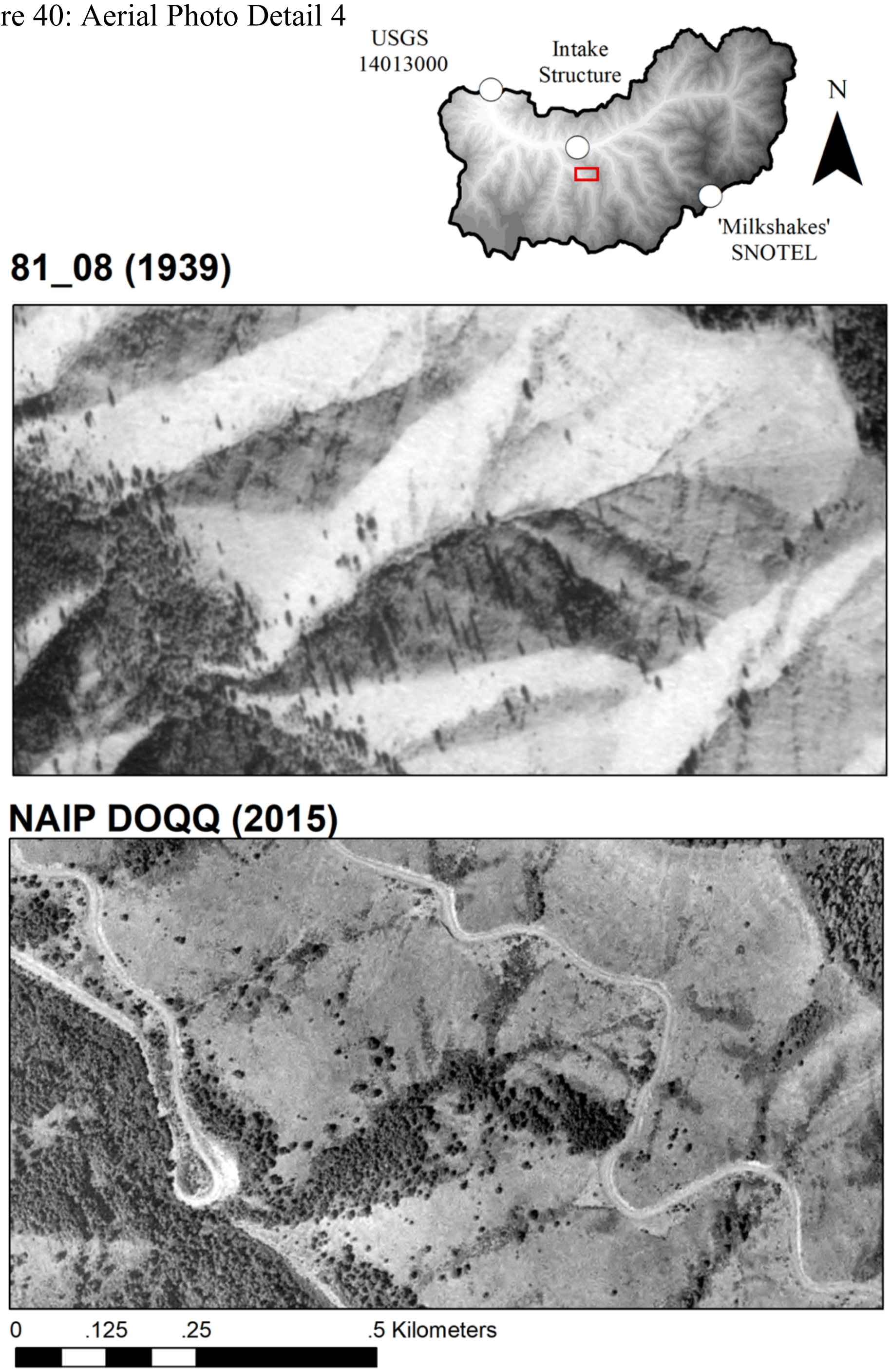


Figure 40: Aerial Photo Detail 4



TABLES:

Table 1: Minimum Flow Requirements for Walla Walla River Basin: Mill Creek Stream Management Unit (MP-1) measured at USGS 14013000.

Month	Minimum Instream Flow Reccomendation (cfs)
January	110
February	125
March	150
April	150
May	125
June	100 (Closure)
July	53 (Closure)
August	41 (Closure)
September	41 (Closure)
October	48 (Closure)
November	100 (Closure)
December	110

Table 2: Water Rights Permits and Certificates Issued to the City of Walla Walla, WA. Point of Diversion: Mill Creek. Umatilla County, OR. Tributary to the Walla Walla River. (Latitude 45.9901 longitude -118.04083)

Certificate Number	Priority Date	Max Rate (cfs)	Max Rate (MGD)	Period of Use
Oregon Permit S-54483	3/2/2001	10	6.46	11/1-4/15
Oregon Certificate: 87647	3/2/2001	10	6.46	11/1-4/16
OR Certificate: 13276 (issued 4/5/1940)	12/31/1866	28	18.10	Annual

Table 3: Period of Record, Location, and Coverage Data for Precipitation, and Temperature. GHCN = refers to the Global Historical Climatology Network- Daily Data for the NOAA Cooperative Observer Program (COOP) Network . SNOTEL = SNOwpack TELemetry Network

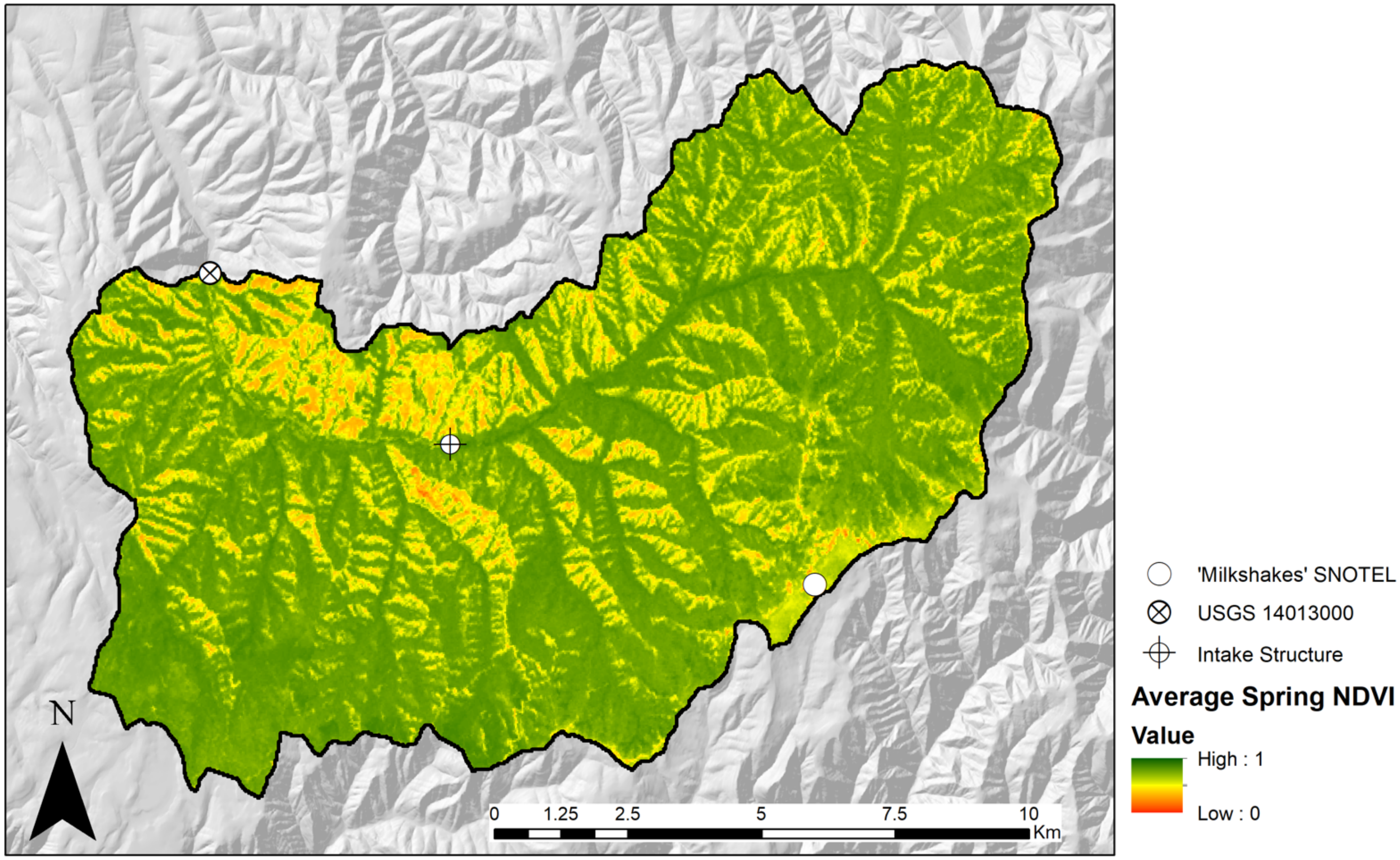
Data Provider	Site ID/Name	Lat, Lon (DD)	Elev (m)	Site Name	Start Date	End Date	Coverage
GHCN	USW00024160	46.0947, -118.2869	355.4	Walla Walla Regional Airport, WA US	01/01/49	07/13/17	95%
SNOTEL	MLKO3 (1079)	45.98194, -117.9489	1706	Milk Shakes, (OR)	10/1/07	09/30/16	100%

Table 4: Period of record, location, and coverage for Discharge and Withdrawal Data Used in Study. City of Walla Walla Public Utilities provided mean daily withdrawal rates (cfs) from Mill Creek at the Intake Structure, and observation of mean daily discharge rates (cfs) 100m below the Intake.

Data Provider	***Lat, Lon (DD)***	***Elev(m)***	***Drainage Area km²***	***Variable***	***Start***	***End***	***Coverage***	***Data Gaps***
City of Walla Walla	49.989856 - 118.049289	*850m*	89.1701	Withdrawal (cfs)	06/01/2001	12/31/2015	98%	53 zero 46 null
				Staff Gauge (ft/in)	06/01/2001	12/31/2015	100%	
				Discharge (cfs)	06/01/2001	12/31/2015	74%	1367 values "off chart"
USGS: 14013000	46.008056 -118.1175	608.3	151.9052	Discharge (cfs)	1913	1918		
					1940	1977		
					1980	2017		

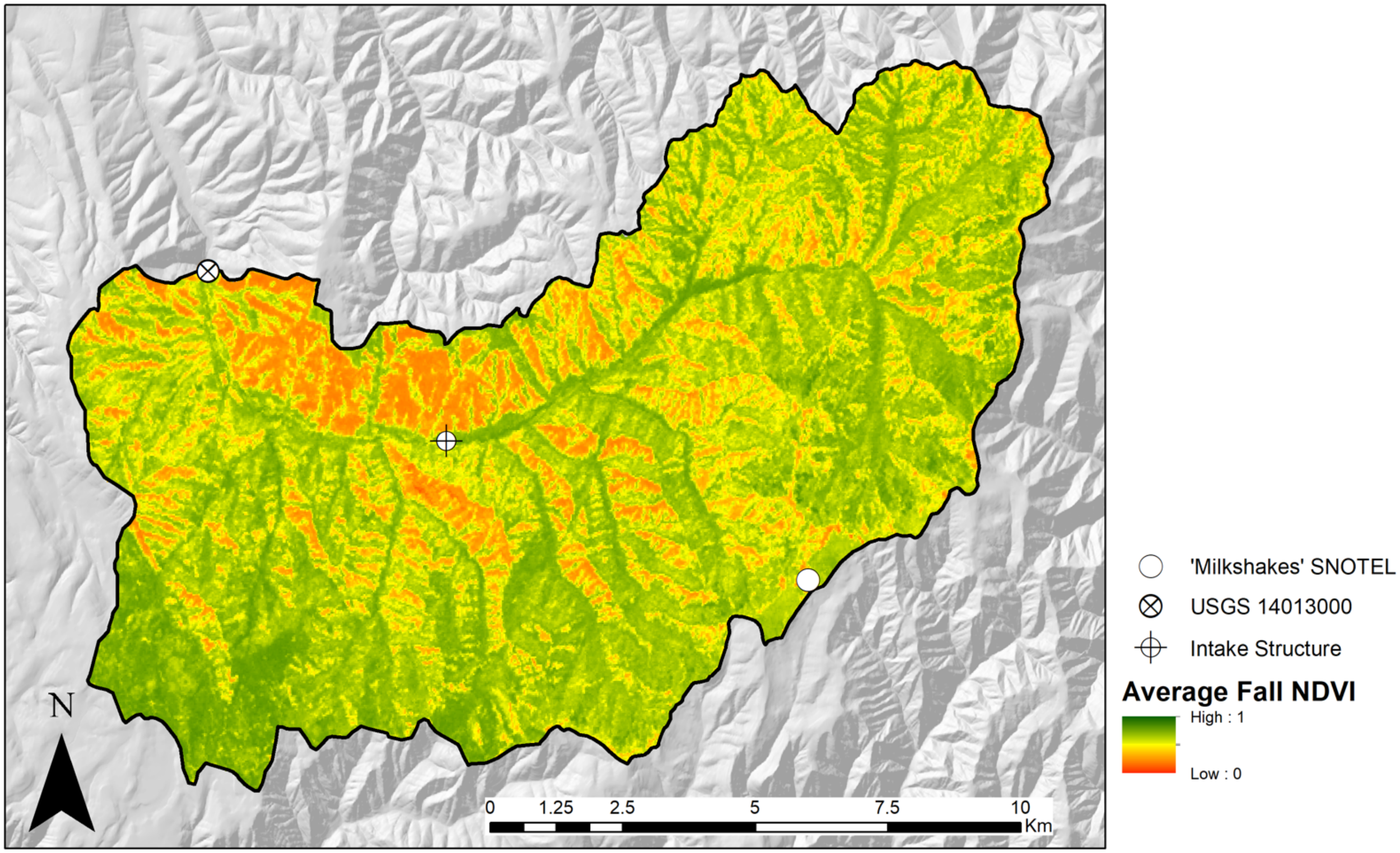
APPENDIX A: NDVI ANALYSIS OF THE UPPER MILL CREEK CATCHMENT.

Figure A1: Average Spring NDVI for All Analysis Pairs



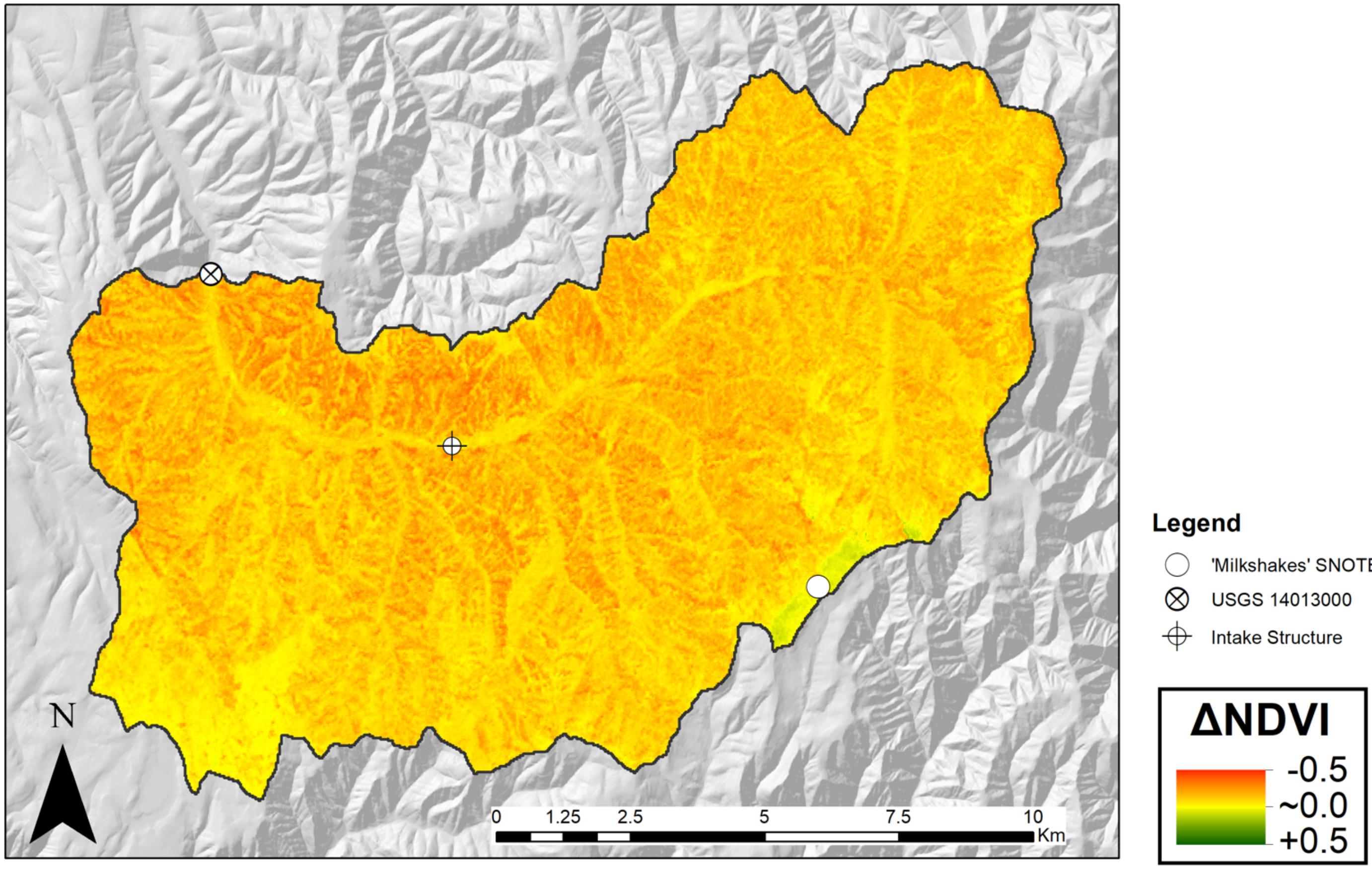
Data Source:
EROS ESPA, Tier -2 Landsat Data Products
LEDAPS Surface Reflectance derived NDVI
Projection: USGS Equal Area Conic Datum: NAD83

Figure A2: Average Fall NDVI for All Analysis Pairs



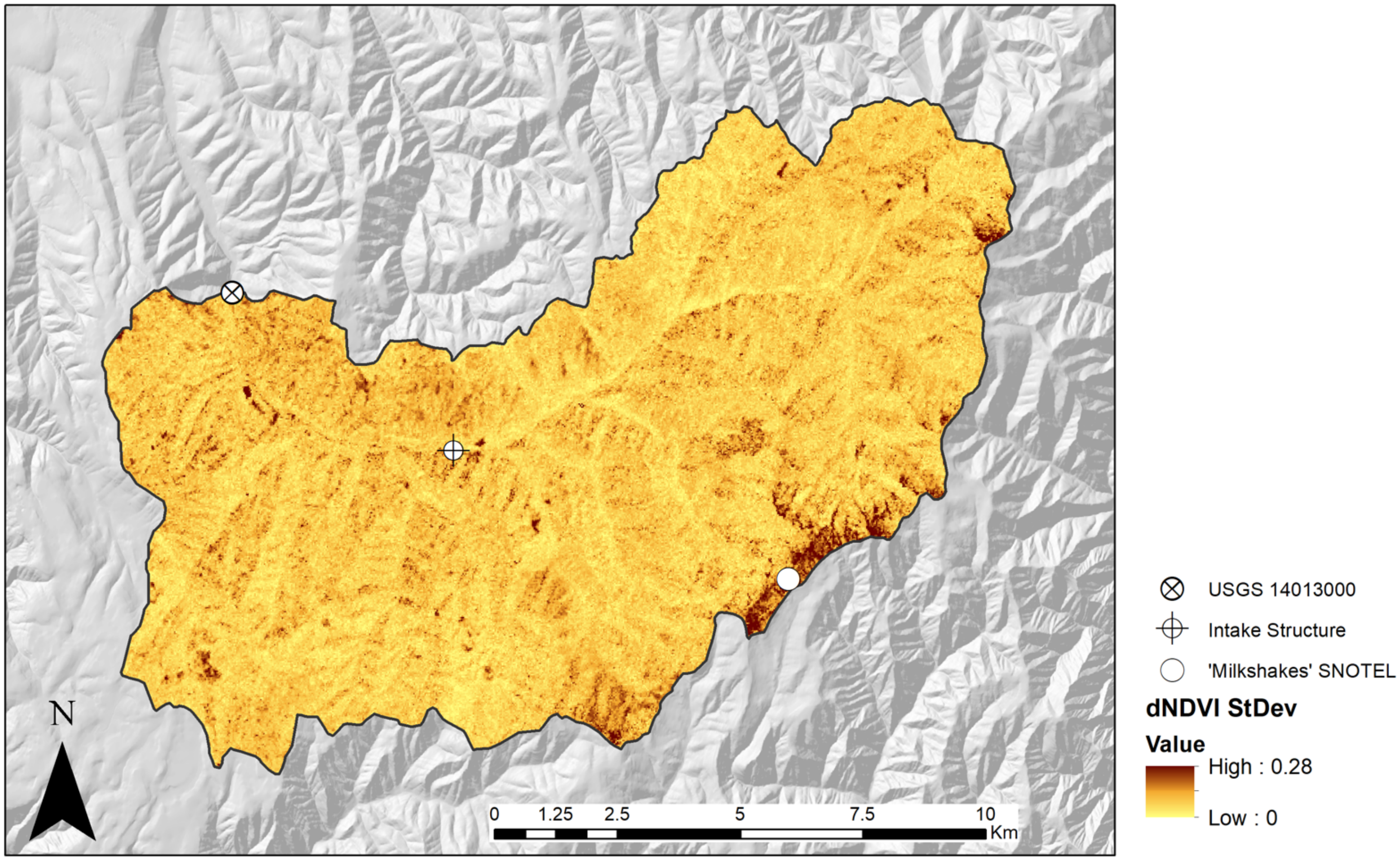
Data Source:
EROS ESPA, Tier -2 Landsat Data Products
LEDAPS Surface Reflectance derived NDVI
Projection: USGS Equal Area Conic Datum: NAD83

Figure A3: ΔNDVI for all Analysis Pairs (ΔNDVI = Spring NDVI- Fall NDVI)



Data Source:
EROS ESPA, Tier -2 Landsat Data Products
LEDAPS Surface Reflectance derived NDVI
Projection: USGS Equal Area Conic   Datum: NAD83

Figure A4: ΔNDVI for all Analysis Pairs (ΔNDVI = Spring NDVI- Fall NDVI)



Data Source:
EROS ESPA, Tier -2 Landsat Data Products
LEDAPS Surface Reflectance derived NDVI
Projection: USGS Equal Area Conic Datum: NAD83