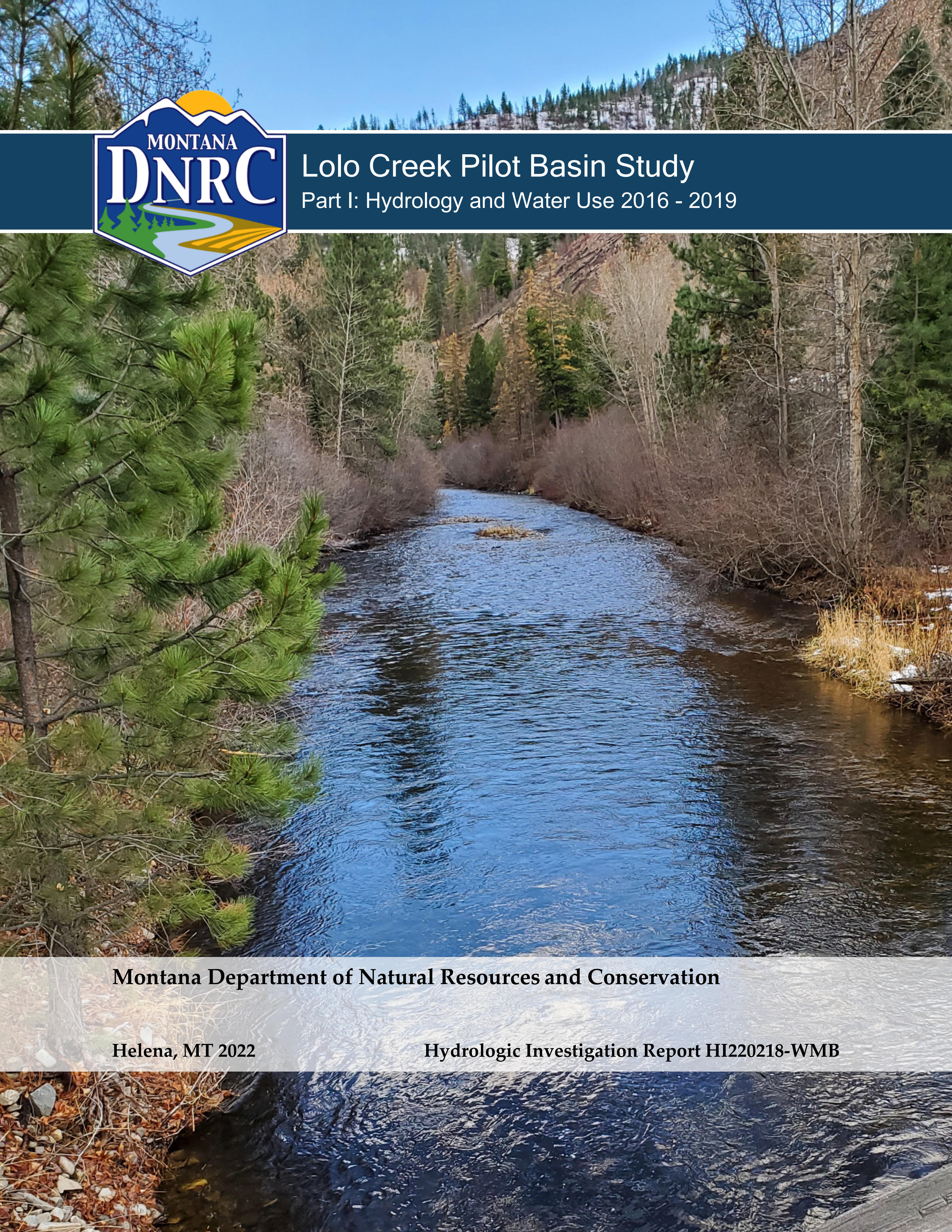

Lolo Creek Pilot Basin Study

Part I: Hydrology and Water Use 2016 - 2019

Montana Department of Natural Resources and Conservation

Helena, MT 2022

Hydrologic Investigation Report HI220218-WMB

Cover: Lolo Creek near Lolo, Montana, November 2020. Photo by Todd Blythe, MT Department of Natural Resources and Conservation.

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Part I: Hydrology and Water Use 2016 - 2019

DNRC Hydrologic Investigation Report HI220218-WMB

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February 2022

Suggested citation…

Blythe TL, Folnagy AJB, Ketchum DG, Kurth VJ. 2022. Lolo Creek Pilot Basin Study Part I: Hydrology and Water Use 2016 – 2019. Helena (MT): Montana Department of Natural Resources and Conservation, Water Management Bureau. Hydrologic Investigation Report HI220218-WMB.

Acknowledgements

We would like to express a deep appreciation for the many groups and individuals who made this project a reality. The Lolo Watershed Group was central to this project's success, their planning and coordination efforts are much appreciated. A special recognition goes to Department of Natural Resources and Conservation staff Aaron Fiaschetti and Dave Amman, both of whom were instrumental in starting this project, coordinating with landowners and stakeholders, developing a data collection plan, and collecting valuable surface water data. Thanks also to Danika Holmes for valuable input and comments on this report. We would also like to recognize Montana Bureau of Mines and Geology staff Cam Carstarphen, John Wheaton, Ali Gebril, and Ginette Abdo for their indispensable collaboration, field work, and technical groundwater support. Furthermore, thank you to Travis Ross with Missoula County Water Quality District, Jasen Neese with Lolo Water and Sewer District, and Bobbie Bartlette for your guidance, insights, and data contributions. Finally, we thank all the landowners and water users in the Lolo Watershed that participated in this project, this work would not be possible without your support and cooperation.

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Executive Summary

Water is a critical but limited resource in the western United States. The vast prairies and mountain ranges of Montana straddle the Continental Divide, draining water to both the Atlantic and Pacific Oceans. Montana is the headwaters of the Missouri River, a notable North American waterway. Major tributaries of the Columbia River Basin also originate within or pass-through the state's borders. The water in Montana's streams and aquifers is vital to the state's agriculture, recreational economy, indigenous culture, and freshwater aquatic life. It is the Montana Department of Natural Resources and Conservation's mission to "*help ensure that Montana's land and water resources provide benefits for present and future generations*." This requires informed and adaptive management of natural resources based on citizen engagement and the best available information. Managing water resources in semi-arid climates is complex and the Department of Natural Resources and Conservation must create and update a regulatory framework to distribute limited water supplies to meet multiple demands. The success of these management actions is completely dependent on understanding water quantity, where water originates, and how it moves through and across Montana's landscapes.

The Water Management Bureau, part of the Montana Department of Natural Resources and Conservation's Water Resources Division, studies Montana's hydrology, quantifies water supply, and collects information to address water resource concerns. This information helps local water management, water rights appropriation and adjudication, and compact implementation. The amount of hydrologic data created and distributed has steadily increased in recent years, particularly remotely sensed information. It is significantly easier now to obtain and use large hydrologic or meteorologic spatial datasets for modeling or water budgets. This type of data was not used or available for Water Management Bureau's past studies. Following the update of the State Water Plan in 2015, Water Management Bureau initiated a pilot project on Lolo Creek in western Montana to incorporate new methods and datasets in their water resource studies.

The purpose of the Lolo Creek Pilot Basin Study is to update Water Management Bureau's hydrologic investigation methods by incorporating new datasets, remote sensing, integrated hydrologic modeling, real-time water data, and collaboration with local stakeholders. These contemporary hydrologic data and methods, combined with existing methods developed over decades of conducting similar studies, will provide new water management tools and information. The framework developed for this Pilot Basin Study will provide a template that can be applied to future Water Management Bureau investigations in other basins. The Lolo Creek Pilot Basin Study was written as a two-part series. This report is Part I, which describes the hydrologic cycle of the Lolo Creek watershed and basin-wide water use for a four-year study period (calendar years 2016 – 2019). Existing spatial and tabular data were combined with field collected data to quantify a coupled surface-groundwater balance for the runoff component of the hydrologic cycle.

Lolo Creek was chosen for the Pilot Basin Study because it is a small to medium sized watershed with an active watershed group that raised concerns about whether water supply was sufficient to meet human and environmental needs. Lolo Creek is valued as a source of irrigation water, critical habitat for native trout, and is an important tributary of the Bitterroot River, a major agricultural and recreational basin in western Montana. In recent years, state and federal agencies, non-governmental organizations, and residents have documented a variety of water quality and flow impairments throughout the watershed. Lolo Creek has dried up, losing connection to the Bitterroot River, more frequently in the last twenty years. This has a negative impact on native fish species, including the endangered Bull Trout. Near its mouth, the creek naturally loses water to the aquifer and is diverted for irrigation use. Population growth and new development has created an increasing demand for groundwater. Lolo residents and the watershed group acknowledged that a better understanding of water supply and use was required to find solutions to Lolo Creek's flow impairments.

Summary of Key Results

Hydrology of Lolo Creek

- Temperature in the Lolo Watershed has increased since the 1980's while amount of precipitation has not changed.
- Increased temperatures have contributed to changes in precipitation type and timing, with more fall rain, sporadic winter/spring snow, and dryer summers.
- The rate of snowmelt in 2016 – 2019 was higher than the long-term average, resulting in shorter duration, higher magnitude spring floods.

Water Balance

- Approximately one-third of Lolo Creek's water supply originated from each of the following sources: the headwaters (East and West Forks), the South Fork of Lolo Creek, and other small tributaries across the watershed.
- Groundwater was significantly lower in 2016 compared to the 2016 – 2019 average conditions.
- Exported water was the greatest consumptive use in the Lolo Watershed.

Water Use and Losses

- Irrigation use accounts for the majority (53%) of all water use and losses.
- The most water use and losses occured in the Lower Lolo Valley.
- Streamflow loss from Lolo Creek to the aquifer was very high in 2016 compared to other years in the study period.

Patterns of Water Supply and Demand

- In very dry years, water demand equaled, or nearly equaled, water supply in August and September. In normal years, demand was approximately 40 – 50 percent of supply.

- Water supply in 2016 was the lowest observed in the study period and Lolo Creek annual flow was the lowest observed in 18-years of data, approximately 58% of average.
- Dewatering of Lolo Creek in August/September of 2016 was the result of normal to less-than-normal surface water diversions but higher-than-normal streamflow loss.
- Domestic and municipal groundwater withdrawals were not above average in 2016, suggesting they were not the primary cause of the higher-than-normal streamflow loss.

Recommended Actions for Water Management

Water Supply and Demand

- Develop a drought plan.
- Use "natural storage" reservoirs (such as floodplains, shallow or deep aquifers, wetlands, etc.) where practical and possible to store water that is released slowly back to Lolo Creek.
- Assess historical alteration of floodplains in the watershed and if there are water supply benefits to enhancing floodplain connection to Lolo Creek channel.
- Conduct a comprehensive feasibility study to see if beaver activity and/or beaver mimicry can have a positive effect on late summer water supply and if so, develop implementation strategies.
- Assess the feasibility of using small off-channel storage reservoirs/ponds to decrease surface water diversions during low-flows.
- Expand the Lolo Water and Sewer District service area to encompass future growth while concentrating associated municipal wells in the Bitterroot aquifer.

Water Use Administration

- DNRC – Explore the legality, consequences, and benefits of "source switching" as a solution to decreasing exported irrigation water during low flows and maintaining flow in Lolo Creek.
- DNRC – Review of current rules for permit-exempt wells (i.e., wells with a maximum use of 35 gpm not to exceed 10 acre-ft/year), promote the best practices for their use in water resource development, and encourage further study of their potential impacts to senior water right users.

Water Information

- Use data produced by DNRC's Stream Gage Program for water management, restoration projects, or early warnings on Lolo Creek.
- Consider developing an "adaptive management" framework for water distribution based on real-time flows.

- Explore opportunities for cost-sharing with DNRC to ensure the longevity of the Lolo Creek real-time stream gages.

Ecological Health and Environment

- Continue conservation work being done by local organizations.
- Continue using Montana's available laws for leasing water rights for instream flow protection.
- Continue screening diversions to mitigate fish mortality in ditches and conduct public outreach about this issue.

Collaborative Water Planning and Coordination

- Maintain the Lolo Watershed Group as a central body for agency/other organization collaboration on watershed projects.
- Continue to leverage the Lolo Watershed Group and Lolo watershe for grant funding for water and restoration projects.
- Make use of DNRC's technical and planning resources to continue educational opportunities and outreach for issues related to Lolo Creek.

Photo by Demitra Blythe

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Abbreviations, Definitions, and Conversion Factors

Units of Measure and Conversion Factors

Commonly used US Customary units and conversions

*Multiply	By	To Obtain
	Length	
mile (mi)	5,280	foot (ft)
yard (yds)	3	foot (ft)
	Area	
square mile (mi^2)	640	acre
	Volume	
cubic foot (ft^3, cu. ft.)	7.48	gallon (gal.)
acre-foot (acre-ft)	43,560	cubic feet (ft^3, cu. ft.)
	Flow Rate	
cubic foot per second (ft^3/s, cfs)	40	miner's inch
cubic foot per second (ft^3/s, cfs)	448.8	gallons per minute (gpm, gal/min)
acre-foot per day (acre-ft/day)	0.504	cubic feet per second (ft^3/s, cfs)

*Conversions can be done in reverse by dividing the unit in the right column by the middle column to obtain the left column.

US Customary units to International System of Units

*Multiply	By	To Obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.59	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3, cu. m)
	Flow Rate	
cubic foot per second (ft^3/s, cfs)	0.02832	cubic meter per second (m^3/s, cms)

*Conversions can be done in reverse by dividing the unit in the right column by the middle column to obtain the left column.

Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as: $°F = (1.8 \times °C) + 32$

Degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as: $°C = (°F - 32)/1.8$

Water Year (WY) is the 12-month period from October 1 – September 30 of the following calendar year. WY is designated by the calendar year in which it ends. Example: WY 2020 is October 1, 2019 – September 30, 2020.

Abbreviations

AE----------Application efficiency
AMSL ------Above mean sea level
BDA --------Beaver dam analog
BLS---------Below land surface
CFC---------Clark Fork Coalition
DEQ --------Montana Department of Environmental Quality
DNRC------Montana Department of Natural Resources and Conservation
ET -----------Evapotranspiration
FDC---------Flow duration curve
FLU---------Montana Department of Revenue Final Lands Unit
FWP --------Montana Department of Fish, Wildlife, & Parks
GPS ---------Global Positioning System
GWIC ------MBMG Ground Water Information Center
GWIP-------MBMG Ground Water Investigation Program
LWG--------Lolo Watershed Group
LWSD------Lolo Water and Sewer District
MBMG-----Montana Bureau of Mines and Geology
MCA -------Montana Code Annotated
MCO -------University of Montana; Montana Climate Office
MDT--------Montana Department of Transportation
METRIC---Mapping EvapoTranspiration at high Resolution with Internalized Calibration
NAIP -------National Agriculture Imagery Program
NIR ---------Net irrigation requirement
NRCS-------Natural Resources Conservation Service
NRIS--------Natural Resource Information System
PBS----------Pilot Basin Study
POD --------Point of diversion
POU --------Place of use
PWS --------Public water supply
SNOTEL---Snow Telemetry
SWE --------Snow water equivalent
TMDL------Total maximum daily load
USGS-------United States Geological Survey
VWC -------Volumetric water content
WRP--------Watershed Restoration Plan
WRS --------Montana water resource survey

Lolo Creek Pilot Basin Study

Part I: Hydrology and Water Use 2016 - 2019

Introduction

Like many streams and rivers in Montana, and the western United States (US), people and the environment rely on Lolo Creek for multiple purposes. The creek is valued as a source of irrigation water, critical habitat for native trout, and is an important tributary of the Bitterroot River, a major agricultural and recreational basin in western Montana. Human activities including historic timber harvest, road building, and recent suburban expansion have impacted the creek's geomorphology, hydrology, and water quality. In recent years, state and federal agencies, non-governmental organizations, and residents have documented a variety of water quality and flow impairments throughout the watershed.

Historically, Lolo Creek supported healthy populations of Bull Trout, Westslope Cutthroat Trout, and Mountain Whitefish. In recent decades, native trout populations have declined due to habitat alterations and proliferation of non-native species (Zelazny 2004). The most significant alteration of Lolo Creek was the construction of US Highway 12 in the 1950s. Long segments of Lolo Creek were straightened to accommodate the highway, resulting in the loss of aquatic habitat complexity. The watershed also has a long history of extensive timber harvest and related activities, much of which occurred before the inception of Montana's Streamside Management Zone law and rules (1991 and 1993, respectively; MT DNRC 2006). The effects of this include an excess of roads, stream crossings, and lack of mature trees (Zelazney 2004; Wade et al. 2016). Impairments from timber harvest can increase sediment loads in streams, decrease soil-moisture storage, and degrade the quality of aquatic habitat. Lolo Creek was recently identified as having the lowest stream connectivity in the Lolo National Forest due to the prevalence of culverts (Wade et al. 2016). Still, populations of native trout persist in the watershed, and Lolo Creek, South Fork of Lolo Creek, and Mormon Creek were designated critical habitat for Bull Trout by US Fish and Wildlife Service in 2010 (Federal Register 2010). This designation was retained in 2012 (except for segments in the Plum Creek Native Fish Habitat Conservation Plan; LWG 2013), underscoring the watershed's inherent value as a native trout fishery and the importance of ongoing monitoring efforts in the watershed.

Impairments to the water quality in the Lolo Watershed have been well documented by state and federal agencies over the last two decades (MT DEQ 2003, 2011, 2014; LWG 2013; CFC 2017). In the Montana Department of Environmental Quality's (DEQ) 2003 total maximum daily load (TMDL) assessment of the upper Lolo Watershed, the DEQ identified impairments to aquatic life and fisheries. Impairments include bank erosion from the extensive network of forest roads and traction sand applied to US Highway 12 during winter. The TMDL assessment also noted the prevalence of fish passage barriers at culvert crossings throughout the forest road network. A subsequent TMDL evaluation (MT DEQ 2011) documented substantial progress in implementing best management practices to improve fish passage and mitigate sedimentation by the US Forest Service and Montana Department of Transportation (MDT). However, the granitic parent material in the upper watershed region forms easily erodible soils, and activities that compromise bank stability (e.g., bank armoring or removal of riparian vegetation) continue to promote erosion and sedimentation throughout the watershed.

The most notable impairment is dewatering of the lower reach of Lolo Creek from the community of Lolo to the mouth. Dewatering is common in low flow years, raising concerns about water supply, water use, and fish passage (Zelazny 2004; MT FWP 2005; MT DEQ 2014). Montana Fish, Wildlife & Parks (FWP) identified the lower three miles of the creek as chronically dewatered, meaning it is considered a significant problem for the fishery in virtually all years (MT FWP 2005). Flow intermittency occurs throughout this reach during late summer baseflow conditions. While dewatering was recorded as early as the mid-20th century, events were reported more frequently over the last 20 years (e.g., 2007, 2012, 2013), with the most recent occurring in 2016. Some infiltration is natural in this area because of the influence of the Bitterroot Aquifer, porous alluvial geology (Sullivan 2003; Zelazny 2004), and fractured shallow bedrock (Oruba 2017), but withdrawals for domestic, municipal, and irrigation water use likely contribute to streamflow loss.

Concerns about the creek's impairments grew over the years, which led to a grassroots effort to restore water quality and address dewatering. The Lolo Watershed Group (LWG) formed in 2003 in response to the mounting concerns about the health of the creek's trout fisheries (Zelazny 2004). The group's mission is to "understand and conserve the unique characteristics of the Lolo Creek watershed, including its wildlife and fisheries, scenic and rural character, local agriculture, and recreational opportunities while supporting private property and water rights." The group conducts a variety of monitoring, restoration, and outreach activities. LWG and DEQ developed a watershed restoration plan (WRP) to mitigate impairments identified in the TMDLs (LWG 2013). The WRP provides detailed descriptions of the existing impairments and a comprehensive list of recommendations for addressing them, including real-time streamflow and temperature monitoring, groundwater monitoring, and development of a drought management plan. Similarly, the Missoula-based Clark Fork Coalition (CFC) identified restoration priorities on Lolo Creek as part of its Bitterroot Strategy (CFC 2017) and has collaborated with LWG, local landowners, and other entities such as Trout Unlimited and the Lolo National Forest to implement projects that enhance flow connectivity and reduce sediment supply.

Motivated by the obvious and potential impacts of dewatering, LWG successfully advocated for a comprehensive water resource investigation by Montana Department of Natural Resources and Conservation (DNRC). The goal of this investigation was to better understand the hydrology, water use, and future risks to water supply for the entire watershed. In 2016, LWG successfully nominated Lolo Creek for a Montana Bureau of Mines and Geology (MBMG) Ground Water Investigation Program (GWIP) study. The GWIP study goal was to develop a detailed groundwater model to quantify the mechanisms of dewatering in the lower reaches of Lolo Creek. The similar timing and goals of the DNRC and MBMG investigations allowed the two agencies to work cooperatively on data collection and monitoring. The DNRC hydrologic investigation will serve as a Pilot Basin Study (PBS) for a new State-wide series of water resources investigations to characterize the hydrology and water use of small to mid-sized Montana watersheds. The GWIP study will provide a detailed analysis of what factors (e.g., water use, climatic patterns, Lolo Aquifer-Bitterroot Aquifer interaction, etc.) influence Lolo Creek streamflow losses near the community of Lolo. Collectively, these studies will provide both broad and targeted information that will enhance our understanding of the watershed's complex hydrology.

The methods and techniques used in this PBS vary in complexity, purpose, and limitations. Therefore, the Lolo Creek PBS was written as a two-part series. This report is Part I of the two-part Lolo Creek PBS. The purpose of the PBS is to update DNRC's hydrologic investigation methods by incorporating new meteorological datasets, satellite based hydrologic information, integrated hydrologic modeling, real-time (telemetered) water data, and collaboration with local stakeholders. These contemporary hydrologic data and methods, combined with existing DNRC methods developed over decades of conducting similar studies, will provide new water management tools and information. The framework developed for the PBS will provide a template that can be applied to future DNRC investigations in different basins. For Part I of the PBS, we described the hydrologic cycle of the Lolo Creek watershed and basin-wide water use for our four-year study period (calendar years 2016 – 2019). We used existing data with collected data to quantify a coupled surface-groundwater balance for the runoff component of the hydrologic cycle. Water use and losses were analyzed in the context of low flow years and dewatering events. Part II of the PBS will focus on modeling a water balance for the entire hydrologic cycle, analyzing long-term trends and climactic patterns, and applying various water supply scenarios for management consideration. The data and analyses from the Lolo Creek PBS will aid in implementing the LWG WRP and future water management or water rights administration.

Study Area

The Lolo Creek watershed encompasses an area of 273 mi^2 in the

Bitterroot Mountain range in western Montana (Fig. 1). Lolo Creek flows approximately thirty miles from its headwaters near the Idaho-Montana border to its confluence with the Bitterroot River. The creek begins upstream of Lolo Hot Springs where the West Fork and East Fork of Lolo Creek flow together. Other small tributaries of the West and East Forks include Lee Creek and Lost Park Creek. The upper and middle segments of the creek flow primarily through a narrow, high-gradient canyon, lacking a frequently connected floodplain. Occasional widening of the canyon creates semi-confined alluvial valleys with more developed floodplains and wetlands. The upper portion of Lolo Creek accumulates flow from small tributaries including Granite Creek, Howard Creek, and Graves Creek. The middle segment includes the South Fork of Lolo Creek, the largest tributary, which flows into Lolo Creek downstream of Bear Creek. The South Fork contributes a significant amount of streamflow to Lolo Creek and includes other small tributaries such as West Butte Creek and Dick Creek. Just downstream from the mouth of the South Fork, Mill Creek contributes additional flow. The lower segment of Lolo Creek begins where the stream exits the mountains via a narrow constriction referred to as the pinch point by Carstarphen et al. (2016). The Lower Lolo Valley begins downstream of this constriction and continues to the confluence of Lolo Creek and the Bitterroot River. West of the community of Lolo, the Lower Valley widens into the Bitterroot Valley and Lolo Creek flows across an alluvial fan. The creek has a much lower stream gradient through the Lower Valley and incorporates two small tributaries, Mormon and Sleeman Creeks. Mormon and Sleeman Creeks are intermittent, primarily flowing during spring runoff. The Lower Valley is where interactions with groundwater complicate the hydrology of Lolo Creek and where dewatering events occur.

The Lolo Creek watershed is primarily mountainous, steep terrain, with an average slope of 37%. This type of landscape can create sporadic localized weather where precipitation and temperature vary considerably based on elevation and aspect. The variation in temperature and precipitation relative to elevation is particularly important for water supply. The median elevation of the Lolo Creek watershed is 5,109 ft above mean sea level (AMSL; Fig. 2a) with 50% of the watershed area 4,000 - 6,200 ft AMSL (Fig. 2b). Snow accumulation is common from November to April throughout the watershed and may continue into May or June at the highest elevations around Lolo Peak.

The most prevalent land cover type in the watershed is evergreen forest, with portions of shrub, grassland, and barren rock. Small quantities of agricultural land and wetlands exist in valley bottoms. All developed land exists around the community of Lolo and is small relative to the entire watershed. The land cover type is an important characteristic of the watershed and determines how much water infiltrates into the ground versus how much immediately

Figure 1. Map showing the Lolo Creek watershed, relevant geographic landmarks, and labeled hydrography. The study area encompasses the entire watershed area as well as parts outside the topographic divide including the town of Lolo and certain irrigated lands (see Figure 3).

becomes surface flow. The Lolo Watershed is subject to large wildfires that alter land cover and runoff dynamics. The most recent and largest recorded wildfire in the watershed occurred in 2017. This wildfire burned approximately eighty-four square miles (not all the burned area was in the Lolo Watershed) in the middle and lower segments, upstream from the mouth of the South Fork to just upstream of the lower valley. Another recent wildfire occurred in 2013 and burned approximately seventeen square miles along US Highway 12 in the middle segment of the watershed.

The most upstream surface water diversions in the watershed are on the South Fork and the mainstem just downstream from Bear Creek. There are not many diversions on Lolo Creek and all points of diversion are primarily between the mouth of the South Fork and the confluence with the Bitterroot River. Diverted water is used primarily for irrigating grass hay and pasture. Irrigated fields within the watershed are adjacent the floodplain, however, the largest acreage of irrigated land lies outside the topographic boundary of the Lolo Creek watershed. Lolo Creek water used to irrigate these lands is exported from the watershed and any return flows go to smaller drainages south of Lolo Creek or directly to the Bitterroot River. In total, there is approximately 1,050 acres of agricultural land currently irrigated with Lolo Creek water, 47% of which is outside the watershed.

The community of Lolo has a Water and Sewer District (LWSD, Missoula County RSID #901) that services residents within the immediate city limits via three municipal, public water supply (PWS) wells and gravity storage tanks. One of the LWSD wells withdraws water west of Lolo within the Lolo Watershed. The other two LWSD wells are northeast of Lolo on the Bitterroot River floodplain. Other PWS (outside of the LWSD service area) and individual wells are prevalent in the Lower Valley and the dominant source of domestic water use in the watershed. While the community of Lolo is small, continued growth in the Bitterroot and Missoula Valleys has contributed to a steadily increasing population and demand for groundwater.

Our study area included the entire Lolo Creek drainage area, defined by topographic divides, such that all water flows to a single outlet. The watershed was delineated using a 10 m (~30 ft) digital elevation model to determine flow directions

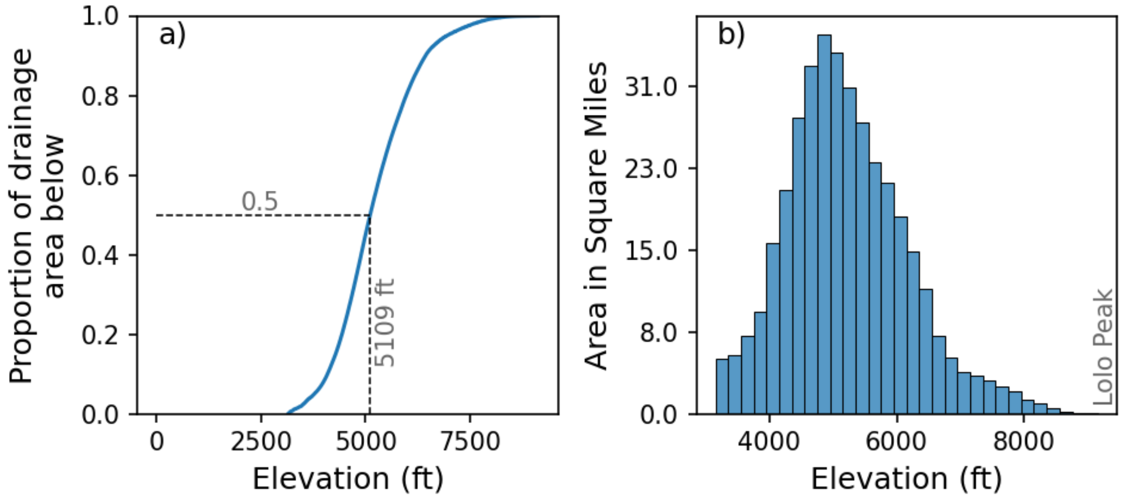


Figure 2. Graphs showing (a) the cumulative distribution of elevation in the Lolo Creek watershed (i.e., the proportion, or percent, of the land area below a given elevation) and (b) a histogram of elevation displaying the actual area, in square miles, between 200-foot contour intervals. Lolo Peak is labeled as the highest point in (b) with an elevation of 9,137 ft MSL.

that converge at the confluence of Lolo Creek and the Bitterroot River. Water that enters the topographic boundary via precipitation moves across the landscape as surface or groundwater flow to the outflow point or is removed by other means, such as evaporation or exported for consumptive uses. Within the study area streamflow gaging sites were used to subset the watershed into smaller regions where additional data were collected and categorized. Additionally, some irrigated lands outside of the watershed were included in the study area for targeted analysis.

Hydrogeology

The geology in the Lolo Creek basin includes alluvium in the valley bottoms and mountainous terrain composed of Belt Supergroup and Idaho Batholith granite and grano-diorite. From the community of Lolo to Lolo Hot Springs (refer to Fig. 1), the valley floor is made up of unconsolidated alluvium whose width and thickness varies with valley confinement. The principal aquifers of the Lolo Creek watershed occur in basin-fill alluvial deposits and the fractured bedrock of the Belt Supergroup (Smith et al. 2013). Unconsolidated alluvium forms a nearly continuous unconfined basin-fill aquifer within 10 – 50 ft below land surface (BLS). Basin fill aquifers at depths greater than 50 ft are composed of coarse-grained deposits with multiple, discontinuous layers of low permeability silt and clay. Locally, these lenses of silt and clay could confine water-bearing sand and gravel, affecting groundwater gradients and flow paths (Oruba 2017). Rocks from the Belt Supergroup have sufficient fracture permeability to form a bedrock aquifer that yields water to wells. Cross-sections constructed by MBMG around the community of Lolo showed the Belt Supergroup overlain by Tertiary and Quaternary basin-fill (Chambers 2016). Depth to bedrock in these cross sections varied between 100 and 150 ft BLS.

The steep slopes surrounding the Lolo Creek valley are made up of Belt Supergroup. Higher in the watershed, beginning near Lolo Hot Springs and encompassing the headwaters, the mountains and hillslopes are composed of Idaho Batholith members. The Idaho Batholith makes up approximately 25% of the surficial geology mapped in the basin. Lolo Creek flows over several faults that influence groundwater flow, and possibly surface water flow (Lewis 1998). A synoptic run conducted by DNRC in the Lower Lolo Valley showed that between the head of the valley and Sleeman Creek, where a fault has been mapped, Lolo Creek lost 16.6 cfs. Whether this loss of water was related to the fault, thickening basin fill, or recharge to the shallow aquifer is unknown. In the Lower Lolo Creek valley, the streambed is composed of coarser grained channel deposits and hydraulic gradient increases (Chambers 2016). The geology and hydraulic gradient of lower Lolo Creek appear to be the controlling factors of streamflow loss to the shallow unconfined aquifer and will be addressed in more detail by MBMG's GWIP study.

Recharge to the basin-fill aquifer is mostly from infiltration of precipitation and losses from Lolo Creek and its tributaries.

Secondary recharge in the middle and lower segments of Lolo Creek comes from irrigation water that percolates through fields or seeps from canals and ditches. In upper and middle segments of Lolo Creek, groundwater from the basin-fill aquifer discharges to springs and seeps along the valley bottom. Groundwater discharges directly to Lolo Creek in most of the upper and middle valleys.

Previous Work

Previous hydrologic work in the Lolo Creek basin focused primarily on groundwater. Boer (2002) constructed a numerical groundwater model of the Lower Lolo Valley to examine contaminate (nitrates) transport. This work included a 3.3-hour aquifer test that was used to generate a mean transmissivity of 23,000 ft^2/day and mean hydraulic conductivity of 400 ft/day. Land and Water (1996) generated a transmissivity value of 34,677 ft^2/day from a 24-hour aquifer test conducted on LWSD PWS #3 (Groundwater Information Center (GWIC) # 149678). The calculated groundwater flux through the Lolo Creek area near the community of Lolo was estimated to be 20-30 cfs with a mean gradient of 0.005 (Boer 2002). LaFave (2006A) developed a potentiometric map for the shallow aquifer and bedrock aquifer in the Lolo area. LaFave (2006B) sampled wells in the Lolo Creek watershed and constructed water quality parameter maps for the area. Waren and Patton (2007) generated maps with groundwater statistics related to well depth, well density, type of wells, hydrographs, and generalized geology. Smith et al. (2013) conducted a regional study to describe the aquifers and summarize their data collection results. Chambers (2016) identified gaining and losing reaches in the Lower Lolo Valley using temperature, radon, and incremental streamflow to estimate groundwater/surface-water flux. The incremental streamflow data showed gains for some reaches and losses for others, resulting in a net loss of streamflow. They also determined that while some reaches show net loss of streamflow, higher radon measurements suggest that there are locations where groundwater was discharging to Lolo Creek in the lower valley. Oruba (2017) used geophysical surveys to show that the shallow bedrock and a subsurface fault downstream of US Highway 93 could contribute to dewatering of the Lolo Creek during low flow periods in the late summer. While this collective work highlights the complex interaction between Lolo Creek and its aquifers near the town of Lolo, there has been no comprehensive quantification of water supply, water use, and hydrologic processes. The intent of this report is to fill this information gap for Lolo Creek and incorporate previous work to supplement our findings.

Methods of Data Collection and Analysis

Streamflow Measurement

The history of stream gaging on Lolo Creek extends as far back as the early 20th century. The US Geological Survey (USGS) operated two stream gages on lower Lolo Creek that have since been discontinued. The first USGS gage, Lolo Creek near Lolo, MT

Table 1. Information for stream gages used in the Lolo Creek PBS.

Stream Gage Name	Managing Agency	Station ID	Gage Type	Latitude (Degrees)	Longitude (Degrees)	Period of Record
Lolo Creek below Highway 93	DNRC	76HB 09600	real-time	46.74931	-114.08205	2015-10-15 to Present
Lolo Creek below Sleeman Creek	DNRC	76HB 09550	non-real-time	46.76054	-114.29728	2016-05-14 to 2016-11-10
Lolo Creek above Sleeman Creek near Lolo, MT	USGS	12352000	real-time	46.74411	-114.14343	1950-11-01 to 1960-09-29
Lolo Creek above Sleeman Creek	DNRC	76HB 09500	real-time	46.74296	-114.15476	2016-08-12 to Present
Lolo Creek near Lolo, MT	USGS	12351500	real-time	46.75415	-114.22006	1911-04-25 to 1915-03-31
South Fork Lolo Creek at Mouth	DNRC	76HB 05800	non-real-time	46.76190	-114.26463	2016-06-01 to 2019-12-04
South Fork Lolo Creek below West Butte Creek	DNRC	76HB 05500	non-real-time	46.75295	-114.28772	2016-06-12 to Present
Lolo Creek below Bear Creek	DNRC	76HB 03000	non-real-time	46.76054	-114.29728	2016-06-01 to 2019-12-04
Graves Creek at Highway 12	DNRC	76HB 02800	non-real-time	46.78245	-114.39817	2016-06-01 to 2019-11-21
Lolo Creek at Dodson (MDT)	DNRC	76HB 01500	non-real-time	46.75137	-114.51150	2016-07-06 to 2020-01-07
Lolo Creek below Granite Creek	DNRC	76HB 01000	non-real-time	46.73351	-114.52857	2015-11-03 to Present

(12351500), was located just downstream from the mouth of Mill Creek and operated from 1911 to 1915. The second USGS gage, Lolo Creek above Sleeman Creek near Lolo, MT (12352000), was located approximately three river-miles downstream from USGS gage 12351500, in the mouth of the canyon where the lower valley begins. The gage above Sleeman Creek was operated from 1950 to 1960. No streamflow records for Lolo Creek exist from 1960 until around 2008, when the CFC began monitoring streamflow at select gage sites. One of the CFC's gage sites was in the vicinity of the historic USGS gaging locations while the rest were concentrated around the community of Lolo and US Highway 93. While historic streamflow data is useful for the objectives of this study, it did not cover the geographic extent necessary.

To collect the necessary streamflow data for this study, we installed a network of nine stream gages throughout the Lolo Creek watershed. Geographic locations for the stream gages are shown in Figure 3, and additional details for each site are provided in Table 1. Stream gage locations were identified through field reconnaissance, discussions with landowners/residents, and review of previous hydrologic/water quality studies and reports. Seven of the gages were small diameter stilling wells designed to be installed within the water column. The stilling wells consisted of a six to eight foot long, 3/8 in angle iron driven into the streambed, a 1.5 - 2 in diameter PVC pipe with locking cap, and a 3.3 ft staff gage. Water height, or stage, was measured at thirty minute intervals using a TruTrack WT-HR 1000 capacitance-type water level logger installed in the stilling well. We installed real-time (telemetered) stream gages at two of the historic sites. The most upstream real-time site was located several hundred yards downstream of Mormon Peak Bridge, which is located between the former USGS gages and just downstream of the CFC site at Fort Fizzle. The downstream real-time site was installed at the US Highway 93 bridge, which replaced an existing CFC gage site. Real-time gages measure stage every fifteen minutes and transmit the data via satellite to DNRC data servers. DNRC hydrologists use the stage data to calculate stream discharge and then distribute that data to the public. Real-time gages were outfitted with a Sutron Accubar Constant Flow Bubbler and a Satlink 2 data collector/transmitter installed in a permanent instrument panel. Staff gages at the real-time gage locations were installed in the stream as a vertical staff gage or on the bank as a cantilever with wire weight.

We visited each stream gage site every four to six weeks at which point a DNRC hydrologist made a manual discharge measurement and stage reading. Maintenance needs were also addressed during field visits. Data from non-real-time sites were manually downloaded each field visit. Discharge measurements were made using Sontek FlowTracker1® or FlowTracker2® flow meters following standard USGS methodology (Turnipseed and Sauer 2010 and others) and DNRC standard operating procedures. When flows in Lolo Creek were too high to wade safely, high flow measurements were made using bridge equipment or a Sontek River Surveyor acoustic-Doppler current profiler. Rating curves, or mathematical relations between manually measured stage and discharge from field visits, were developed using the Aquatic Informatics Aquarius® Rating Curve Development program. A rating curve is unique to each stream gage location and was used to calculate continuous discharge from the 15-min (for real-time gages) or 30-min (non-real-time gages) water height data. Select gages were operated during winter months (Table 1) and required significant data correction because of icing. DNRC hydrologists corrected winter flow data, following established protocols, to remove anomalies in the streamflow data caused by icing.

We surveyed the real-time gages and the non-real-time gage at the Dodson (MDT) site, into a local datum using a Sokkia Automatic Level and stadia rod. Elevation benchmarks were established or occupied near gage sites to serve as stable references. Benchmarks consisted of re-bar or pins in the ground located away from trails, roads, or areas where they might be disturbed. Benchmarks were surveyed using a Trimble

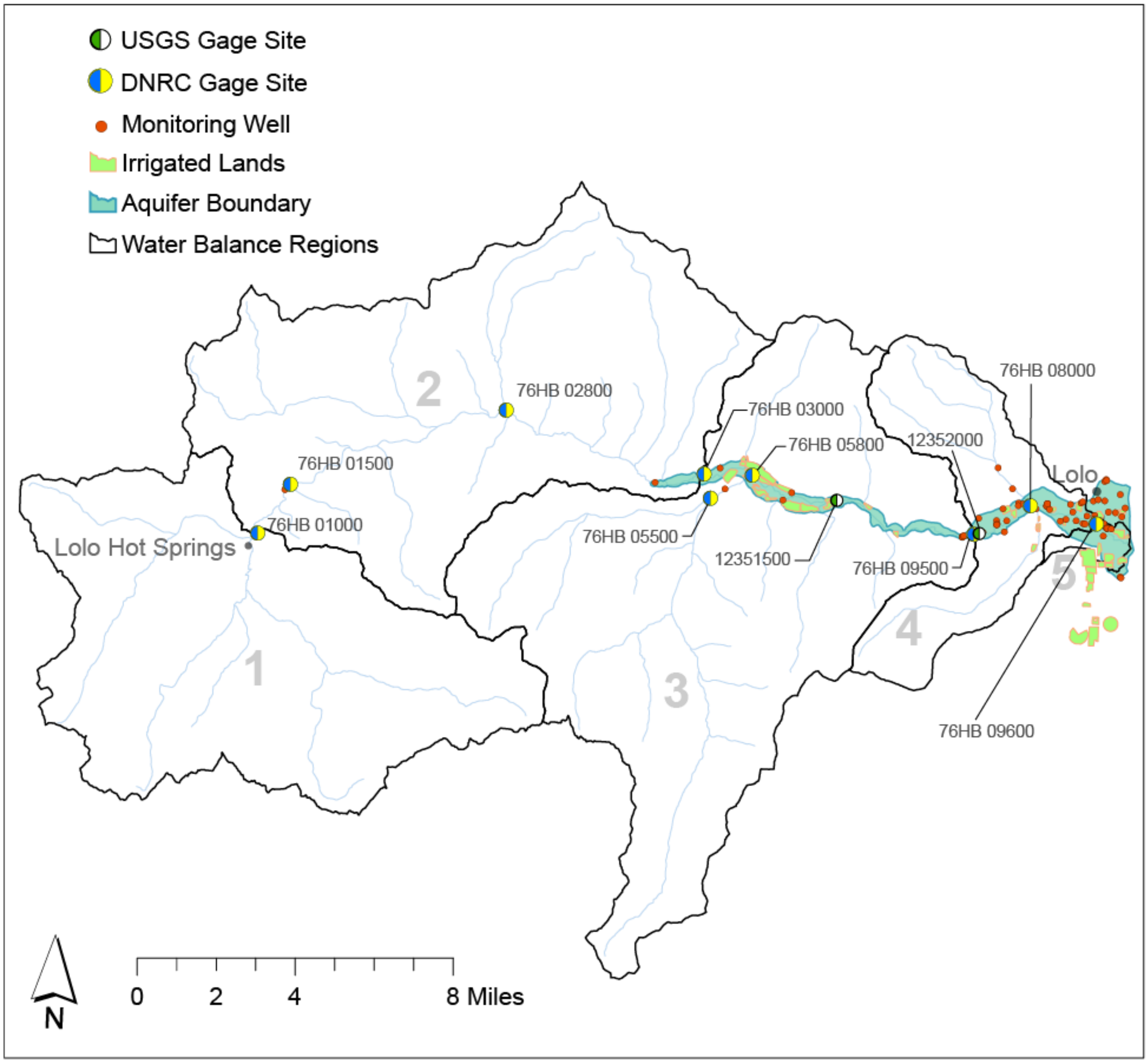


Figure 3. Map of all monitoring/data collection sites used for this study. Other relevant spatial datasets are also shown including Water Balance Regions used in the water balance, irrigated lands (at the time of this study) and the extent of the unconfined-shallow aquifer used for the groundwater balance. The aquifer boundary in Water Balance Region 4 and 5 approximate the extent of the Lower Lolo Valley.

Geo 7X GPS with Zephyr 2 antenna and local datums were translated into real-world coordinates and elevations. Elevation data were collected for the Dodson (MDT) non-real-time gage only because of associated groundwater measurements that required real elevations for calculations or comparison. Survey data allows DNRC hydrologists to check for elevation changes in bubbler lines, stilling wells, and staff gages that would cause inaccurate data if not corrected for.

Groundwater Measurement

Groundwater data collection was a collaborative effort between DNRC and MBMG. MBMG established 73 measurement wells and piezometers concentrated in the lower valley portion of the watershed in or around the community of Lolo. MBMG instrumented 26 of the wells to collect hourly water level, DNRC instrumented an additional 9 wells for sub-hourly readings, and the remaining 38 wells were measured monthly using an electronic tape meter. DNRC's monitoring wells were strategically located near stream gage sites or upstream of the Lower Lolo Valley to extend MBMG's monitoring network higher in the drainage. Wells and piezometers in the groundwater monitoring network had variable periods of record (Fig. A5 and Table A1 in *Appendix A*). Wells consisted of a mixture of dedicated monitoring wells that were drilled by MBMG as well as existing private and PWS wells identified through public outreach. All data for the groundwater monitoring wells can be accessed from MBMG's GWIC.

We installed 8 Solinst® electronic pressure transducers and 1 OTT® Pressure Level Sensor in 7 wells and 2 piezometers that collected water level data at 10-min intervals if the well was near one of the LWSD wells, and 30-min intervals at the other locations. MBMG installed In-Situ Level Troll ® electronic pressure transducers at 26 sites that collected hourly data. All 73 wells were measured manually once a month by MBMG, DNRC, or Missoula Valley Water Quality District staff using an electronic water level meter. Depth was measured from a consistent measurement point marked on the well casing and recorded with an uncertainty of 0.01 ft. The elevation of the marked measurement point was surveyed using the same equipment and methodology as the stream gage benchmarks so that water table depths could be translated into real elevations AMSL.

The absolute pressures collected by electronic transducers include the hydrostatic pressure of the water as well as the barometric pressure of the atmosphere. Select wells fitted with electronic transducers included a second transducer that was suspended above the water to collect barometric pressure, at the same time interval. The absolute pressures were converted to gage pressures by subtracting the barometric pressures for each time increment. Water levels were also calculated from gage pressures using the In-Situ Baro-merge® software or the barometric compensation tool in the Solinst® Data Wizard, which allows for additional correction to water depth based on temperature and density of the water. Water levels were converted to depths-to-water using the reference point on the well casing and subsequently converted to groundwater elevations using the surveyed top-of-casing elevation data accessed from MBMG's GWIC (http://mbmggwic.mtech.edu/).

Shallow, hand driven piezometers were installed near the surface water monitoring sites along the stream bank of Lolo Creek. Chambers (2016) installed 4 piezometers relevant to their study objectives. We installed 2 piezometers in the Lolo Creek watershed that were measured in conjunction with DNRC stream gages at Dodson (MDT) and below Highway 93. The purpose of these piezometers was to collect temperature and water level data for examining thermal profiles, vertical gradients, and differences between surface water and groundwater hydrographs that describe surface-groundwater interactions. Water level measurements were measured using an electronic water level meter and measuring points were surveyed using the same procedures described previously. Continual recording (30-min interval) pressure transducers were installed in the shallow piezometers.

DNRC and MBMG coordinated five synoptic measurements on Lolo Creek in the fall of 2015 and spring/summer of 2016. Synoptic measurements are a series of longitudinal (progressively downstream) discharge measurements on the mainstem, tributaries, and active diversions over a short span of time (usually 24-hours or less). This method provides a snapshot of the hydrology in time and, for this study, was used to estimate reaches of Lolo Creek that gain flow from groundwater or lose flow to the aquifer. The synoptic measurements occurred over different lengths of stream and had varying measurement locations between measurements such that there is a significant amount of uncertainty in the results. Figure 4

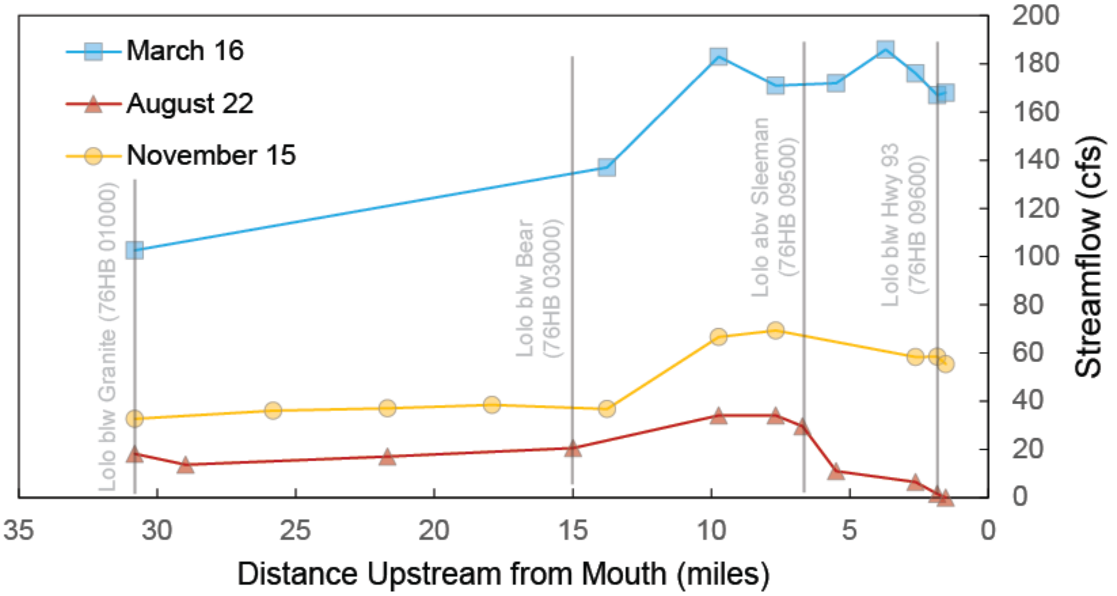


Figure 4. Graph showing mainstem synoptic survey measurements (tributaries and diversions not shown here) for 3 complete synoptic surveys of Lolo Creek in March, August, and November of 2016. Measurements are plotted at the linear distance along the stream beginning at the upstream most gage and ending approximately 1 mile from the mouth of the creek (longitudinal profile). The August 22 survey was completed during a dewatering event.

Table 2. Summary of metrics used for calculating domestic and lawn and garden irrigation water use.

Source	Total Households	Households in Watershed	Average Lawn Size (acres)
Municipal, LWSD	1208	121	0.19
Domestic, PWS	342	208	0.46
Individual Well	513	513	0.49

LWSD per household use	232 gallons per day
LWSD per capita use[1]	100.4 gallons per day
USGS Montana per capita use[2]	106 gallons per day

[1]Based on 2.31 persons per household (US Census Bureau 2019).

[2]From *Estimated Use of Water in the United States in 2015* (Dieter et al. 2018), included for comparison only.

provides a visual summary of the results of the three most complete synoptic surveys of

Lolo Creek. For this study, two synoptic measurements were taken outside of irrigation season, so ditch measurements were not necessary. If small un-gaged tributaries were too low to measure accurately, their discharge was estimated. For measurements during irrigation season, discharge was recorded using the flume on active ditches, leakage at the headgate and any flows returned back to the creek were noted.

The well measurements and synoptic measurements were used to calculate a basic groundwater balance for the portion of Lolo Creek below the South Fork of Lolo Creek from June 2016 to August 2018. This was combined with the surface water balance to estimate the volume of streamflow that is derived from groundwater or that recharges the aquifer (see Water Balance methods below for more details).

Domestic and Municipal Use

Domestic water in the Lolo Creek watershed can be described by source and purpose of use. We categorized two primary sources of domestic water in the Lolo Watershed: 1) PWS and 2) individual wells. The two primary purposes of use were used in this study including: 1) indoor household use and 2) outdoor use, or lawn and garden irrigation. Municipal use is defined as the use of water by a municipality or unincorporated town. Municipal use can have many purposes other than household needs including fire suppression, dust abatement, irrigation, commercial, industrial, or mining. Water withdrawn or diverted for municipal use is distributed to a service area by a water and sewer district. For Lolo, water pumped and consumed by the LWSD was classified as municipal use. Domestic use was not directly measured, so we used a variety of data sources and methods to extrapolate data from the LWSD to the domestic sources in the watershed.

The LWSD is serviced by three municipal PWS wells that pump water to three gravity storage tanks (a 125,000 gal tank and two 500,000 gal tanks) from which water is distributed (LWS 2010). We acquired water use data from LWSD which consisted of monthly pumping volumes from each of the three wells and the number of service connections to the system per year. The water use data provided by LWSD did not include estimated system loss or leakage, which may inflate use estimates from the dataset. We assumed that pumping occurred at the same rate that the storage tanks were emptied such that the pumped volume was representative of actual use and not just withdrawal of water for future use. We also assumed that the number of service connections per year was equal to the number of households serviced by LWSD, such that the per household use could be calculated with this dataset. The per household use within the LWSD service area was used to estimate domestic use for the Lolo Watershed. We did not use the estimated lawn and garden irrigation volume derived from LWSD data to extrapolate outdoor use for the two domestic sources because we recognized that the size of lawns may differ. Therefore, we conducted a spatial analysis of irrigated lawn size within the LWSD and the two domestic sources. Estimated municipal, lawn and garden irrigation in the LWSD was used to calculate a net irrigation requirement (NIR). The acreage of irrigated lawn and garden was converted to withdrawal and consumed volumes using the NIR for lawns in the Lolo Watershed and an assumed sprinkler efficiency. For a more detailed explanation on quantifying indoor and outdoor household water use, as well as assumptions made, see section A3.0 in *Appendix A.*

We used a simple method of seasonal averaging to separate LWSD municipal use data into indoor and outdoor uses. Visual inspection of the data showed a nearly constant volume of water delivered to the service area for the months January, February, March, November, and December, which coincided with the times of the year with negligible outdoor water use. For each year of LWSD data, we took the average water volume for these non-irrigation months and used it as a constant volume for the remainder of the irrigation months (April, May, June, July, August, and September) of the same year to produce monthly household water use for the years 1990 – 2018. The proportion of outdoor water use was estimated by calculating the excess volume of water delivered, or the difference between the original, monthly LWSD data and the estimated, monthly indoor water use. The monthly indoor water use data was divided by the number of LWSD connections for each year to determine the indoor water demand per household. We assumed that indoor water demand per household did not differ between LWSD and the domestic sources. With this assumption, the total water withdrawal for indoor use (domestic or municipal) was the number of households multiplied by the monthly indoor water demand per household. The number of households was determined using the Montana structures dataset from the Natural Resource Information System (NRIS; https://nris.msl.mt.gov/) of the Montana State Library's GIS resources (Table 2). The amount of water consumed (i.e., not returned to the system via drains, plumbing, and water treatment) was calculated as 5% of the withdrawal amount for LWSD municipal use and 10% of the withdrawal amount for domestic use (MT DNRC 2018).

To accurately estimate lawn and garden irrigation, we analyzed LWSD data to calculate the water used per acre of lawn within the service area and adopted the same value for domestic sources. Irrigated lawn acreage was delineated for households in the LWSD service area and the two domestic sources. We used National Agriculture Imagery Program (NAIP) color and inferred imagery, Montana State Library's parcel boundary dataset (https://geoinfo.msl.mt.gov/msdi/cadastral), the LWSD service area boundary, and GWIC well location data for the lawn size analysis. Using the Montana Cadastral parcel data, we isolated only parcels that contained single family homes by removing large tracts of federal and private lands greater than 50 acres. This resulted in 1,923 parcels that could have potential lawn and garden irrigation. Rather than delineating lawn and garden acreage for nearly 2,000 parcels, we considered the 1,923 parcels a finite population and used Equations 1 and 2 below (Cochran 1963) to determine a representative sample size.

$$n_0 = \frac{Z^2 p(1-p)}{e^2} \qquad \{Eq.1\}$$

In Equation 1, n_0 is the sample size of a large population of unknown size. Z is the Z-score that determines the confidence interval and in this case is equal to 1.96 (for a confidence interval of 95%). p represents the proportion of the mapped parcels that have irrigated lawn acreage. We used $p = 0.5$ or 50% which is a conservative estimate. e is the desired precision, we chose $\pm 5\%$ or $e = 0.05$. Because we had a finite population, n_0 was adjusted using Equation 2 with a known population size of $N = 1{,}923$ parcels.

$$n = \frac{n_0}{1 + \frac{n_0 - 1}{N}} \qquad \{Eq.2\}$$

The representative sample size (n) of 1,923 parcels, from Equation 2, was equal to 320. We randomly selected 320 parcels from the 1,923 and determined the source of supply by geographic location. If the parcel was within the LWSD service area it was assigned to that source. The DEQ Water Systems Database (MT DEQ 2019) indicated seven domestic PWS wells outside of the LWSD service area. Data from DEQ, GWIC, Montana Cadastral, and DNRC water rights were cross-referenced to estimate the service area of each domestic PWS well. If a parcel was within one of the non-LWSD PWS service areas, it was assigned to the PWS domestic source. The remaining parcels were assigned to the individual well domestic source. Irrigated lawns (if present) were delineated for each of the 320 parcels using NAIP color and color infrared imagery for the years 2009, 2011, 2013, 2015 at a scale of 1:2000. We then grouped delineated lawns by source water and calculated the average lawn and garden acreage in each group (Table 2).

To estimate the amount of water consumed by outdoor use we used the LWSD monthly outdoor use data, the average lawn and garden acreage for the LWSD service area, and an efficiency coefficient. An application efficiency (AE) coefficient determines the performance of an irrigation system without needing conveyance losses in the system nor crop consumption. AE is the ability of an irrigation system to distribute a target amount of water and has been estimated for most irrigation practices. With some simple assumptions, AE can be used to estimate the volume of water consumed by lawn irrigation (Burt et al. 1997). For this study, we assumed that the amount of water used for lawn and garden irrigation within the LWSD service area was representative of the entire watershed, and that the only difference in lawn and garden irrigation among households was the size of the lawn irrigated. The LWSD outdoor use volume estimates were converted to a NIR for one acre of lawn, using Equation 3.

$$d_{NIR\,(i,j)} = \frac{V_{t\,(i,j)}^{\,LWSD}\ e_a}{\bar{A}_{LWSD}} \qquad \{Eq. 3\}$$

In Equation 3, (V_t^{LWSD}) is the fraction of the LWSD withdrawal volume that was used for lawn and garden irrigation, (e_a) is the AE coefficient of lawn sprinklers, ($\bar{A}_{LWSD}$) is the average size of lawns in the LWSD service area, and (d_{NIR}) is the NIR as a depth per acre of lawn. We used an AE of $e_a = 0.7$, or 70%, based on accepted lawn sprinkler application efficiency coefficients (Rogers et al. 1997, MT DNRC 2008, Sandoval-Solis et al. 2013). The subscript (i) refers to the month, and the subscript (j) to the year, during the study period. The NIR is the total water requirement of the grass (or garden) minus precipitation. Without any additional information on lawn irrigation in the watershed, we assumed that the withdrawal volume used for lawn and garden irrigation, V_t^{LWSD}, was sufficient to supply 100% of the NIR and any losses in the sprinkler system. If NIR is 100% satisfied, d_{NIR} is equal to the amount of water consumed by the grass through evapotranspiration (V_C) divided by the average LWSD lawn acreage. We used Equation 4 with these assumptions to estimate the volume of water withdrawn for lawn and garden irrigation (V_t^S), from any household source (S).

$$V_{t_{(i,j)}}^{S} = \frac{d_{NIR\,(i,j)}\ \bar{A}_S\ N_{S\,(,j)}}{e_a} \qquad \{Eq. 4\}$$

$\bar{A}_S$ is the average lawn size in acres for a domestic source (S) from Table 2; d_{NIR} is the NIR calculated previously as monthly values using Equation 3, and N_S is the number of households serviced by a domestic source (S) for an area of interest. For this study, V_C is equal to the numerator of Equation 4, such that $V_C = V_t \times e_a$. By applying these methods, we were able to use LWSD municipal data to estimate outdoor use domestic sources while maintaining monthly temporal resolution. There are a series of important assumptions that accompany these methods, which are discussed in Section A3.3, *Appendix A*.

Diversions and Ditch Seepage

Diversion rates were measured for the four major irrigation ditches in the Lolo Creek watershed: 1) the McClay Ditch, 2) Holt Canal, 3) OZ Lolo Ditch, and 4) OZ South Fork Ditch. All but one ditch had flumes for measuring diversion rates. We collected diversion data using the same methodology as the non-real-time stream gages, using a water level logger and a relationship between water level and discharge. Flumes are engineered as a fixed structure with a rating curve specific to the dimensions; therefore, in ditches with flumes, water level measured by the logger was correlated with the stage in the flume to get continuous discharge. Discharge was measured manually to check accuracy of the flumes and develop ratings where there was not a flume or measurement device. The four continuously measured ditches are the largest in the watershed, however, there are smaller ditches that were not measured directly for this study. The diversion amounts that were not measured directly were estimated using remotely sensed evapotranspiration (ET) data, as described later in the methods section. Synoptic measurements, using the same methods discussed previously in the groundwater section, were employed on two diversions on the OZ Lolo Trail Ranch (OZ Lolo and OZ South Fork Ditches) to estimate seepage (see Tables A3 – A6 in *Appendix A*). Similar measurements were not taken on the Holt Ditch and DNRC was not granted permission to access and measure the McClay ditch, so we used seepage data from the OZ Ranch ditches to estimate seepage for the other two ditches. This entailed developing a proportionality equation that compared characteristics (i.e., ditch length, hydraulic conductivity, and diversion rate) between a ditch with synoptic measurements and one without. Ditches were chosen for comparison based on common soil types, as mapped by the Natural Resources Conservation Service (NRCS), and the known characteristics of the ditch without synoptic measurements were used to estimate the unknown seepage loss. A more in-depth description of diversion measurements and how seepage was estimated is outlined in Section A4.1 of *Appendix A*.

Several sources of seepage loss data are available in the Lolo Watershed. The most pertinent are the 1976 Soil Conservation Service Salvage Report (USDA 1976) for county wide data on irrigation requirements, supply, efficiency, and losses. While this information is useful as a reference, it aggregates all agriculture in Missoula County, which may not be representative of specific irrigation systems in the Lolo Creek watershed. The synoptic surveys were used instead of county-wide values because they were specific to irrigation in the Lolo Creek watershed. While it would have been better to collect more measurements throughout the irrigation season to describe any monthly fluctuations in seepage, this was beyond the scope of the project. Seepage between the two synoptic measurements for both ditches were similar, so we used the average of the two measurements as a constant seepage percentage throughout the irrigation season.

Boer (2002) provided a specific synoptic measurement of the McClay Ditch as well as an estimate of its conductivity, using a shallow piezometer. Their results showed a hydraulic conductivity $K = 4$ ft/day and a total loss of 2.2 cfs over approximately 0.95 miles of ditch length. A hydraulic conductivity of 4 ft/day is very close to 3.96 ft/day, which is the upper end of hydraulic conductivities listed for the dominant soil type that the McClay Ditch flows through. The 4 ft/day from Boer (2002) was used because it was a measured, published value. The dominant soil type of the OZ Lolo ditch was the same as the McClay ditch, so we assumed the hydraulic conductivity for these two ditches was the same. No hydraulic conductivity information was known about the OZ South Fork Ditch or the Holt Canal, so we used a basic groundwater flow equation to develop a proportionality equation (see Equations A10 – A11 in *Appendix A*) to calculate the unknown hydraulic conductivity of the OZ South Fork Ditch. Because the soil types were identical between the OZ South Fork Ditch and the Holt Canal, the same hydraulic conductivity was applied to both. The calculated hydraulic conductivity value for the OZ South Fork Ditch was also within the range of hydraulic conductivities listed by the NRCS soils data. Attributes of the four irrigation ditches relevant to seepage are summarized in Table 3.

Irrigation Water Use

Methods to estimate crop irrigation requirements and crop ET are numerous and vary widely in both computational and input data requirements. For Lolo Creek, we found mapping ET at high resolution with internalized calibration (METRIC; Allen 2007) to be well suited to the geographic scope of the study area and to the available geospatial, meteorological, and satellite data. METRIC uses optical and thermal satellite images, and ground-based meteorology data to calculate the residual of the energy balance at the Earth’s surface. The residual surface energy is assumed to be ‘lost’ in the evaporation of

Table 3. Ditch and canal seepage information.

Ditch/Canal	Dominant Soil[1]	Hydraulic Conductivity (ft/day)	Seepage	Length of ditch/canal evaluated (ft)
OZ South Fork	Moiese Gravelly Loam	2.92	36.9%	3,722
OZ Lolo	Bigarm Gravelly Loam	4.00	79.1%	9,090
Holt	Moiese Gravelly Loam	2.92	47%	8,565
McClay	Bigarm Gravelly Loam	4.00	22%	17,300

[1] Based on USDA Web Soil Survey

water from bare soil and transpiration by plant tissue (i.e., latent heat of vaporization), and is converted to an estimate of ET in depth of water. METRIC ET estimates are constrained by a weather-based reference ET (ET_r), a calculation of the atmospheric water vapor demand established as accurate and dependable. By using high resolution Landsat data, this image-processing approach allows us to map ET continuously over space, and periodically through time to reconstruct the time-integrated consumption of water by crops. We applied this algorithm to the Lolo Watershed study area for the years 2014 - 2019. For additional details about the METRIC method and its application to this study see Section A4.2 in *Appendix A*.

We began our analysis by delineating agricultural fields irrigated with Lolo Creek water, following a similar procedure as mapping irrigated lawn and garden acreage (see methods on lawn and garden irrigation use and Section A3.2 in *Appendix A*). Delineations were done at a scale of 1:6000 using Montana Water Resource Survey (WRS) data (Montana State Engineer's Office 1962), Montana Department of Revenue Final Lands Unit (FLU) data (available through the MT State Library https://mslservices.mt.gov/geographic_information/data/datalist/datalist_Details.aspx?did=%7B4754A734-303D-4920-8CAA-F027D5F3EE58%7D), and NAIP imagery. The WRS and FLU data provided an initial template of the geographic extent of irrigated fields and after finalizing the boundary of each field, they were checked against multiple years of NAIP imagery (2009, 2011, and 2013) to determine if irrigation was present or not present. If a field was identified as sub-irrigated, this counted as no irrigation present. Each field with irrigation present was assigned an irrigation type from a list of common irrigation systems in Montana (e.g., center pivot sprinkler, wheel line sprinkler, several types of flood, etc.; Administrative Rules of Montana 36.12.115 – Water Use Standards). We estimated crop type using a 2011 cropland dataset from the National Agricultural Statistics Service (USDA 2011) and estimated the source of irrigation water via analysis of aerial imagery and WRS maps. All irrigated fields and their attributes were accounted for as accurately as possible given the available datasets and maps; fields that were visible from public roadways were verified visually in the field.

To apply the METRIC method to the delineated fields, we collected and processed the required satellite and ground-based data for the Lolo Creek watershed. We used data from the Landsat Program, a series of Earth-observing satellite missions jointly operated by USGS and the National Aeronautics and Space Administration that collect optical and thermal data at a regular frequency. We acquired thumbnail images of all Landsat 7 (Enhanced Thematic Mapper; ETM+) and Landsat 8 (Optical Land Imager/Thermal Infrared Sensor; OLI/TIRS) overpasses of the Lolo Creek watershed from 2014 - 2019. These Landsat missions follow a nearly identical path over the Earth in a sun-synchronous orbit described by the World Reference

System 2, a USGS coordinate system labeling image path and row locations for each Landsat image capture area. The Lolo Creek watershed falls within path 41, rows 27 and 28. Each satellite passes over each path/row location every 16 days and are spaced such that they acquired an image over our study area every 8 days during the study period. Not every image is usable, however, because clouds and smoke obscure the optical and thermal signal from the surface. Obscured images must be masked or excluded from the analysis to prevent erroneous ET estimates. We selected usable images through visual inspection. We found 20 to 34 usable images over the study area for each year of the study period (see Table A8 in *Appendix A*).

Meteorology data for this study was acquired from the GridMET archive (Gridded Meteorology; Abatzoglou 2013), a gridded dataset consisting of 30+ years of daily 4 km resolution meteorology variables. GridMET combines the temporally high resolution North American Land Data Assimilation System Phase 2 (NLDAS-2; Mitchell et al. 2004) dataset with the spatial resolution of the Parameter-elevation Regressions on Independent Slopes Model (PRISM; Daly et al. 2008) to produce a high resolution, continuous daily dataset. We used precipitation, minimum and maximum temperature, and reference evapotranspiration (ET_r) from GridMET. ET_r is simply the rate of evapotranspiration from a reference alfalfa crop at a height of 0.5 m (1.64 ft) that is healthy and actively growing. ET_r varies based on local meteorological conditions. GridMET is known to provide ET_r estimates that are biased in agricultural areas. To find the GridMET bias, we compared the gridded data to the Montana Climate Office's (MCO) Mesonet meteorology observations near the town of Lolo (lololowr; https://mco.cfc.umt.edu/mesonet_data/) for the 2018 growing season. We found that the Mesonet-based ET_r was 49% less than the GridMET estimate at that location (see Figure A17 in *Appendix A*). We corrected the GridMET data uniformly over the grid to maintain the continuous spatial coverage of GridMET while incorporating the local accuracy of Mesonet.

We calibrated and applied the METRIC algorithm to the irrigated fields in the Lolo Creek watershed to obtain an estimate of total ET for each field in millimeters per day (converted to feet per day). The cumulative sum of all daily ET values was calculated to produce the total monthly ET for each field. The total ET includes all the water consumed by the crops, derived from both rainfall and irrigation. For this study, we were concerned with the volume of irrigation water that was consumed by the crops. We used a standard equation (see Equation A14 in *Appendix A*) from the National Engineering Handbook to estimate the portion of total ET from rainfall, referred to as the effective precipitation (NRCS 1997). Crop consumption from irrigation water (CU) is the difference between total ET and effective precipitation (P_e), as shown in Equation 5.

$$CU = ET - P_e \qquad \{Eq. 5\}$$

Crop consumption was multiplied by the area of each irrigated field to calculate the monthly volume consumed by irrigation.

Water Balance

The water balance for this study consisted of quantifying the fate of streamflow, or runoff. Runoff is the volume of water left-over from precipitation that flows out of the watershed via stream channels. Part II of this study will discuss the total, landscape water balance (including precipitation, soil moisture, total evapotranspiration, etc.) in more detail. We calculated the streamflow-specific water balance for Lolo Creek by splitting the basin into five Water Balance Regions, hereafter referred to as Regions (Fig. 3). Separate water budgets were completed for Regions 2-4 and aggregated into a basin-wide budget. We applied the governing water balance equation (Equation 6), to both surface water and groundwater inflows and outflows. Equation 6 was used with Equation 7 to calculate shallow aquifer storage within the groundwater balance. All inflow and outflow data were lumped into one of the Regions based on their geographic location, except irrigated fields, which were included in the Region from which the irrigation water was diverted. The interaction between the groundwater and surface water balances was calibrated using the synoptic measurement data on Lolo Creek. The combined groundwater, surface water balances were used to complete a comprehensive water budget for the basin for monthly time steps at the spatial resolution of individual water balance regions.

Each Region was determined by the location of stream gaging stations. A complete water balance was calculated for regions that had an upstream and downstream gage (at a minimum). Region 1 represents the headwaters of Lolo Creek, there was no inflow data for this region because the creek begins as several low order streams with negligible water use. Thus, flow at the Lolo Creek below Granite Creek gage represents approximately natural streamflow and water supply from the headwaters. Region 5 is the most downstream part of the watershed between US Highway 93 and the Bitterroot River (the last mile of the creek). There was no outflow data for this region because the most downstream gage used in this study was located at Highway 93. This segment of Lolo Creek also flows through the Bitterroot floodplain and it would have been impossible to constrain inflows and outflows to the Region without incorporating a segment of the Bitterroot River (which was beyond the scope of this project).

We calculated water balances for Regions 2-4, each with an upstream and downstream gage. Before calculating each water balance all datasets (i.e., streamflow, diversions, ET, domestic use, etc.) were grouped by water balance region. Tributaries and diversions were assigned to a water balance region based on their geographic location. Irrigated fields were assigned to a region based on the source of the irrigation water, when available. If a source could not be identified, the field was assumed to be irrigated by water in the same region that it was physically located. We used the structures dataset from the domestic use methods section to count the number of households within each water balance region. The number of households was multiplied by the LWSD household use per day and the number of days in the month. Two of the LWSD wells are outside of the Lolo Creek drainage area and based on their deeper well depths, pump water from the Bitterroot River Aquifer. LWSD Well #3 is within Region 4, and therefore withdraws water from the basin-fill aquifer hydraulically connected to Lolo Creek. Structures that existed within a region but serviced by the LWSD were excluded from the per household calculations. Instead, the monthly volumes pumped from LWSD Well #3 were used as the withdrawal amount for municipal use. For lawn and garden use, we counted the number of households serviced by each municipal and domestic source (LWSD, domestic PWS, and individual wells) within each region, multiplied the number of households by the average lawn size for each source category and summed the results to get the number of lawn acres irrigated. Finally, we multiplied the total area of irrigated lawn by the monthly NIR values calculated previously to get monthly volumes for outdoor domestic uses. More information on how domestic and municipal use were assigned to a water balance region can be found in Section A3.4 of *Appendix A.* After grouping by water balance region, datasets were categorized as inflows or outflows from the region.

We calculated water balances for each region using Equation 6.

$$\Delta S_{(i,j)} = I_{(i,j)} - O_{(i,j)} \qquad \{Eq. 6\}$$

I represents the sum of all inflows and O the sum of all outflows for each month (i) and year (j). Figure 5 shows a conceptual diagram summarizing the complete water balance with definitions for inflows and outflows used in this study. The water balance model accounts for Lolo Creek runoff (i.e., the left-over precipitation) and its interaction with the shallow aquifer because these are the sources of water managed for beneficial use. Measuring the other components of the hydrologic cycle that determine runoff, such as landscape ET and soil moisture storage, was beyond the scope of this study. Water management decisions typically do not affect these components of the hydrologic cycle, however, land use or climate change can. In Part II of this report, we use a runoff model to estimate these larger scale components of the overall water balance. There is no surface water storage (i.e., reservoirs) on Lolo Creek, so we assumed $\Delta S = 0$ when evaluating Equation 6. Given this assumption, the sum of all surface water inflows equals the sum of all surface water outflows at a monthly time step. This assumption was not used for the groundwater balance because storage does occur in the aquifer, much like a reservoir.

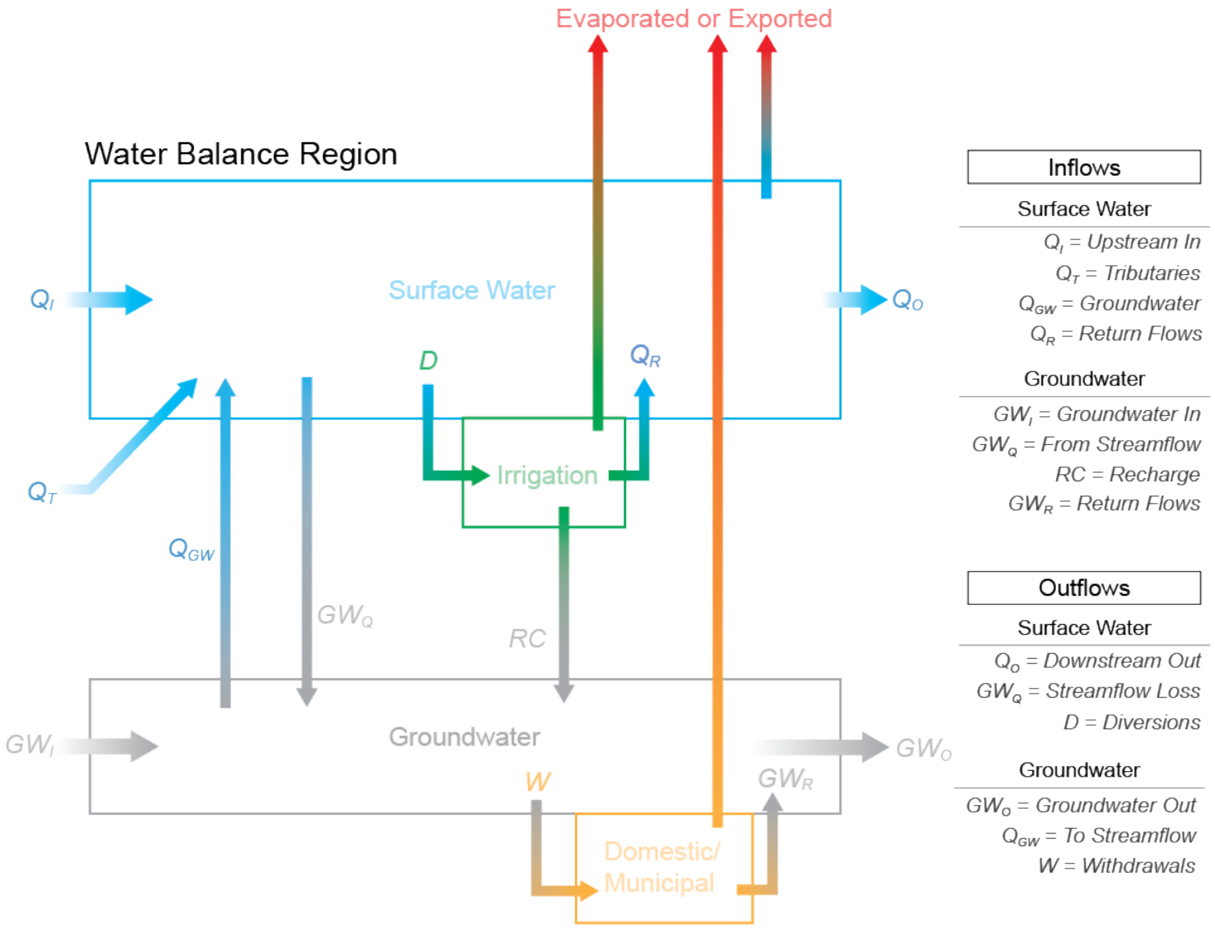


Figure 5. Conceptual diagram of Lolo Creek water balance with definitions for each variable.

Groundwater balances were calculated for Regions 3 and 4 using water level data from the well monitoring network to create monthly potentiometric surfaces. These surfaces were interpolated using Kriging with External Drift, such that they incorporate the local topography in determining the depth to the water table (Desbarats et al. 2002). A detailed summary of the interpolation methods used to develop the monthly groundwater elevation maps is provided in Section A2.2 of *Appendix A*. We used the resulting potentiometric surfaces with Equation 7 to calculate the difference in groundwater elevations between months and multiply them by the aquifer area to get ΔS as a monthly change in volume.

$$\Delta S_{(i,j)} = \left(GWE_{(i,j)} - GWE_{(i-1,j)}\right)A \qquad \{Eq.7\}$$

ΔS is multiplied by an aquifer storage coefficient (i.e., specific yield) to calculate actual change in storage for unconfined sand and gravel aquifers (Lohman 1972). This process differed from the surface water balance because many of the inflows and outflows were not directly measured, so we calculated storage directly as you would with a reservoir of known dimensions. Groundwater inflow and outflow variables are also shown in Figure 5. Some of the outflows from the surface water balance were inflows to the groundwater system, thus, we used a calibration procedure to calculate inflows from surface water and outflows to surface water. For more information on this method and the resulting storage coefficients by Water Balance Region, see Section A2.3 of *Appendix A.*

Using the results of the coupled surface-groundwater balance, we calculated a natural streamflow dataset for each water balance region of Lolo Creek. This dataset represents flow at the downstream gage of each region adjusted for all human consumptive use. When calculating the surface water portion of the water balance we assumed that $I = O$ because there were no surface water storage reservoirs; however, there was an inflow component of un-gaged inflows (UG_I) and an outflow component of un-gaged outflows (UG_O). The un-gaged inflows and outflows did not always equal each other, such that when completing the water balance there was a volume of water un-accounted for because it was not measured or estimated. In general, UG_I are primarily unmeasured tributaries and UG_O represent streamflow loss to the aquifer or natural conveyance losses. These un-gaged flows are important for calculating the natural flow of Lolo Creek, so we used Equation 8 to calculate the net value of un-gaged flows which we used as a natural input (positive value) or output (negative value).

$$\delta_{(i,j)} = O_{(i,j)} - I_{(i,j)} \qquad \{Eq. 8\}$$

To estimate natural flows, we started with Region 2 and applied Equation 9 iteratively downstream to Region 4.

$$Q_{(i,j)} = Q_{IN_{(i,j)}} + Q_{T\,(i,j)} + \left(\delta_{(\mathrm{i,j})} - GW_{f_{(i,j)}}\right) \qquad \{Eq. 9\}$$

δ is un-gaged inflows or outflows from Equation 8, Q is the natural flow out of the water balance region, Q_{IN} is natural flow into the water balance region, Q_T are all measured tributary inflows, and GW_f is the fraction of groundwater inflow to the stream resulting from irrigation and domestic recharge. $GW_f = 0$ when there is no groundwater inflow to the water balance region. When applying this method, Q for the upstream region becomes Q_{IN} for the downstream region. Graves Creek at its mouth and the South Fork of Lolo Creek below West Butte Creek were considered natural tributary inflows because there is negligible use upstream of these gages. The methodology for estimating GW_f is described in Section A2.4 of *Appendix A.*

Hydrology of Lolo Creek

The following results describe the contemporary hydrology of the Lolo Creek watershed based on weather station, stream gage, and monitoring well data. Each section below highlights a specific component of the water cycle. It is important to note that some data is limited geographically, and at-a-station observations may not capture small scale processes throughout the watershed. In the case of Lolo Creek, there is very limited data for high elevation terrain, which is an important contributor to water supply. The highest weather station is at 5,240 ft and approximately 40% of the watershed area lies above this elevation (Fig. 2). Additionally, many datasets do not extend far enough into the past to develop a robust characterization of variability or frequency of occurrence. Part II of this study will use hydrologic modeling and gridded data to supplement the weather station analysis presented in this report to estimate patterns in the water cycle.

Precipitation

There are three weather stations in the Lolo Creek watershed that collect precipitation data. The first is the USDA SNOTEL site at Lolo Pass (588; https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=588), which is located on the Montana-Idaho border at an elevation of 5,240 ft. The second is the MCO Mesonet station used previously for the METRIC analysis, which is located approximately 5 miles upstream of the mouth of Lolo Creek at an elevation of 3,274 ft. The third is the MCO Mesonet station located 1.7 miles northeast of Lolo Hot Springs, at an elevation of 4,070 feet. This station was not used in the precipitation or temperature analyses as it had similar trends to the other two stations. The Lolo Pass SNOTEL site has been recording hourly data since October 1, 1982 and the two Mesonet stations have been recording 30-min data since September 22, 2016. While there are still significant portions of the watershed above the Lolo Pass station, it does serve as a good representation of the average conditions because it is situated at an elevation close to the median elevation for the watershed. The Mesonet station, near the community of Lolo, captures the low elevation valley precipitation, which is a much smaller portion of the watershed.

The average total annual precipitation (based on data from 1982 – 2020) at Lolo Pass is 47 in and at the lower valley Mesonet station (based on data from 2016 – 2019) it is 16.6 in. When averaged over the same period as the Mesonet station, Lolo Pass was still 47 in. Despite the difference in the amount of data to calculate statistics between the two stations, it is evident that there is a steep gradient in precipitation between lower and higher elevations in the watershed (Fig. 6). This is typical of mountainous landscapes where moisture is orographically lifted, producing higher precipitation amounts in the mountains. The total annual precipitation is consistent at Lolo Pass with a standard deviation of 7.4 in, or about 16% of the mean, and no significant trends over the last 4 decades (Fig. 6).

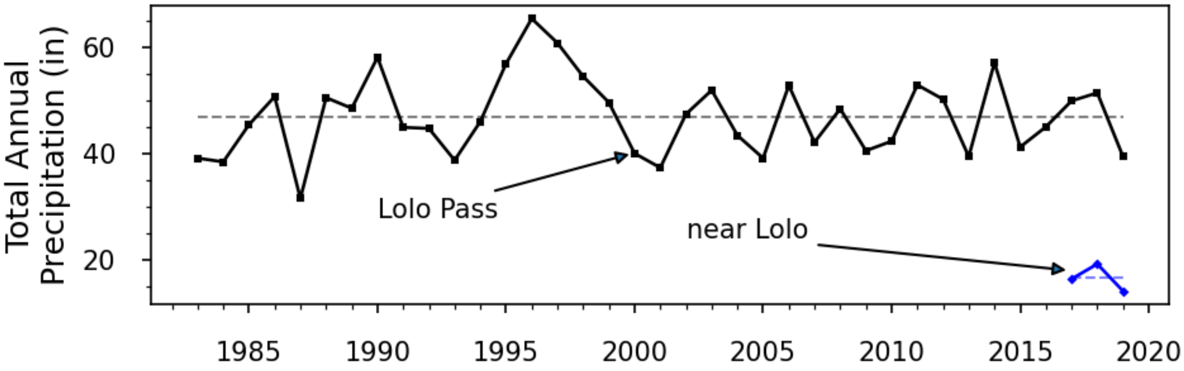


Figure 6. Total Annual precipitation for the 2 weather stations in the Lolo Creek watershed. Dashed lines represent the average over the period of record.

At the Lolo Pass SNOTEL station, precipitation typically peaked in the winter months between November and January, and slowly decreased throughout the spring into summer (Table 4). At the Mesonet station, precipitation peaked in the spring, around April, with increases in the fall due to rainstorms (Table 5). Monthly precipitation in May, June, July, and August at lower elevations more closely matched precipitation at Lolo Pass. Thus, precipitation at higher elevations has a different annual pattern than the valleys, with the most moisture in the fall and winter rather than spring. Average monthly precipitation accumulation at Lolo Pass was consistently 4 in, or more, higher than the Mesonet station from November to March (Tables 4 and 5). Lolo Creek watershed has consistent fall precipitation influenced by atmospheric rivers from the Pacific Ocean.

Cumulative water year (Oct. 1 of the previous year to Sept. 30 of the current year) precipitation at the Lolo Pass SNOTEL station was normal (between the 25th and 75th percentiles calculated from all daily observations for the period of record) for years 2016, 2017, and 2019 (Fig. 7a). The 2018 water year had above normal (between 75th percentile and maximum) cumulative precipitation. In 2016, the year of the observed dewatering event, water year precipitation was very similar to 2019, less than the median but still normal based on typical inter-annual variability. Snowfall accounted for between 55% and 65% of the total cumulative, water year precipitation (Fig. 7b). During winter months, as much as 98% and as little as 60% of moisture was snowfall. This percentage is dependent on how much fall precipitation there was and whether it was rain or snow. Rainfall encompassed 35% to 45% of the water year precipitation (Fig. 7c). At Lolo Pass, rainfall amounts were typically higher than snowfall in October with snowfall being the dominant precipitation type in November.

Table 4. Monthly precipitation for years 2016 – 2019 compared to 1983-2020 average monthly precipitation at the Lolo Pass SNOTEL station (elevation 5,240 ft).

Month	2016	2017	2018	2019	Average
	Precip (in)	Precip (in)	Precip (in)	Precip (in)	Precip (in)
January	5.2	3.7	6.6	4.3	6.4
February	4.9	7.1	9.0	6.5	5.1
March	5.9	8.8	3.1	2.0	4.8
April	2.3	3.0	5.4	7.1	3.7
May	2.4	2.3	3.0	2.6	3.3
June	1.0	4.0	5.1	1.0	2.8
July	2.4	0.1	0.0	0.5	1.2
August	0.2	0.2	1.2	2.0	1.4
September	2.9	2.6	0.2	2.9	2.1
October	7.7	3.8	4.4	4.5	3.8
November	2.8	6.8	7.5	2.1	6.1
December	7.4	7.6	6.0	4.0	6.0

Table 5. Monthly precipitation for years 2016 – 2019 compared to 2016-2019 average monthly precipitation at the lower Lolo Mesonet station (elevation 3,274 ft).

Month	2016	2017	2018	2019	Average
	Precip (in)	Precip (in)	Precip (in)	Precip (in)	Precip (in)
January	-	0.5	1.4	0.9	0.9
February	-	3.1	1.3	0.9	1.8
March	-	2.6	1.2	0.9	1.5
April	-	0.9	2.7	3.1	2.2
May	-	1.1	2.5	1.5	1.7
June	-	2.1	3.2	0.5	1.9
July	-	0.1	0.1	1.2	0.5
August	-	0.0	0.5	1.4	0.6
September	-	1.1	0.1	2.0	0.8
October	2.7	1.1	1.9	0.8	1.6
November	0.6	2.8	3.1	0.7	1.8
December	0.4	0.9	1.3	0.5	0.8

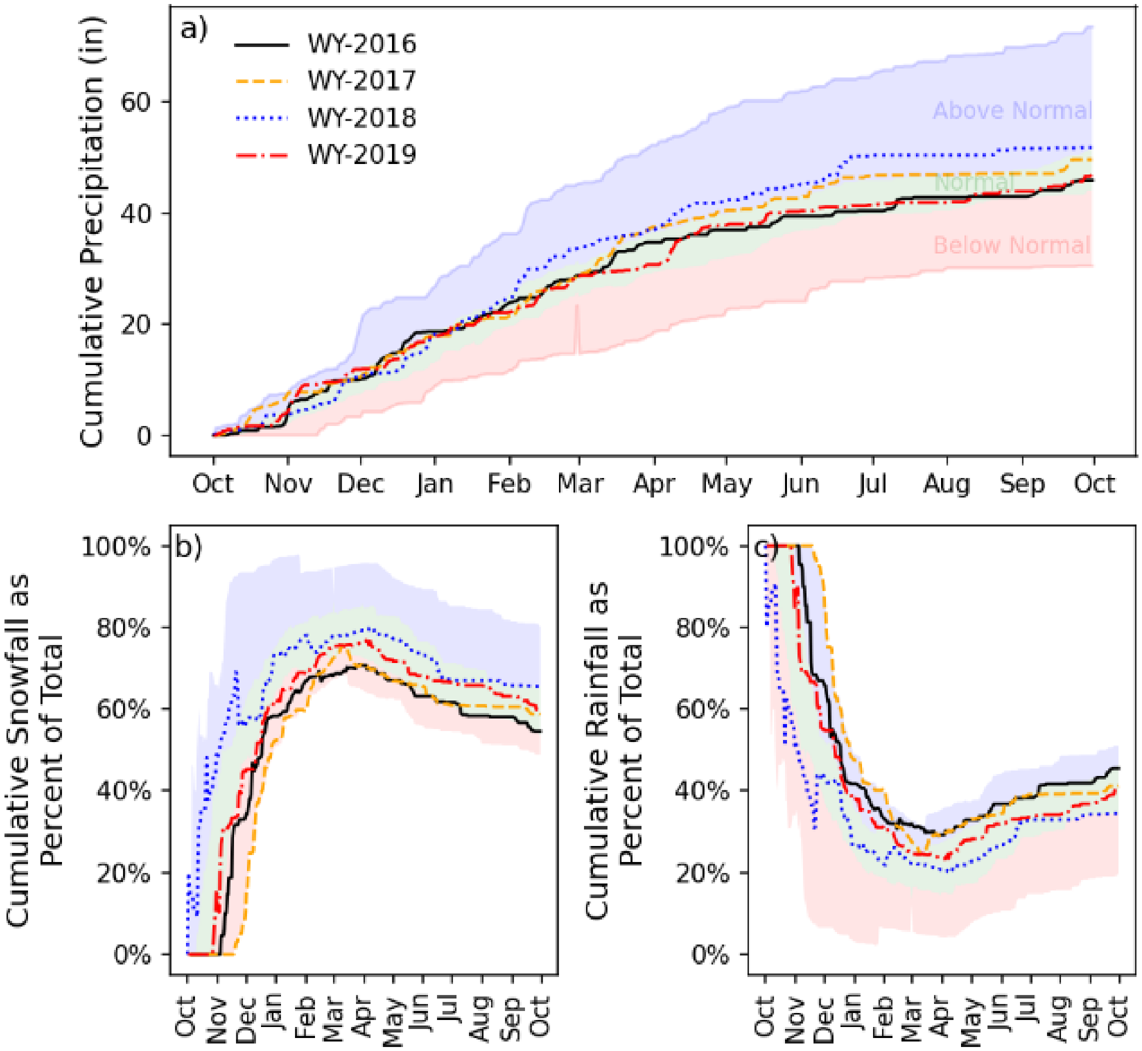


Figure 7. Graphs of Lolo Pass a) cumulative water year (Oct. 1 of previous year – Sep. 30 of current year) precipitation with lines for each water year in the study period and shading to represent the variation in precipitation based on 1983 – 2020 statistics; b) cumulative water year snowfall represented as a percentage of the total cumulative precipitation; and c) cumulative water year rainfall as a percentage of the total cumulative precipitation. Shaded regions in a) – c) represent minimum observed for any given day to 25th percentile (red), the inter-quartile range (25th to 75th percentile; green), and 75th percentile to maximum observed (blue).

Both precipitation types occur in October and November. Snowfall is the dominant precipitation from December to April. Snowfall is less frequent in the spring where when the percent of cumulative precipitation that is snow declines for the rest of the water year (Fig. 7b), and the percentage of rainfall increases (Fig. 7c).

Water years 2017 and 2019 had normal snowfall and rainfall amounts. Water year 2016 had below normal snowfall and above average rainfall. Inversely, 2018 had above average snowfall and below average rainfall. Water year 2016 had consistently lower snowfall throughout the year with rain occurring late into November. Water year 2017 had the lowest percentage of early season snowfall of any year in the 37-year period of record. Precipitation was 100% rain as late as the third week of November. Snowfall remained below normal until February when increased snow returned percentages to approximately normal. Minimal to no precipitation occurred in 2017 from mid-June to September. 2018 was a higher-than-normal precipitation year and was dominated by early snowfall that continued until later than normal in the spring. July to September of 2018 were exceptionally dry with very little precipitation. Water year 2019 was normal for both types of precipitation throughout the year.

Snowpack

The Lolo Pass SNOTEL is operated as a specialized weather station equipped to collect real-time snowpack data including the liquid water content or snow water equivalent (SWE), snow depth, and the proportion of precipitation that falls as snow. While snow depth and density can be important variables for understanding snowmelt dynamics, the most important data for water supply is SWE. The SWE is a quantitative measure of the depth of water stored as snow on a given day and, in mountainous regions, is generally a good indicator of summer streamflow.

Annual SWE curves showed that water year 2016 and 2019 were approximately normal based on maximum SWE for the year (Fig. 8 and Table 6). Water years 2017 and 2019 were above normal for maximum SWE. In a typical year (based on 37 years of data), snow accumulation at Lolo Pass began the last week of October and accumulated at a rate of 0.16 in per day (Table 6). SWE peaked the first few days in April and the snowpack melted at a rate of about 0.46 – 0.48 in per day, lasting until May 28 – 31. Water year 2016 had approximately normal SWE from October to January. A month-long lack of moisture in February created below normal conditions (Fig. 8). SWE accumulation and peak SWE were normal for water year 2016, however snowmelt occurred at a faster than normal rate and the snowpack was depleted by a much earlier date than normal (Table 6). Water year 2017 started with below average conditions until January. SWE was normal to below normal into mid-February when rapid accumulation led to above normal March conditions. However, after a very early peak (March 15), SWE declined for the rest of the season (Fig. 8 and Table 6). The rate of snowmelt in 2017 was significantly (40-50%) lower than the other years in the study period, but was normal compared to the long-term average melt rate. Water year 2018 began with above normal conditions and largely remained that way except for a lack of snowfall in December. SWE peaked higher and later in the year than normal. However, above average conditions gave way to exceptionally rapid snowmelt. Water year

2019 had normal SWE for the entire season with a later than normal peak.

While most snowpack metrics for the study period were within the expected variability observed in the 37-year record at Lolo Pass, snowmelt rates were consistently high. When viewing water years 2016 - 2019, the prolonged snowmelt season in 2017 appears to be anomalously low. However, when compared with long-term average snowmelt rates, 2017 was normal and the other years in this study were notably high. This suggests that contemporary snowmelt rates may be increasing compared to past rates. Part II of this report will explore these patterns more.

Temperature

The same two weather stations used for precipitation analysis also collect air temperature data. Air temperature is often overlooked for its role in water supply but can negate higher precipitation by creating temperature driven droughts (Udall and Overpeck, 2017). The period from 2000 to present, termed the "Turn-of-the-Century Drought," is one of the most severe events in the last century. There is some debate as to when or if the Turn-of-the-Century Drought is over. We do not speculate on completion or progress of this event in this study because drought is most accurately determined as a deviation from some average condition. It will take many more years of data to determine the actual end date. The Turn-of-the-Century Drought is unique because precipitation during this sustained period of low streamflow remained normal, thus the severity of this drought was attributed more to rising temperatures in the 21st century

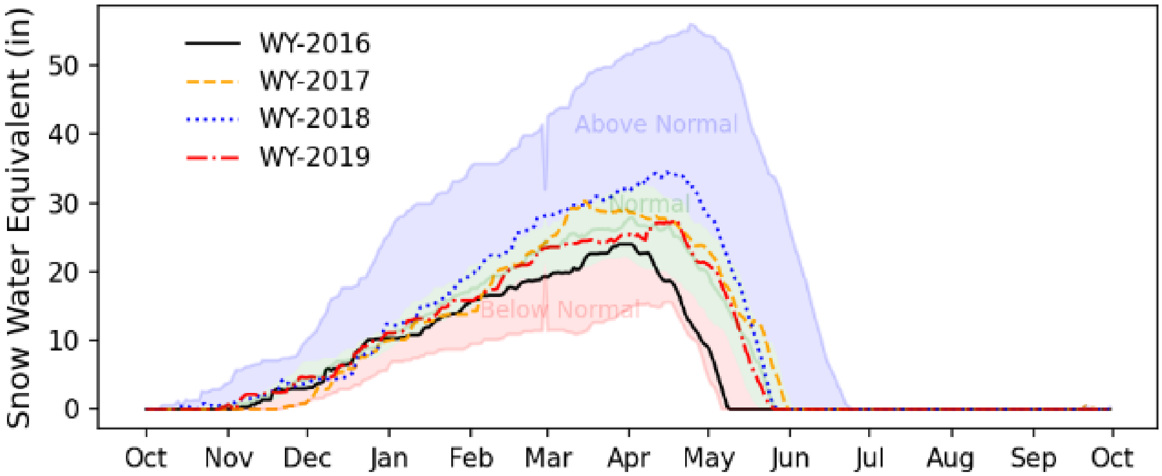


Figure 8. Snow Water Equivalent (SWE) at Lolo Pass SNOTEL station for the 4 water years of the study period. The 1983 – 2020 median is shown as a light green, solid line. Shaded regions represent minimum observed for any given day to 25th percentile (red), the inter-quartile range (25th to 75th percentile; green), and 75th percentile to maximum observed (blue).

Table 6. Snowpack, snowfall, and snowmelt characteristics observed at the Lolo Pass SNOTEL station.

Snow Variable	Water Year				Water Year 1983 – 2020 Statistics			
	2016	2017	2018	2019	Average	Standard Deviation	Median	Inter-quartile Range
Peak Annual SWE (in)	24.0	30.3	34.5	27.6	27.1	7.3	26.7	9.1
Date of Peak SWE	Apr 2	Mar 15	Apr 15	Apr 18	Apr 2	19 days	Apr 3	17 days
Max Depth (in)	64	100	98	88	86.8	19.6	92.0	30.5
1st Day of Snowfall	Nov 6	Nov 20	Oct 3	Oct 29	Oct 20	23 days	Oct 22	18 days
Snow Accumulation Rate (in/day)	0.16	0.26	0.18	0.16	0.16	0.03	0.16	0.02
Snowmelt Rate (in/day)	0.65	0.39	0.80	0.73	0.48	0.11	0.46	0.10
Last day of melt	May 9	Jun 1	May 28	May 26	May 29	12 days	May 31	16 days

(Udall and Overpeck 2017; Martin et al. 2020). The Turn-of-the-Century Drought was not unique to the state of Montana. The effects of this persistent drought were observed across much of the western US creating major concerns about future drought and water supplies.

The average, of an entire year, mean daily temperature at Lolo Pass was 38 degrees Fahrenheit (°F); with an average daily minimum of 29 °F and daily maximum of 49 °F. These were based on the 37-year (1983 – 2020) period of record of the Lolo Pass SNOTEL station. The average mean daily temperature at the Mesonet station near the community of Lolo was 43 °F, with an average daily minimum of 33 °F and daily maximum of 56°F. Although limited by the short period of record for available meteorology data, the Lolo Creek watershed appeared to show a similar increase in temperatures from the mid-20th century to the present (Fig. 9). There was a significant linear trend from the 1980s to the present in the annual average of daily mean temperatures at Lolo Pass (Fig. 9b). Analysis of the annual average of daily minimum (Fig. 9a) and maximum (Fig. 9c) temperatures suggests that the increase in mean daily temperatures is primarily driven by increased minimum daily temperatures. Although 2000 – 2020 daily maximum temperatures have increased since 1983, they have done so to a lesser degree than the minimums. It is unclear if these same trends exist in the valleys. We were unable to analyze long-term trends at low elevations

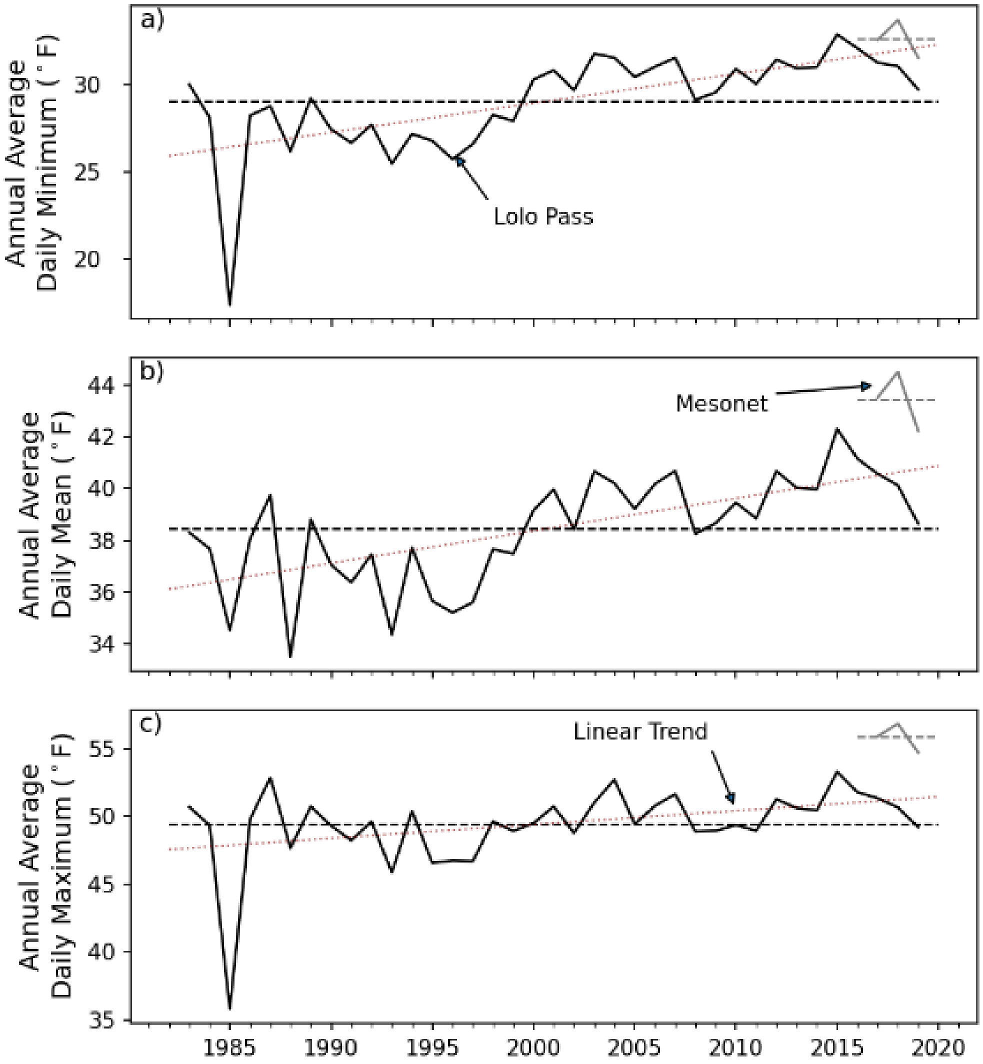


Figure 9. Graphs showing a) annual averages of daily minimum temperatures; b) annual averages of daily mean temperatures; and c) annual averages of daily maximum temperatures for both weather stations. Dashed lines through each data series represent the mean and the dotted trendlines (red) show the long-term trend in the Lolo Pass SNOTEL data.

because of the limited period of record at the Mesonet stations.

Monthly temperatures peak in June, July, and August; and are lowest in December, January, and February (Fig. 10). Comparing monthly temperatures at Lolo Pass and near the community of Lolo, it is evident that the elevational temperature difference decreases in the colder months and is more pronounced in daytime maximum temperatures (Fig. 10c). Minimum daily temperatures are much more alike at low- and mid-elevations except during the summer. During the study period, Lolo Pass mean daily temperatures were typically higher than

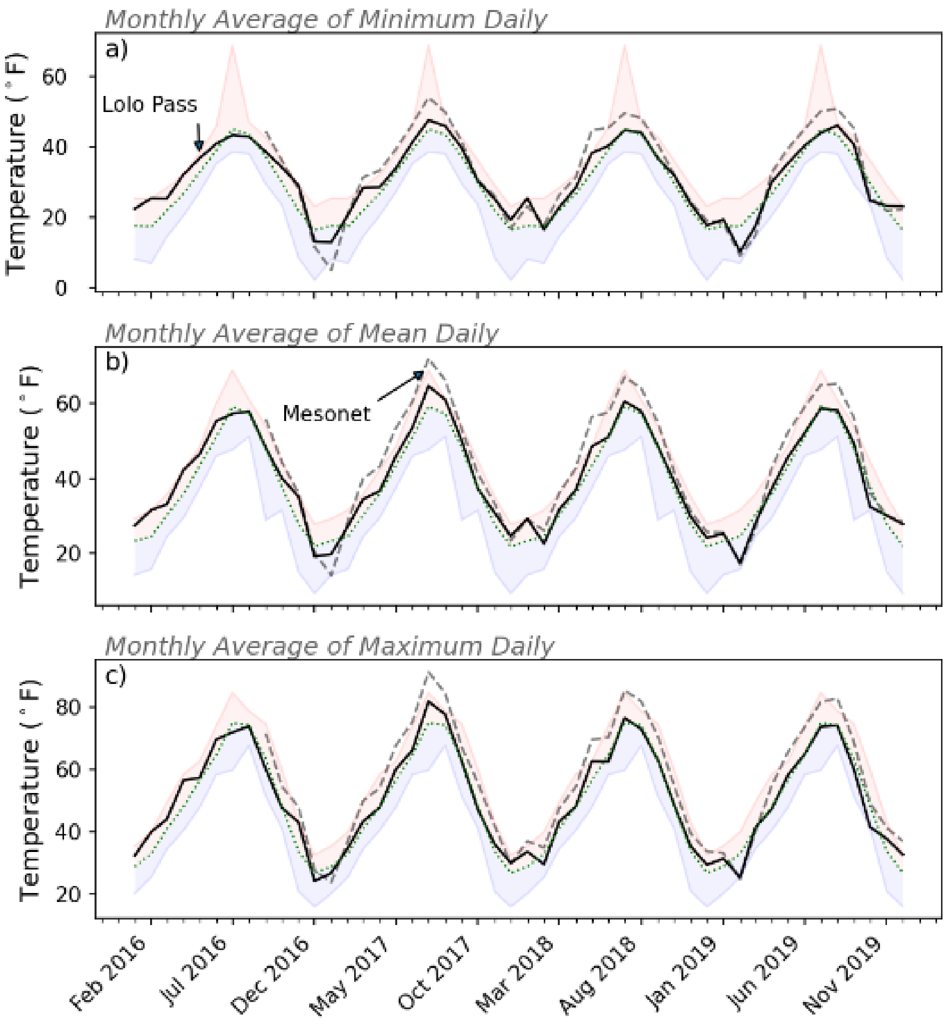


Figure 10. Graphs showing a) monthly average of daily minimum temperatures; b) monthly average of daily mean temperatures; and c) monthly average of daily maximum at Lolo Pass (solid black line) and the Mesonet station (dashed gray line). The 1983-2020 Lolo Pass average monthly temperature (dotted green line) is shown in each plot. Shading represents warmer than average (red is bounded by the maximum) and cooler than average (blue is bounded by the minimum). Mesonet data was included for comparison with SNOTEL and is not relevant to shading.

the long-term average, except for select months (Fig. 10b). 2016 and 2017 had more above average temperatures while 2018 and 2019 were normal but with sporadic fall/winter temperatures. Above average daily minimum temperatures were observed for most months at Lolo Pass. Overall, average daily temperatures have increased in the Lolo Creek watershed beginning around 1999. This increase is synonymous with similar increases in temperature observed across the western US and while complete streamflow records are not available, likely contributed to low streamflow. The increase in temperature appears to be driven by warmer night-time temperatures (i.e., daily lows) with modest increases in daily maximum temperatures. It appears that Lolo Creek shows similar trends observed across the western US during the Turn-of-the-Century Drought. These primarily temperature driven stresses on streamflow could be a contributing factor in the more frequent dewatering of Lolo Creek observed in the last 20 years.

Soil Moisture Storage

Soil moisture data is collected at the Mesonet weather stations and is measured as a volumetric water content (VWC) (i.e., the volume of water in a fixed volume of soil). Water content of the soil is measured at four different depths within the soil profile: 4, 8, 20, and 36 in. While data on soil moisture was limited by the short period of record for the two Mesonet weather stations, they provided some idea of how water moves into, or was stored in the soil. At shallow depths, water moved quickly through the soil with rapid increases and declines in VWC. This was visible at 4 in depth as VWC spiked with each precipitation or snowmelt event (Fig. 11). As depth increased, the same infiltration of water was visible but became muted and had lower VWC. When the soil was drier, infiltration events observed at shallow depths (4 – 8 in) were sometimes not observed at deeper depths (20 – 36 in). Soil moisture at all depths peaked in the spring, was lowest from July until September, and was variable in the fall and winter. Moisture was stored at different times within the soil depending on depth. At

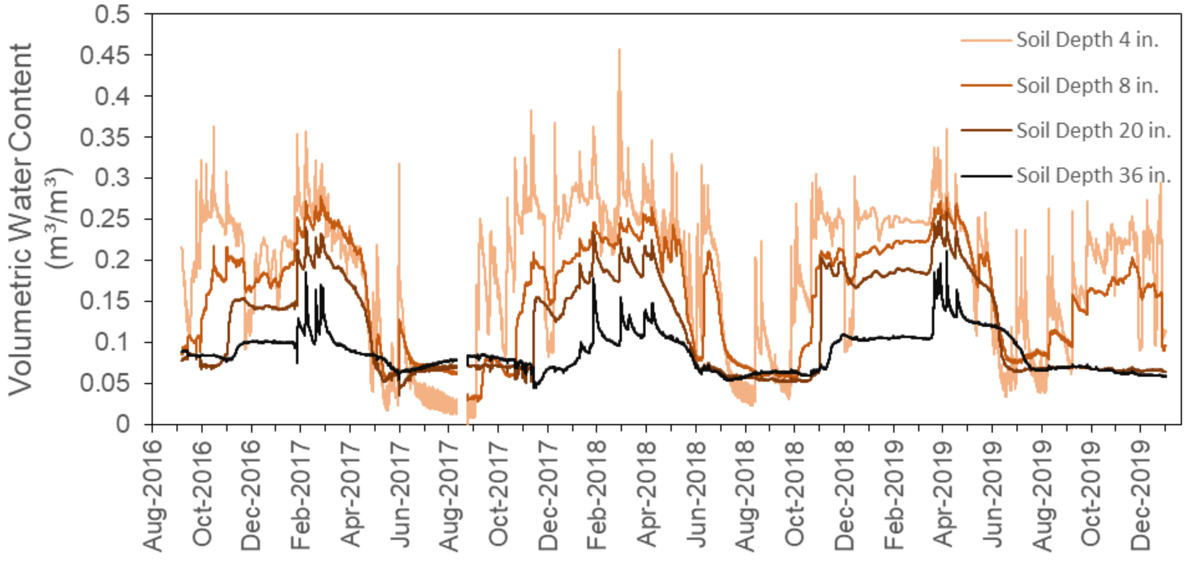


Figure 11. Soil moisture measured at the Lolo Creek Mesonet station near the town of Lolo. Units are in dimensionless volumetric water content, or cubic meters of water per cubic meter of soil. Sensor depths are at 4, 8, 20, and 36 inches deep. Lines are colored lighter for shallow depths and become darker at greater depths.

4 in depth, VWC peaked and declined rapidly suggesting storage was limited to the short-term. During the summer, VWC at 4 in was completely dependent on precipitation. Summer of 2017 was very dry and VWC at 4 in depth dropped to nearly zero from the end of July to September 13, when VWC increased due to infiltration from a rainstorm. Moisture content approached zero at 4 in during the summer of 2018 as well, but August rain reversed the trend. VWC at 8 in was similar to 4 in with smaller peaks during precipitation events and generally higher moisture content during the summer. VWC at 8 in depth and 20 in depth were most alike of the four data series, with 20 in depth consistently less than 8 in. At 36 in depth, VWC was the most constant throughout the year, fluctuating mostly during the spring. Typically, at depths greater than 4 in, more moisture was stored from June to September. Part II of this report will analyze modeled soil moisture storage in greater detail.

Streamflow

Streamflow analysis for Lolo Creek was done using the DNRC stream gage above Sleeman Creek (76HB 09500) because its location was comparable to the two discontinued USGS stream gages. The USGS gage near Lolo, MT (12351500) was located several miles upstream from the existing above Sleeman Creek gage, but there is only one small diversion and no significant tributaries or between the two locations. The USGS gage above Sleeman Creek (12352000) was located just downstream from the existing above Sleeman Creek gage and may include diversions from the McClay ditch. The two USGS gages and DNRC's gage above Sleeman Creek were combined to create an intermittent dataset (1911-1915; 1950-1960; 2016-2019) that included 18-years of streamflow instead of just 4 years of data collected for this study. It was assumed that the location above Sleeman Creek was representative of the entire watershed outflow because the mean daily discharges were comparable with the downstream gage at Highway 93, at least for the purpose of broadly describing the flow regime. All discharge records used represent the flow as it was observed at the gaging station, which included diversions and other water use. Thus, this analysis is of existing conditions

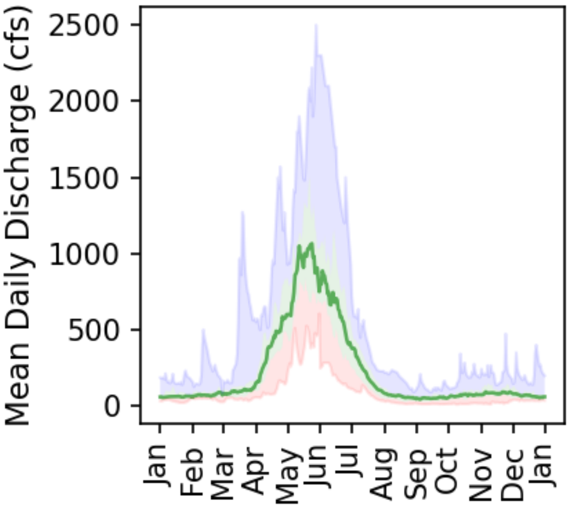


Figure 12. Summary annual hydrograph for Lolo Creek based on 18 years of streamflow records. Median, mean daily flows (green solid line) are shown with minimum to 25th percentile (red shading), interquartile range (green shading), and 75th percentile to maximum (blue shading).

and not of the natural streamflow or water supply of Lolo Creek. A discussion of the natural flows is provided in the Water Balance results below.

A river or stream's flow regime can be broken into components consisting of events (e.g., floods) and the associated magnitude, frequency, timing, and duration of those events. These components can be quantified and summarized by analyzing many annual hydrographs (Fig. 12). In snowmelt dominated streams, like Lolo Creek, the spring runoff flood is the most important event determining the annual hydrology. Aside from this major, annual flood, small rain events may occur but baseflows dominate the hydrograph. Lolo Creek streamflow typically peaked at the end of May, plus or minus a few weeks, and was earlier in low flow years (Fig. 12 and Table 7). Elevated streamflow from snowmelt runoff began in April and ended at the start of July. The start of runoff could occur several weeks earlier or last several weeks longer, depending on the year. Baseflows between 50 and 100 cfs occurred in the winter before runoff began and for the remainder of the year after the flood subsided. Rain driven floods occurred in September through November, causing an increase in streamflow during the fall.

The magnitude of the annual snowmelt flood varied considerably. Floods peaked as low as 500-600 cfs in very low flow years, and as high as 2,400 cfs in very high flow years (Fig. 12). This variability is usually explained via flood frequencies, which

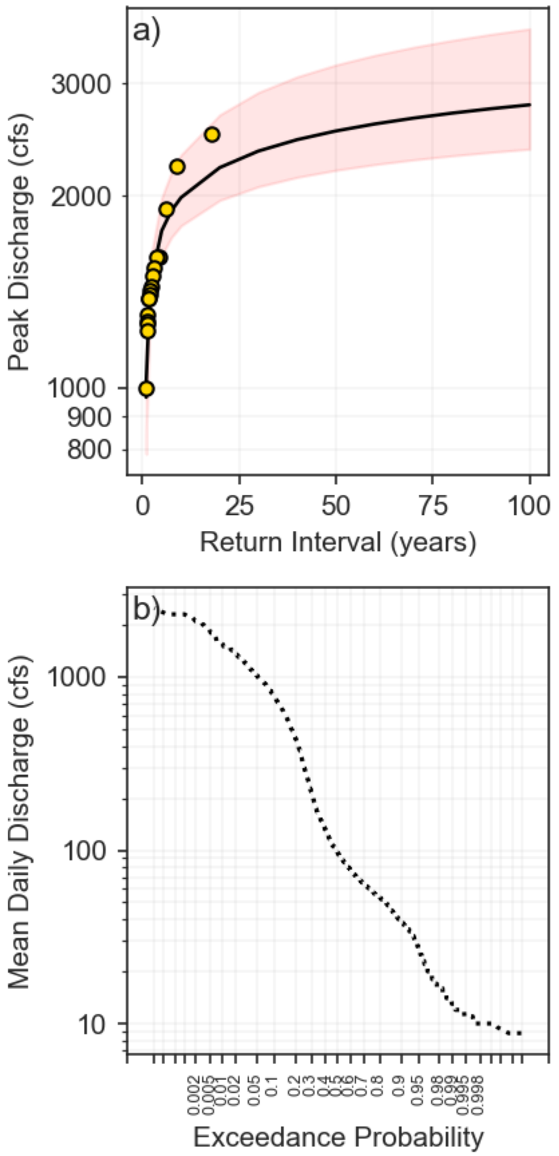


Figure 13. Graphs showing a) flood frequency (based on maximum mean daily flows) of Lolo Creek from combined USGS and DNRC records; and b) a flow duration curve computed using the same records. In a), yellow circles are measured floods, the black line is the Log-Pearson III fit with 95% confidence interval (red shading). In b) the exceedance probability can be interpreted as the percent of time streamflow exceeds that value.

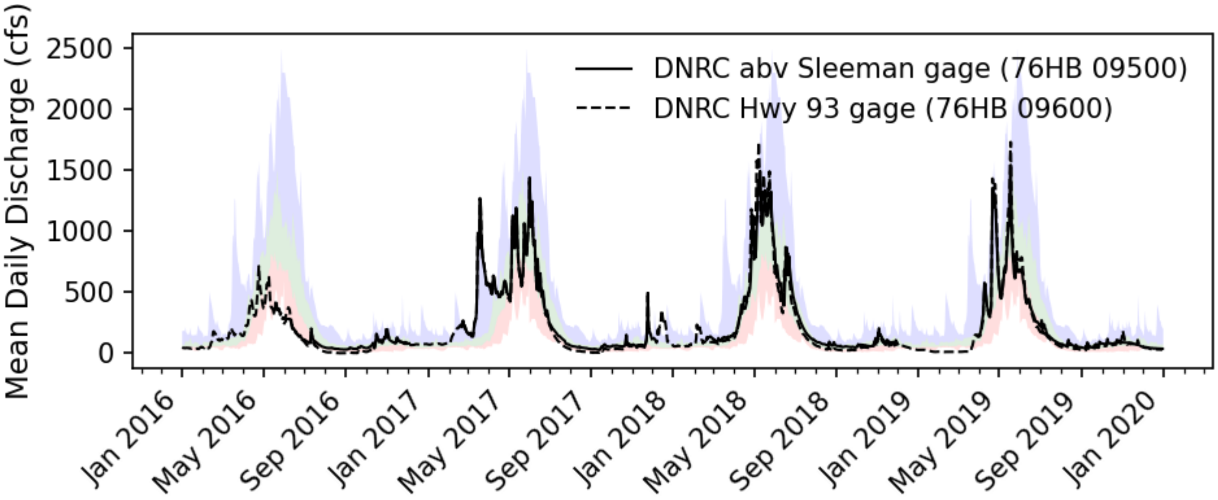


Figure 14. Mean daily discharge at the gage above Sleeman Creek and below Highway 93 for the study period, plotted against the 18-year statistics (shaded regions) from contemporary and historic streamflow. Shading was adopted from Figure 12.

describe various magnitudes of observed floods by their frequency of occurrence. A flood frequency analysis, using the accepted Log-Pearson Type III distribution (England et al. 2019) of Lolo Creek maximum mean daily discharges showed a 1-yr flood of approximately 1,000 cfs (Fig. 13a). Floods are labeled by their recurrence interval, meaning a 1-yr flood is very likely to occur every year. The 2-yr flood (i.e., likely to occur once every 2 years) at the Lolo Creek above Sleeman Creek gaging station was 1,448 cfs. Flood peaks greater than this discharge are increasingly less likely to occur (Fig. 13a). Although we estimated the 100-yr flood for Lolo Creek (Fig. 13a and Table 7), it should be used with caution because it was extrapolated from 18 measured peak discharges (an estimate of the 100-yr flood should be based on a sample size of 100).

A flow duration curve was calculated to further analyze duration and frequency of observed Lolo Creek streamflow (Fig. 13b). A flow duration curve (FDC) displays the probability of a certain flow rate occurring. Each flow rate on the FDC corresponds to a period (in this case 1 day) and can be interpreted as the proportion of time (days) that a given streamflow is exceeded. In the context of one year, a single day represents 0.3% of a year. Lolo Creek flowed at between 30 and 1,000 cfs 90% of the time (i.e., this is the most common range of flows throughout the year). Flows exceeded 1,000 cfs for a short duration of the year and may not have at all in some years. Similarly, flows were less than 30 cfs for days or weeks, if at all in some years. Baseflows were between 50 and 60 cfs, based on streamflow that occurred 25% of the time (exceedance probability of 0.75). Flows that had a duration of less than one day (i.e., 0.997< exceedance probability < 0.003) are flows that are very unlikely and would not have occurred every year. This only includes discharges greater than approximately 1,900 cfs and less than approximately 12 cfs. Analysis of the FDC confirms that peak discharges greater than 1,500 cfs are rare and would only persist for a short duration of time.

Mean daily discharges for the study period (2016-2019) showed that snowmelt peak flows were higher than normal, except for 2016, and were earlier than normal, except for 2017 (Fig. 14 and Table 7). The snowmelt season was characterized by multiple short duration, but high magnitude spikes in flow. The characteristics of the 2016 – 2019 annual hydrographs agree well with both precipitation, snowpack, and temperature observations (i.e., less precipitation falling as snow, warmer temperatures, and earlier and faster snowmelt runoff). Total annual flow and peak discharge in 2016 were below average and with earlier than normal runoff. Baseflows in 2016 at the above Sleeman gage were slightly lower than normal, but low flows (based on minimum flow for the year) were approximately normal. This highlights the importance of groundwater processes and water use in the Lower Lolo Valley because during the span of approximately normal low flows at the above Sleeman Creek gage, the creek was dry at the Highway 93 gage. Shallow groundwater levels at the nearby piezometer (GWIC # 288388) dropped by a foot during the period that the channel was dry and the downstream piezometer (GWIC # **288234**) near Lewis and Clark Drive was dry. Annual average discharge in 2017 was higher than normal because of an anomalous, bi-modal (2 peaks) snowmelt flood that peaked in late March, receded, and peaked even higher on June 1. The higher-than-average flows and bi-modal flood were caused by higher-than-normal precipitation and SWE during the first 5 months of the calendar year. The lowest minimum flows observed at the above Sleeman Creek gage occurred in 2017, lower than 2016, but the creek did not dewater at Highway 93. The low flows of 2017 were a consequence of warmer than average summer temperatures coupled with no precipitation from the start of July to mid-September. All components of the flow regime were above average in 2018, which includes the highest observed annual minimum flows during the study period. In general, 2019 was a below average year for most flows with approximately normal low flows. However, 2019 had the largest peak flood discharge (but very short duration) of the study period. Components of the flow regime compared with individual years 2016 – 2019 are summarized in Table 7.

Groundwater-Surface Water Interactions

In the upper portions of the Lolo Creek watershed, the creek flows through constricted canyon segments and partially confined valleys. At the downstream end of each valley, the constrictions that occur as the creek flows back into a canyon environment likely limit the extent of the water bearing unit (aquifer). Most of the groundwater discharges from the aquifer just before these constrictions and travels as surface water or

Table 7. Flow regime components calculated from combined DNRC and USGS stream gage records with 2016 – 2019 observed values at the Lolo Creek above Sleeman Creek stream gage.

Streamflow Variable	Calendar Year				18-year Statistics			
	2016	2017	2018	2019	Average	Standard Deviation	Median	Inter-quartile Range
Peak Flow (cfs)	714[1]	1,441	1,495	1,544	1,448[2] 2,213[3] 2,775[4]	-	-	-
Median Annual Flow (cfs)	84[1]	156	126	88	-	-	96	239
Average Annual Flow (cfs)	133[1]	323	307	251	257	350	-	-
Minimum Flow (cfs)	30	28	48	37	35	21	34	25
Peak Flow Date	Apr 24[1]	Jun 1	May 10	May 18	May 31	51 days	May 23	20 days
Snowmelt Flood Duration (days)	133[1]	110	111	108	118	15	113	21

[1] Data was missing at the above Sleeman gage for 2016 so flows at Highway 93 were used instead.

[2] 2-yr flood from Log-Pearson III.

[3] 20-yr flood from Log-Pearson III.

[4] 100-yr flood extrapolated from Log-Pearson III.

underflow in the hyporheic zone to the next valley. Once the stream reaches the next valley, it recharges the basin fill aquifer(s). Groundwater hydrographs showed that the shallow and deep basin-fill aquifers near Lolo Creek mimic their nearby, corresponding surface water hydrographs. The groundwater response was more dampened in deeper monitoring wells, especially if the well was terminated in the bedrock of the Belt Supergroup and Idaho Batholith. This suggests that the shallow and deep aquifers are connected to Lolo Creek and that nearby pumping from wells has the potential to capture surface water as described by Lohman (1972).

Groundwater monitoring had less spatial coverage in the upper portions of the Lolo Creek watershed. The stream gage at Dodson (MDT) and its associated piezometer are in a valley segment and serve as an example of how groundwater and surface water interact in the partially confined valleys of upper and middle Lolo Creek. Data at this location showed a negative vertical gradient beginning late in the summer and continuing through winter. Negative vertical hydraulic gradients exist when the groundwater in the piezometer is lower compared to the surface water elevation, indicating the downward flow of surface water to the aquifer (i.e., a losing stream). This site showed neutral conditions to positive vertical gradients during the spring and early summer. Overall, this corresponds to losing streamflow to the aquifer for much of the year and gaining streamflow during the spring, likely when the aquifer is full.

In the lower valley segment of Lolo Creek, Chambers (2016) found that negative vertical hydraulic gradients existed at all four of their staff gages and shallow piezometer pairs. The negative vertical gradients were greatest during the low-flow period in late August and early September. Minimum vertical gradients occurred in June and early July (Chambers, 2016). The lowest negative gradient was observed in the segment just downstream of the above Sleeman Creek gage, approximately 5 miles upstream from the mouth of Lolo Creek. The highest negative gradient was observed just downstream of Highway 93. Although Chambers (2016) showed increasing streamflow for some reaches in the lower valley, synoptic surveys from this study, temperature profiles, and hydraulic gradient at DNRC piezometers showed a net loss downstream of the stream gage above Sleeman Creek. The only time Lolo Creek between the above Sleeman Creek gage and the Highway 93 gage gained streamflow was during spring runoff, which was largely from Mormon and Sleeman Creeks. A negative vertical hydraulic gradient was generally observed between the surface water elevation at the Highway 93 stream gage and the groundwater elevation in the nearby piezometer.

Water Balance

Lolo Creek Summary

The combined surface, groundwater balance for total annual water supply is illustrated in Figure 15. This is the culmination of all water balance analyses and calculations with inflows, outflows, and exchange between surface and groundwater shown using a scaled-arrow diagram. The average total annual yield of Lolo Creek for the study period was 152,200 acre-ft per year (this includes existing water use). Water supply ranged from a minimum of 96,810 acre-ft in 2016 to a maximum of 192,781 acre-ft in 2017. The years 2018 and 2019 yielded 176,542 and 142,864 acre-ft, respectively. The average groundwater outflow was 11,300 acre-ft, which equates to an average flow rate of 16 cfs per day. Irrigation (both consumed and exported from watershed) was the largest use of water from the creek, reflecting general statewide water use patterns, in which irrigation is the highest consumptive use of water. Most of the irrigation water from Lolo Creek was exported from the watershed to irrigate fields to the south, and notably, the largest irrigated acreage in the Lolo Watershed is outside the topographic boundary.

As with all streams and rivers, water supply of Lolo Creek increases with drainage

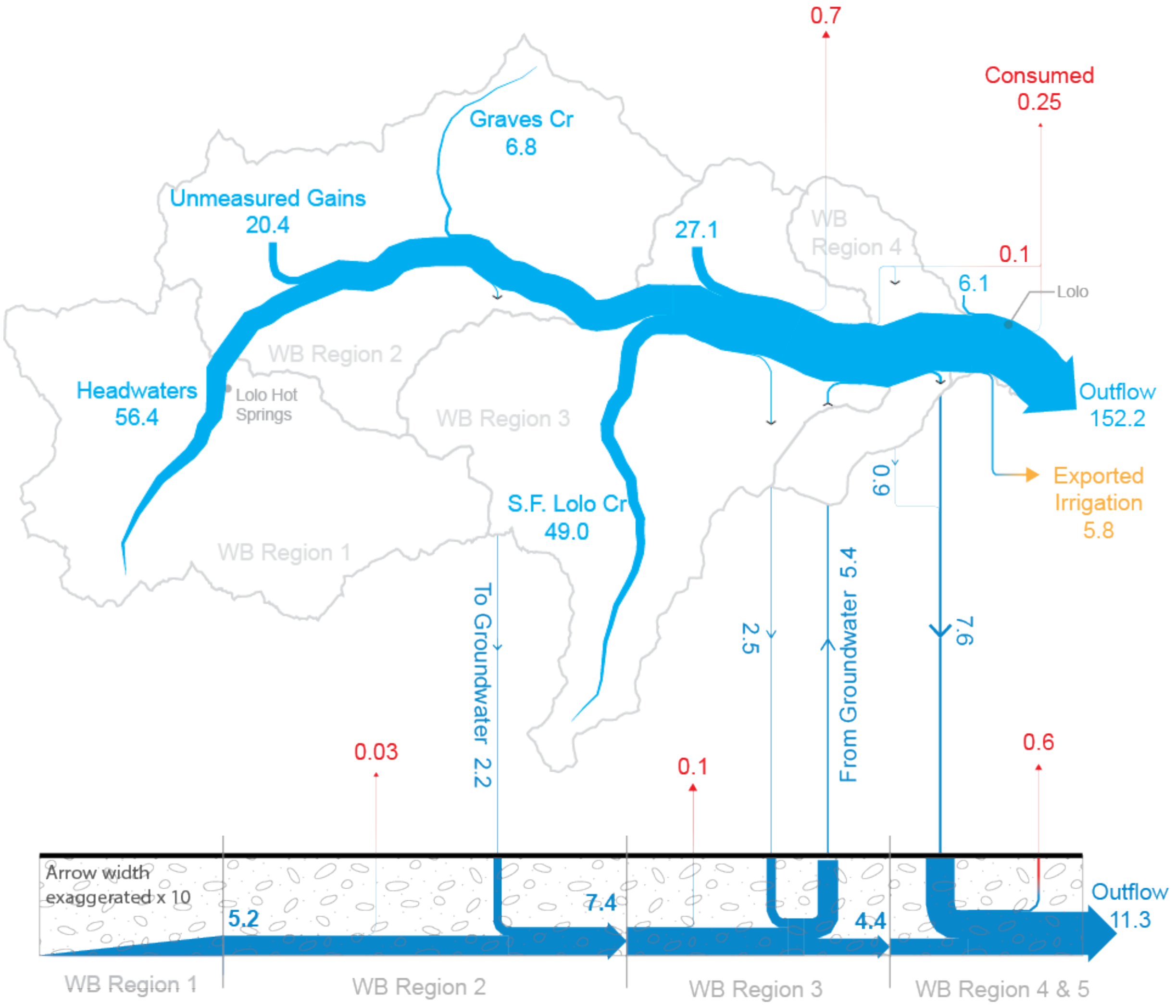


Figure 15. Scaled line diagram of showing average annual (2016 – 2019) Lolo Creek watershed inflows and outflows for surface and groundwater where line thickness is scaled to inflow or outflow at each labeled location. All values are in thousands of acre-feet. Lines for groundwater are exaggerated for easier viewing. Consumed water in this diagram represents water lost through ET and indoor domestic consumption.

area. Water in Lolo Creek originated primarily from the downstream half of the basin, specifically from Water Balance Region 3. Region 3 accounted for 54% of the total annual water supply, with the South Fork of Lolo Creek (the largest tributary) providing 60% of that 50%. The remaining water was from unmeasured tributaries and groundwater gain. The headwaters of Lolo Creek produced the next largest source of water at 37% of the total annual supply. Graves Creek combined with the numerous, small unmeasured tributaries in Region 2 accounted for 18% of the total annual supply. Sleeman and Mormon Creeks in Region 4 accounted for just 4% of the total annual supply. Collectively, the small tributaries across the watershed accounted for more of the annual water supply than the headwaters or the South Fork.

During the study period, the month of May had the highest yield of water across the watershed (Fig. 16a). The small unmeasured tributaries mentioned earlier are important for the overall water supply, but the bulk of that supply was produced during spring runoff. In late summer, fall, and winter, base flows were almost exclusively from the South Fork and the headwaters (Fig. 16a). Groundwater gains were highest in the mid- to late-summer but were a very small fraction of the overall inflows. Total monthly outflows included diversions or withdrawals and natural losses (in this case primarily to groundwater). Diversions and withdrawals had a seasonal peak during the irrigation season because of agricultural and lawn and garden irrigation (Fig. 16). This peak in water diversion and withdrawal typically coincided with decreasing water supply (Fig. 16a). Natural

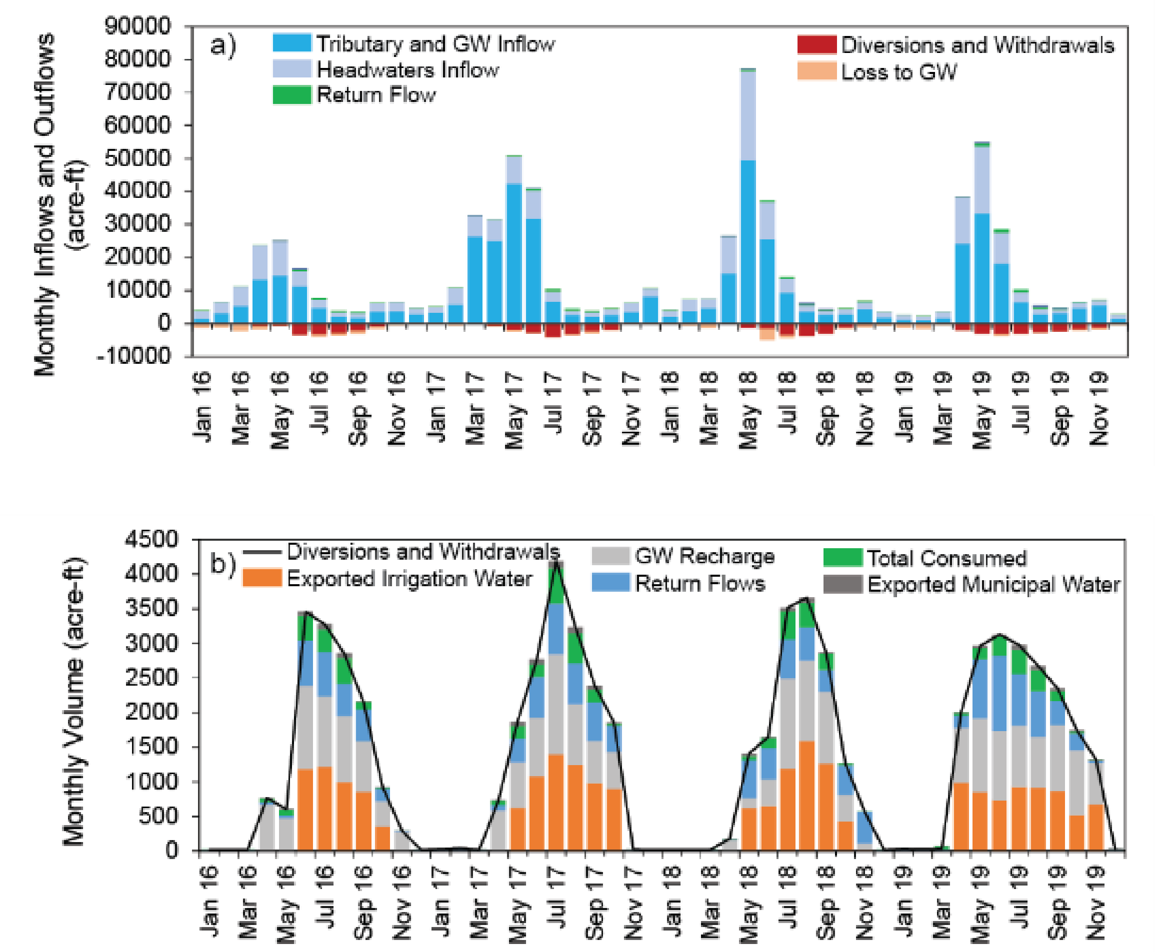


Figure 16. Graphs showing a) monthly volumetric inflows and outflows for the Lolo Creek watershed and b) monthly, total diversions and withdrawals where stacked bars represent the proportion of the diverted and withdrawn water that went to one of the five uses listed in the legend.

loss to groundwater was typically less than diversions and withdrawals during the peak season, however, natural loss dominated during other months of the year when only domestic use was present. Of the diverted or withdrawn water, much of it (approximately 50% in July – September) was exported from the watershed (Fig. 16b). The next largest portion of diverted and withdrawn water went to groundwater recharge and consumptive uses. Consumed water includes ET from crop/lawn and garden consumption. Groundwater recharge is defined as the volume of diverted and withdrawn water that goes to recharge the shallow aquifer. Return flow is defined as the volume of diverted and withdrawn water that returns to the original source. Groundwater recharge and return flows were comparable for most years.

The lowest flows in Lolo Creek were consistently from August to October during the study period. August was the month when water supply was most stressed because of the combination of peak water use with minimum inflows from the headwaters and tributaries. The 2016 dewatering event occurred in August; therefore, we calculated a targeted water balance that compared the average 2016 to 2019 August conditions with conditions measured in August 2016 (Fig. 17). Streamflow out of the watershed in August was normally less (about 57% less, or 2,212 acre-ft/ ~36 cfs) than total inflows. The decline in streamflow began in Region 3 with most of the loss occurring in Region 4. Of the 57% of streamflow lost from the hydrologic system; 54% was diverted water that was exported from the watershed for irrigation, 28% went to the aquifer and left the watershed as groundwater outflow, and 18% was consumed by crops. The aquifer had a net discharge of water to Lolo Creek in Region 3 but gained flow from Lolo Creek in Region 4, nearly doubling the groundwater outflow to a total of 1,309 acre-ft, or 21 cfs (Fig. 17). Household use from all Water Balance Regions combined was approximately 15% of the total groundwater outflow. August of 2016 was drier with inflows equal to 71% of average. The South Fork of Lolo Creek had slightly less than average flows while the headwaters and small tributaries in Region 2 were significantly drier than normal. Total outflow from the watershed was 10% of the total inflows for August 2016. This was the result of average to higher-than-average crop/lawn and garden consumption (exported irrigation water was slightly below the August average) combined with higher-than-average streamflow loss to the aquifer. Groundwater flow from upper and middle Lolo Creek was approximately 50% of the August average in 2016. Streamflow gain from groundwater was also less than average in Region 3. Low groundwater may have contributed to greater streamflow loss by potentially increasing the vertical hydraulic gradient. The estimated total groundwater outflow from the watershed was higher in August 2016 than the August average because of the increased streamflow loss. The Bitterroot River and aquifer also play a key role in determining streamflow loss in Region 4. MBMG's GWIP study will explore the

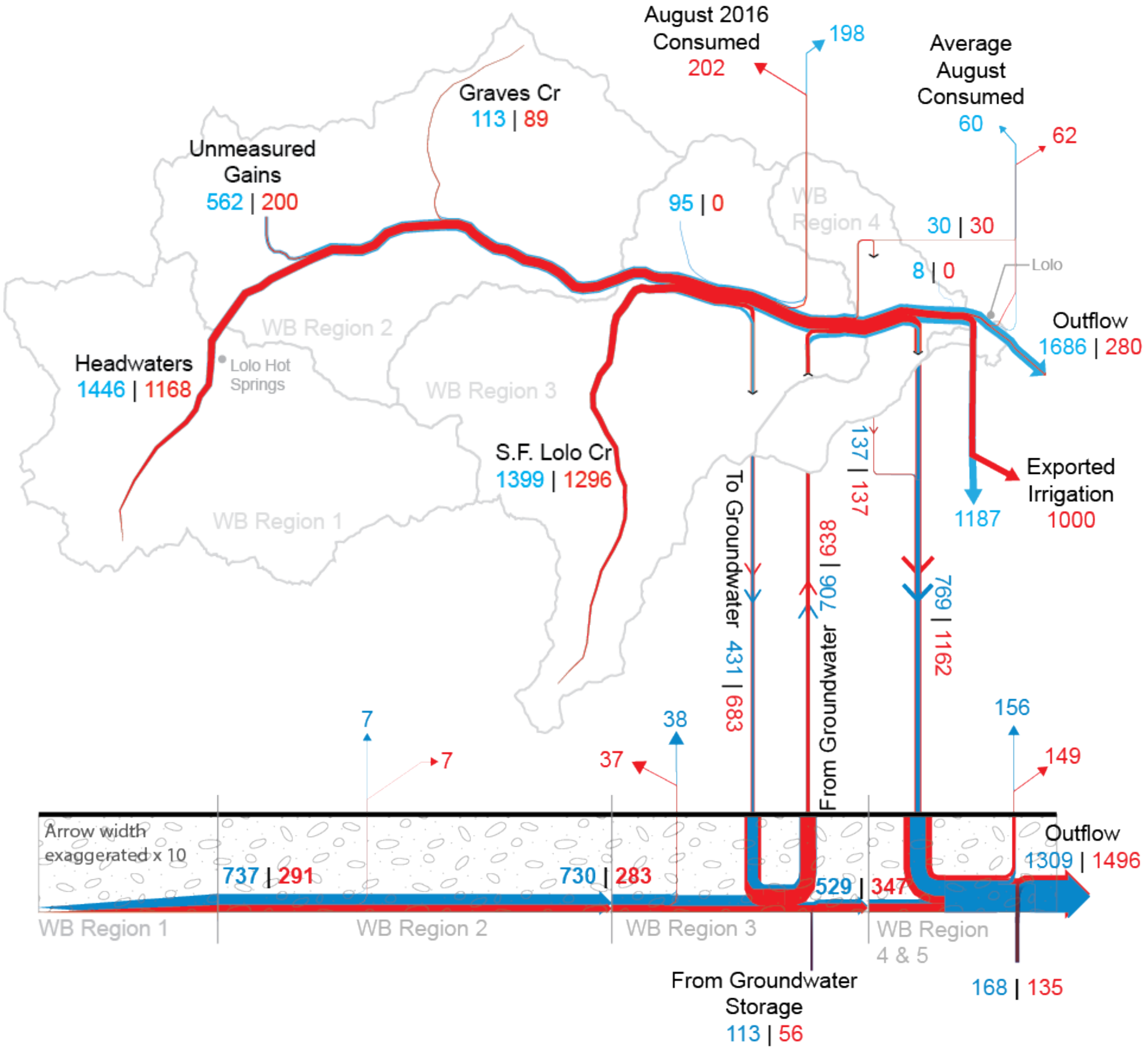


Figure 17. Scaled line diagram showing the 2016 – 2019 average August (blue labels and lines) inflows and outflows compared with August 2016 (red labels and lines) inflow and outflows, where line thickness is representative of inflow or outflow at each labeled location. All values are in acre-feet. Lines for groundwater are exaggerated for easier viewing.

causes of the observed streamflow loss in more depth.

Water Balance Regions

Water Balance Region 1

Region 1 consisted of the headwater tributaries of Lolo Creek. This region was delineated based on the stream gage below Granite Creek and therefore had measured outflow only. No water balance was calculated for Region 1 and flows at the below Granite Creek gage were considered "natural." There were very minimal domestic withdrawals (e.g., Lolo Hot Springs) from groundwater in Region 1 but they are a small fraction of the estimated groundwater outflow. The outflow from the headwaters was considered an inflow to Region 2 and subsequent Water Balance Regions.

Water Balance Region 2

Region 2 encompasses upper Lolo Creek with inflows from the headwaters and small tributaries like Graves Creek. Much of the drainage area in Region 2 is mid to low elevation. There are numerous small tributaries in this Water Balance Region, with Graves Creek being the largest by volume. A relatively small percent of the total water supply of Lolo Creek originates in Region 2, and the primary inflow is from upstream in the headwaters (Fig. 18). Graves Creek provided about the same or slightly more inflow as all other small tributaries combined in all years, except 2017. The other unmeasured tributaries in Region 2 were a very important source of water supply from March to June in 2017. Headwaters inflow during this period was low (lower than 2016), but the combined flow from other small tributaries supplemented this deficit, making 2017 the highest supply year in the study period. This suggests that lower elevation snow was critical in 2017. During low flows, small unmeasured tributaries typically provided more flow than Graves Creek. Outflows from Region 2 were solely streamflow lost to groundwater and were typically a small fraction of the inflows (Fig. 18). Measured streamflow loss was rare, mostly occurring in 2016 and 2019.

Groundwater calculations were not explicitly done for Region 2 because of the discontinuous aquifer that only exists in valleys between canyon segments. The monitoring well network was too sparse to capture changes in storage for each small valley. Instead, the DNRC piezometer and non-real-time gage at Dodson (MDT) were used only for understanding the interaction

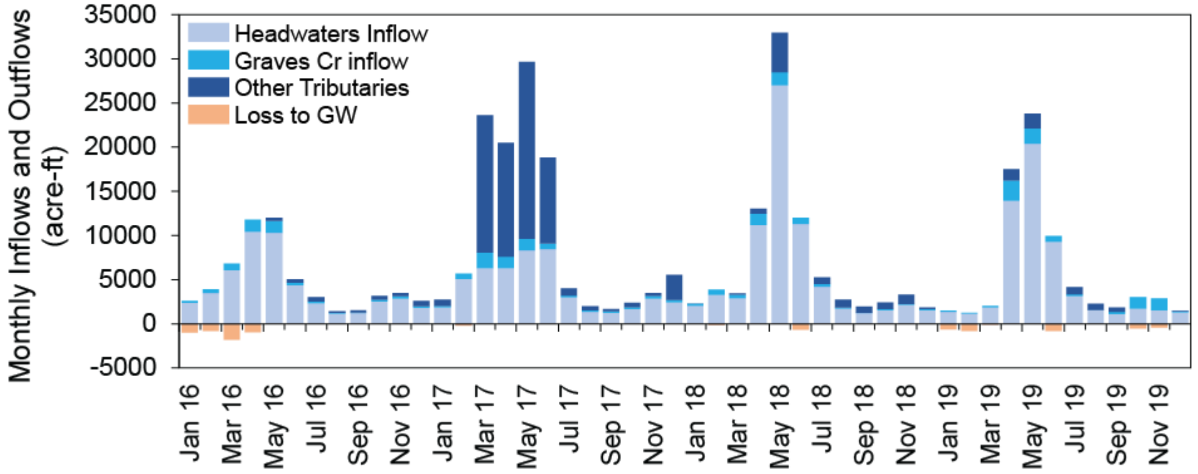


Figure 18. Water Balance Region 2 monthly volumetric surface water inflows and outflows.

between surface and groundwater in these upper valleys of Lolo Creek. There are domestic withdrawals from groundwater in Region 2, but they were a small fraction of the estimated groundwater outflow (Fig. 15).

Water Balance Region 3

Region 3 includes the middle portion of Lolo Creek with inflows from the South Fork of Lolo Creek and other, smaller tributaries. The South Fork is the largest tributary to Lolo Creek and produces a significant portion of the water supply in the watershed, sometimes doubling the discharge of Lolo Creek downstream of its mouth. Region 3 contains the first major valley as you move downstream in the watershed and has greater housing development and agricultural production. The drainage area encompassed by Region 3 contains the highest elevation in the Lolo Creek watershed, including the northern aspects of Lolo Peak with terrain above 9,000 ft.

Sources of inflow to Region 3 included streamflow from the South Fork, other small unmeasured tributaries, inflow from groundwater discharge, and irrigation return flows (Fig. 19a). Small, unmeasured tributaries were the second largest source of inflow to the region. Water supply from these other tributaries occurred mostly from March to June. From July until January, inflow from small tributaries was less than all other sources of inflow. Small unmeasured tributaries in Region 3 produced far less water supply in 2017 than unmeasured tributaries in Region 2, highlighting the complex spatial component of water supply in the watershed. Part II of this report will address this spatial variability more in-depth.

Discharge to Lolo Creek from groundwater was an important source of water supply during low flow months, accounting for as much as 25 – 30% of streamflow in certain years. Return flows from irrigation accounted for about the same volume as groundwater discharge, but peaked earlier, mirroring monthly diversions. Outflows included diversions and streamflow loss to the aquifer (Fig. 19a). Like Region 2, streamflow loss to the aquifer was small and not consistently observed.

The components of the water balance relating to irrigation were analyzed as fractions of monthly diversions to determine the fate of the diverted water (Fig. 19b). Results of this analysis showed that in Region 3, the majority (40 - 60% depending on the month) of diverted water ended up as surface or seepage return flow to Lolo Creek. Water that did not return to Lolo Creek during the irrigation season went to recharging the aquifer, crop consumption, other irrigation losses, or was exported from Region 3 to Region 4. Other irrigation losses here refer to the loss of water not associated with crop ET. The Holt Canal at the very downstream end of Region 3 diverted water to irrigated lands geographically located in Region 4. The water was considered lost to export because even if there were return flows or recharge, it would not return to Region 3.

For groundwater in Region 3, sources of inflow included unmeasured groundwater

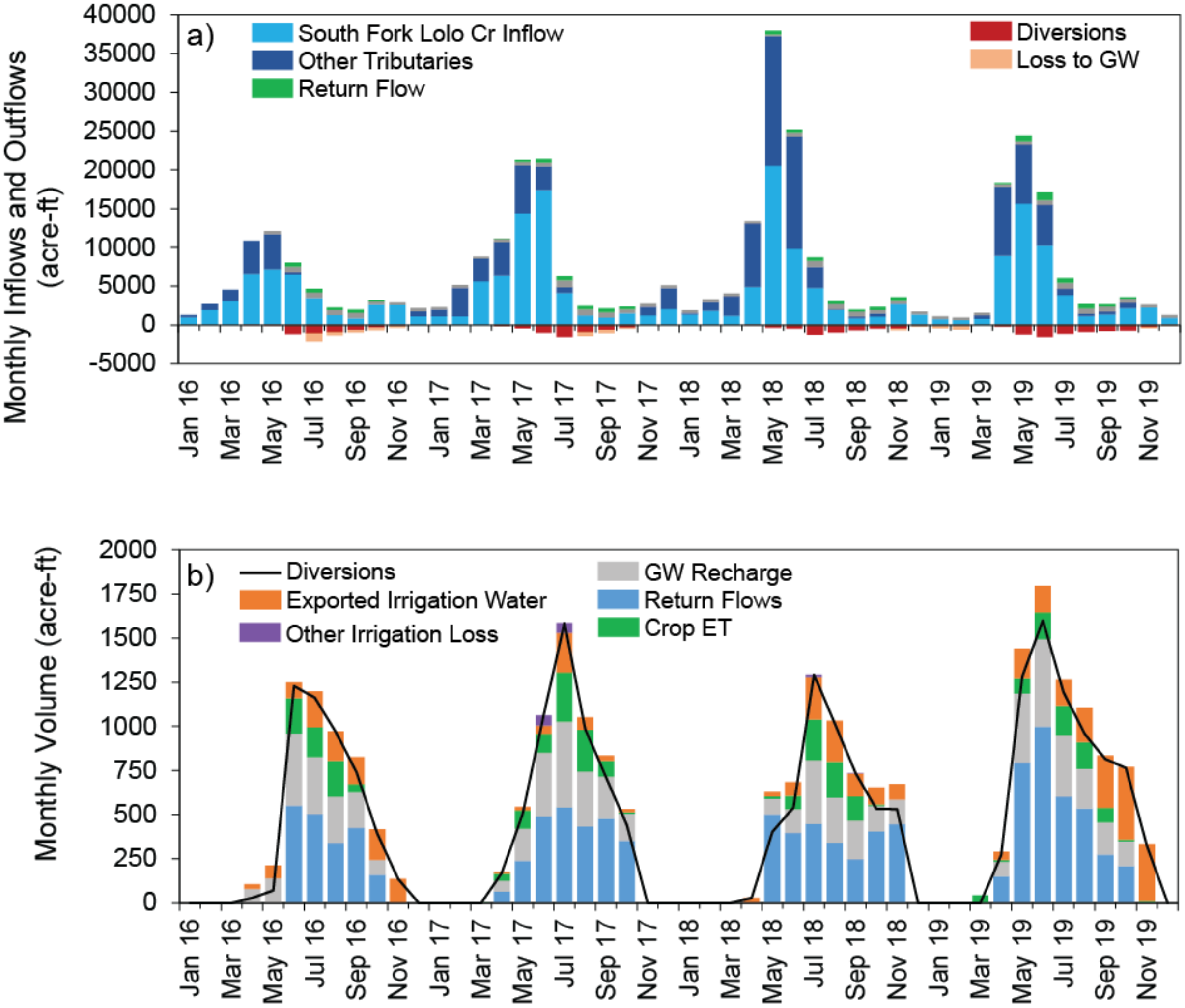


Figure 19. Graphs showing a) monthly volumetric inflows and outflows for Water Balance Region 3 surface water and b) monthly, total diversions where stacked bars represent the proportion of the diverted water that went to one of the five uses listed in the legend. The sum of all categories in b) equals the total diverted volume, for bars that do no match diversion, this is due to error in estimating groundwater recharge and return flows.

inflows (e.g., mountain front recharge, tributary groundwater inflow, or upstream groundwater inflow) and inflow from surface water sources (i.e., Lolo Creek or irrigation). The bulk of groundwater in Region 3 was from unmeasured sources and inflow from surface water was primarily from irrigation (Fig. 20a). Outflows included groundwater outflow from Region 3 to Region 4, discharge to Lolo Creek as streamflow, and withdrawal for domestic and lawn and garden use. Approximately 50% of outflow from Region 3 was groundwater outflow and 50% discharge to Lolo Creek except from June to October,

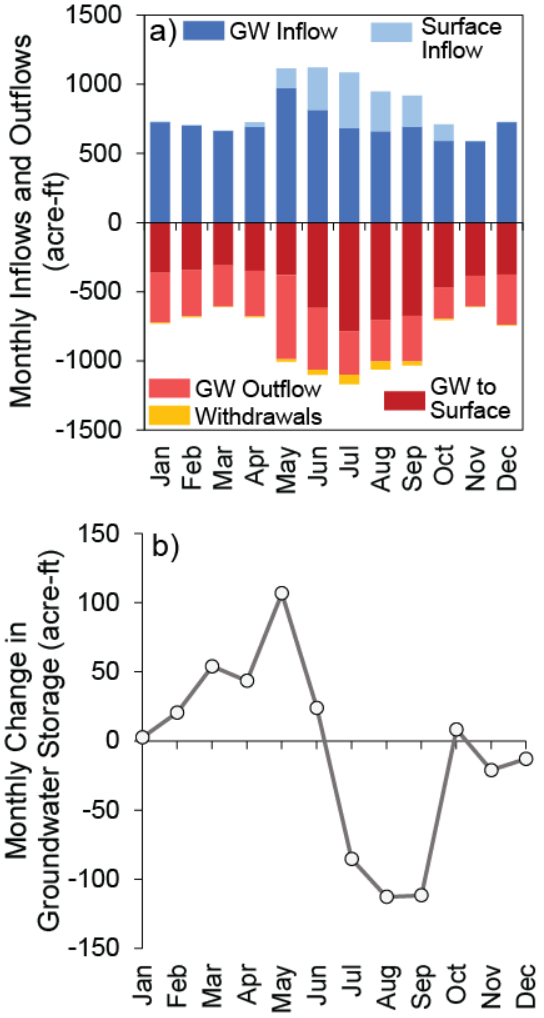


Figure 20. Graphs showing a) monthly volumetric inflows and outflows for Water Balance Region 3 groundwater and b) monthly change in groundwater storage.

when discharge to Lolo Creek was greater. The peak in groundwater discharge to Lolo Creek is a factor of recharge from irrigation, but also lag in groundwater outflow. Because inflow to groundwater occurred faster than water could leave the aquifer, there was storage of water observed in Region 3 (Fig. 20b). From October to February, the basin-fill aquifer in Region 3 was in approximate equilibrium (considering uncertainty in the water balance calculations), meaning that the same amount of groundwater flowing into the Water Balance Region flowed out. From March until May, groundwater inflows were greater than what left the aquifer, creating a surplus of stored water. From June to October, inflows were less than what left the aquifer because the stored water from earlier in the year was discharging. This pattern of change in storage suggests that the bulk of recharge occurs during snowmelt and it takes 3 – 4 months for the surplus water to flow out of the region.

Water Balance Region 4

Region 4 is the lower valley portion of Lolo Creek with sparse (< 5% of total water supply) inflows from Sleeman and Mormon Creeks. These small tributaries provide very little of the total water supply. This Water Balance Region contains rural and urban development surrounding the community of Lolo. Agricultural production within the actual watershed boundary has largely been replaced by housing development. There is a significant area of irrigated land watered by Lolo Creek located to the south, outside the watershed boundary. These irrigated fields are considered not hydrologically connected to Lolo Creek and all water diverted to these lands (that doesn't seep back to the creek before leaving the watershed) is considered exported. Region 4 terminates at Highway 93 where the most downstream gage used in this study is located (76HB 09600; Fig. 3).

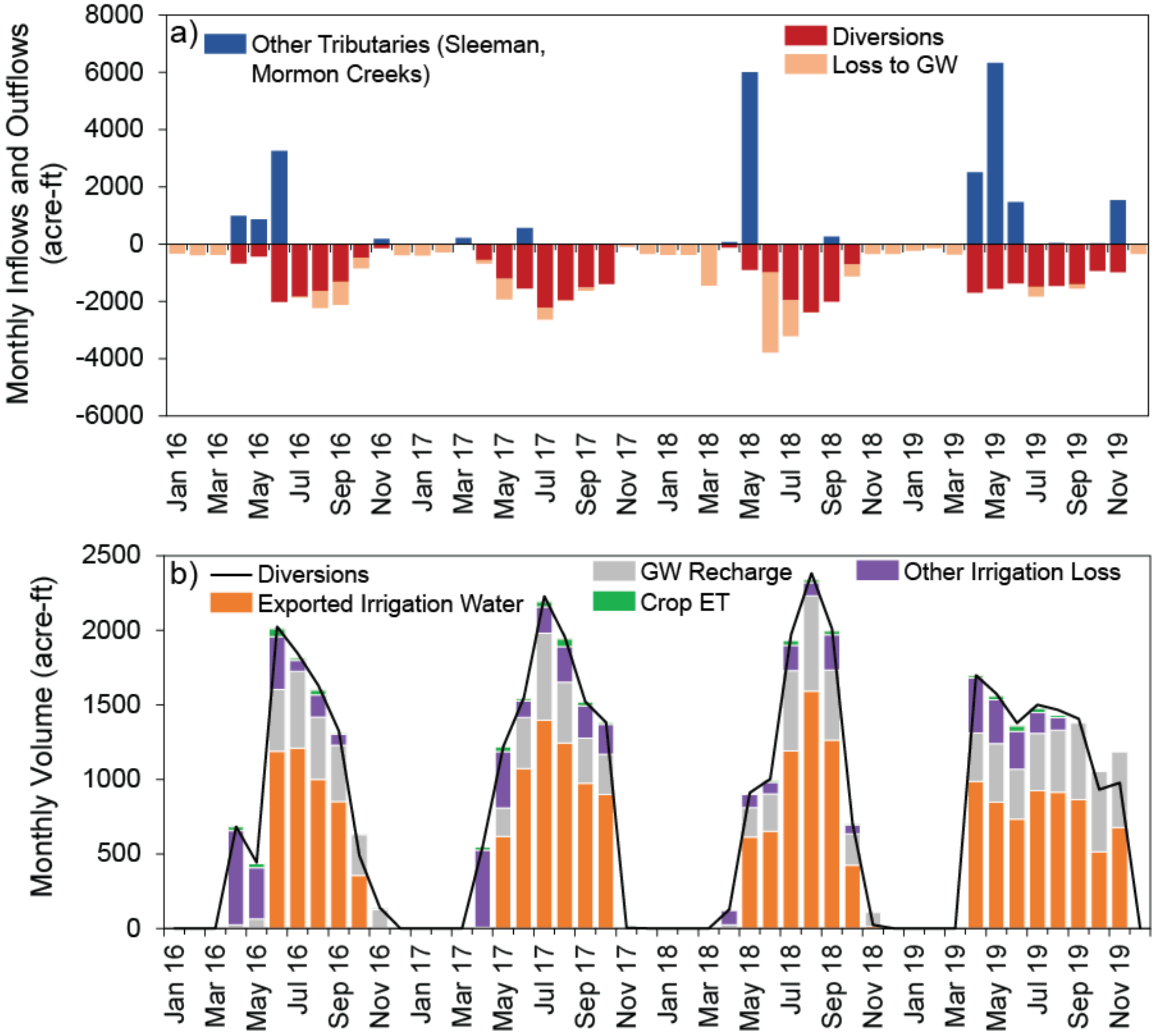


Figure 21. Graphs showing a) monthly volumetric inflows and outflows for Water Balance Region 4 surface water and b) monthly, total diversions where stacked bars represent the proportion of the diverted water that went to one of the five uses listed in the legend. The sum of all categories in b) equals the total diverted volume, for bars that do no match diversion, this is due to error in estimating groundwater recharge and return flows.

Sources of inflow to Region 4 included the unmeasured tributaries, Sleeman and Mormon Creeks (Fig. 21a). Aside from these mostly seasonal streams, there was no water supply produced in Region 4. Sleeman and Mormon Creeks had streamflow contributions during spring runoff and occasionally in the fall during rainstorms. In 2017, these tributaries had very little or no measured streamflow. However, in May of 2018 and 2019, they produced almost as much water supply as similar sized creeks in upper and middle Lolo Creek. Outflows for Region 4 included diversions and streamflow loss to the aquifer (Fig. 21a). Region 4 contained the largest diversion in the watershed, which is reflected by diversion volumes greater than any of the other Water Balance Regions. Region 4 diversions peaked in July or August, except in 2019 which had uniform diversion rates through the irrigation season. Streamflow loss to groundwater was greatest in Region 4 likely due to several factors discussed throughout this report including the geologic setting, interaction with the Bitterroot Aquifer, and groundwater pumping. Measurable streamflow loss occurred year-round, except for certain months during the snowmelt season. Loss likely still occurred during these months but was not measurable by the two stream gages because of high tributary inflows. Region 4 is the only Water Balance Region where streamflow out was generally always less than streamflow in (i.e., there was a net loss of water that was not recovered in the system).

The irrigation components of the water balance were analyzed as fractions of the total monthly diversions to determine the fate of the diverted water (Fig. 21b). One noticeable difference between Region 4 and Region 3 is the absence of return flows. This is based on the observation of net streamflow loss throughout the year. Although Chambers (2016) suggested there may be areas of groundwater discharge in Region 4, we assumed that the eventual fate of return flow was to be lost to groundwater and not recovered within the Water Balance Region. Therefore, instead of return flows, seepage was considered part of "other irrigation losses," because it exited the watershed as groundwater outflow. Most of the diverted water (60 – 70%) is exported to the irrigated lands outside the watershed boundary. Groundwater recharge and other irrigation losses could be considered the same category in this case, but we have isolated them to highlight the fate of non-exported diversions. A very small fraction of the diverted water is consumed by crop ET. Crop ET for the irrigated lands outside the watershed was lumped into the exported water but is higher than any other Water Balance Region.

Sources of groundwater inflow in Region 4 are unmeasured groundwater inflows and inflow from surface water sources. The bulk of Region 4 groundwater inflow was from Lolo Creek. (Fig. 22a). Groundwater inflow from Region 3 was generally less than or equal to surface inflow. Recharge from irrigation was minor compared to Lolo Creek streamflow losses. Outflows included groundwater outflow from Region 4 and withdrawals for household and municipal uses. Groundwater outflow from Region 4, and subsequently the watershed, accounted for nearly all the outflows (Fig. 22b). Groundwater outflow was highest from May to September, with a monthly volume between 1,000 – 1,500 acre-ft, or 16 – 25 cfs (Fig. 22), which agrees with outflow rates estimated by Boer (2002). Region 4 household and municipal withdrawals are the highest of any Water Balance Region, with a peak from May to September when most people are

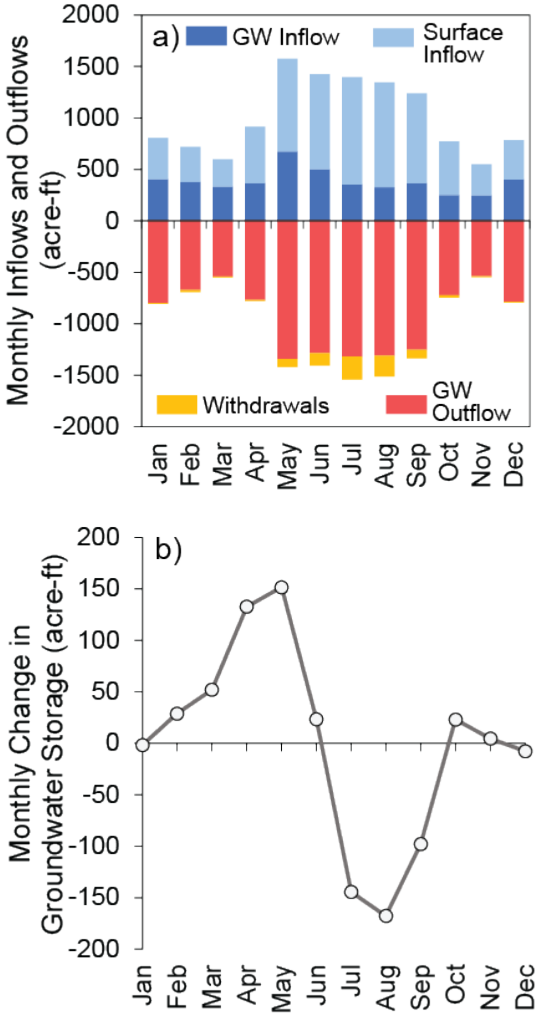


Figure 22. Graphs showing a) monthly volumetric inflows and outflows for Water Balance Region 4 groundwater where negative numbers denote outflows and b) monthly change in groundwater storage where negative values denote loss of storage.

watering lawns. The lag between inflow to the aquifer and discharge in Region 4 is similar to Region 3. More water flows into the aquifer than leaves from February to May, more water is discharged from the aquifer than flows in from May to October, and equilibrium conditions exist the rest of the year (Fig. 22b). The same pattern of recharge during snowmelt and a 3- to 4-month discharge period was also observed.

Water Balance Region 5

Region 5 was downstream of the most downstream stream gage site used in this study and encompassed the very small drainage area for the last 1.5 miles of Lolo Creek from Highway 93 to the Bitterroot River. No water balance was done for this region because no outflows were measured and there was likely a high degree of interaction with the Bitterroot aquifer and floodplain creating a complex system to quantify. However, water use was calculated for this region (see Water Use results below) because of the presence of household and agricultural uses.

Natural Flows and Water Supply

After calculating the water balance, natural monthly flows were estimated by removing all water use from each Water Balance Region. For Region 3, estimating the natural flows was more complicated because of the surface-groundwater interactions. The process for adjusting groundwater discharge to Lolo Creek for a no irrigation scenario is discussed in Section A2.4 of *Appendix A*. All tributaries that were measured for this study had gaging locations above any surface water diversions or significant water use; therefore, there was no difference between the measured flow and natural flow. The natural total annual water supply of Lolo Creek was estimated to be 162,543 acre-ft per year (~224 cfs), which is about 10,000 acre-ft per year (~14 cfs) more than the measured supply at the watershed outlet with current water use.

Natural supply in upstream parts of the watershed was not significantly different than measured supply. Estimated monthly natural flows were not significantly different for Region 3, with a mean average annual flow about 1 cfs, or ~1,400 acre-ft, higher than the observed flow. The largest disparity between estimated natural flows and measured flows was at Highway 93. From July to November, natural flows were noticeably different than measured (Fig. 23). Measured flows during these months could be 10 – 30 cfs lower than the natural flows. The greatest difference was in August – September of 2016 and the smallest difference in August – October of 2019. This supports the observation that at a monthly scale (low flow months in particular), Lolo Creek may have limited supply with current water use. In terms of total annual water supply, Lolo Creek is not as limited as other basins with much greater, year-round water use.

Water Use and Natural Losses

Lolo Creek Summary

Consumptive uses remove water from the available supply such that it is not returned as a reusable resource. This is typically achieved by ET but can also be accomplished by physically transporting water out of the basin via a ditch or pipeline. Water may also go to recharging groundwater where it can flow out of the basin via shallow or deep aquifers without interacting with surface water. For this study, we lumped together groundwater outflows and unmeasured sources of ET, including open water evaporation and riparian vegetation ET, into a "natural losses" category. We refer to this category as losses because it includes both consumptive and non-consumptive components but still represents water that is functionally removed from the system. Natural losses are calculated as the remaining gain or loss of surface water and therefore contain all sources of uncertainty from the water balance. It is impossible to accurately

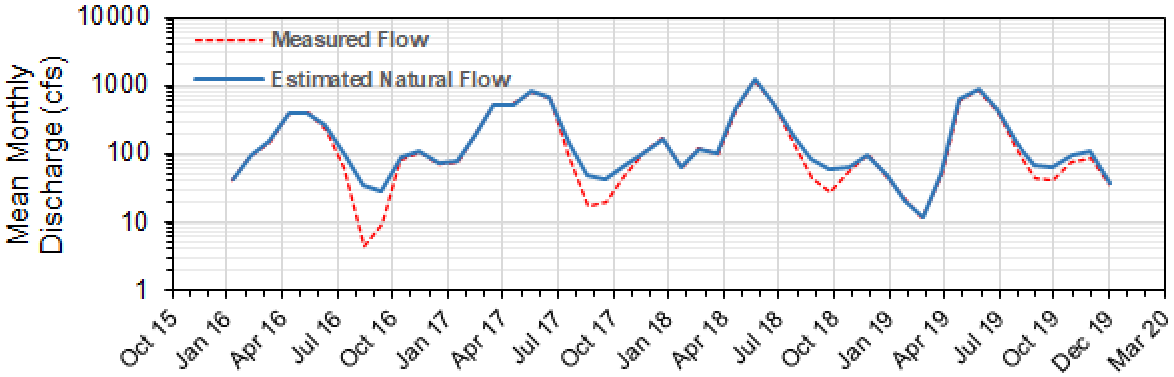
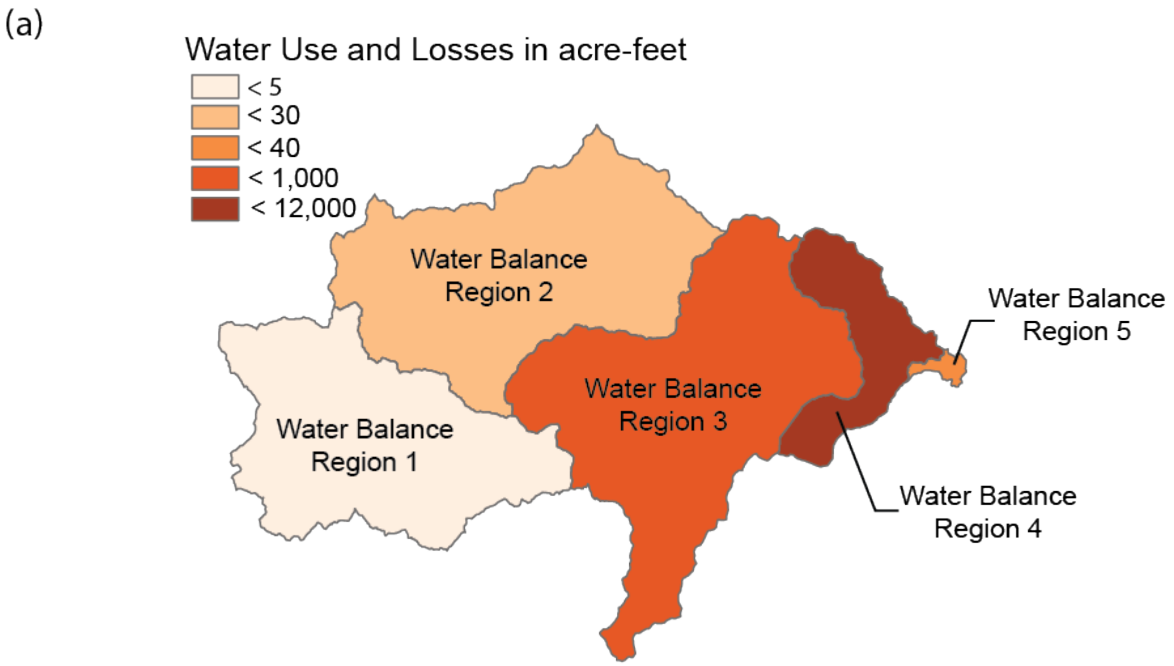


Figure 23. Comparison of measured flows and estimated natural flows at the DNRC Highway 93 stream gage.

determine rates of natural loss during snowmelt conditions without gaging every tributary. Calculated, monthly natural losses for spring runoff were typically small and may not capture the true magnitude of natural loss; however, the reported values are the best estimate using the available data.

Water use in the Lolo Watershed can be summarized by the three primary categories: 1) irrigation, 2) domestic, and 3) municipal. Municipal use, for the Lolo Watershed, was equal to the monthly pumped volumes from LWSD well #3. This category is referred to as "exported municipal water" because it is pumped from the watershed but used, treated, and then returned to the Bitterroot River. Although exported water is an outflow, we considered it a consumptive use such that the total diverted/withdrawn amount at the watershed boundary is removed from the system. For domestic use within the watershed, we used the consumed fraction of diverted/withdrawn water. We identified sub-categories for irrigation and domestic uses to provide additional detail about the fate of the water used for these purposes. The following three sub-categories described consumption and irrecoverable loss of irrigation water: 1) crop consumption, 2) exported irrigation water, and 3) other irrigation losses. Crop consumption is a consumptive use that represents the volume of water used for crop growth, which is removed from the watershed via ET. Exported irrigation water represents the volume of diverted irrigation water that is transported out of the watershed. The entire diverted volume, at the watershed boundary, was removed from the system, as if it had evaporated. Other irrigation losses were defined as another lumped category, like natural losses. This category includes both consumptive uses like incidental ET during transport and delivery of irrigation water and non-consumptive uses like irrecoverable seepage from fields and ditches. Domestic use was divided into the following two categories that were defined previously: 1) indoor and 2) outdoor, or lawn and garden irrigation.

Figure 24a illustrates the spatial distribution of water use by Water Balance Region and Figure 24b shows the average water use by category for the entire watershed over the 4-year study period. The table incorporated in Figure 24b lists use by category and total use for each of the 4 years of the study. Annually, an average of 12,371 acre-ft (~17 cfs per day for a whole year) was consumed, exported, or lost via natural processes in the Lolo Creek watershed. This volume equates to about 8% of the 162,543 acre-ft of water that would have naturally flowed (i.e., with no consumptive uses and only natural losses) out of Lolo Creek each year. The most water was used in Water Balance Region 4, which had the highest population and most agricultural production in the watershed. Irrigation (crop consumption, exported irrigation water, and other irrigation losses combined) represented the largest use of water, collectively accounting for 53% of all water use and losses. Domestic use (indoor and outdoor combined) accounted for roughly 4% of the total water



(b)

Type of Use	2016	2017	2018	2019	Average
Exported Irrigation Water	3308	4454	4128	4640	4132
Crop ET	819	1093	802	868	895
Other Irrigation Losses	1625	1946	834	1136	1385
Natural Losses	5594	3503	7788	2971	4964
Lawn and Garden	493	489	432	462	469
Exported Municipal Water	214	425	193	324	289
Indoor Domestic	19	22	19	25	21
TOTAL	12484	12053	14333	10612	12371

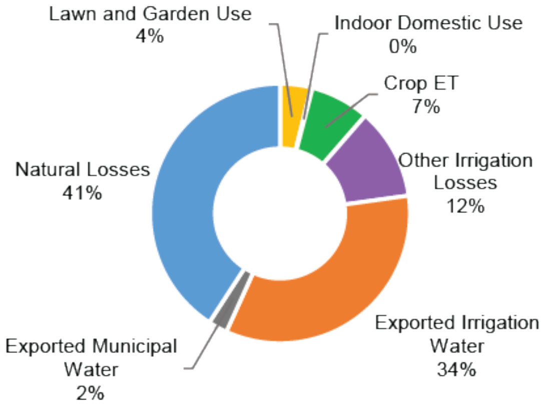


Figure 24. Water use and losses for the Lolo Creek watershed represented spatially by (a) a map of Water Balance Regions where color relates to the 2016 – 2019 average total water use and loss (light colors are lower use, dark colors are higher use); and temporally by (b) a table of annual values for each use or loss category. The pie chart in (b) is a proportional representation of the highlighted column in the table, such that it shows the 4-year average water use for the entire watershed.

use and losses, municipal use was 2%, and natural losses accounted for the remaining 41% of the combined water use and losses in the Lolo Watershed.

The highest total combined water use and loss was in 2018, while 2019 had the lowest. Inter-annually, any patterns in water use and loss were driven by natural losses.

While irrigation use accounted for the highest use and loss in the watershed, it was relatively consistent year-to-year compared to naturally occurring stream losses. The variation in natural losses was largely a factor of the timing of interaction between the groundwater and surface water. Variability was especially high during peak flows and more consistent during low flows. High magnitude, overbank floods increase the amount of water delivered to the floodplain which in turn increases natural soil moisture storage and seepage into the aquifer. This is very dependent on inundated area and can vary based on the characteristics of a given flood event. In Region 4, increased streamflow loss during high flows likely recharged the aquifer and flowed out of the watershed as groundwater. Streamflow loss during base-flows were more consistent but were different between years because of factors that alter the gradient between surface and groundwater (Chambers, 2016).

Water use followed patterns in precipitation and temperature. Excluding natural losses, 2017 had the highest rate of water use during the study period while 2018 had the lowest. Irrigation and lawn and garden uses correlated well with hot, dry summer conditions because more irrigation water was needed to overcome the lack of precipitation and increased ET. Although 2017 had the highest water supply of any year during this study, there was very little precipitation from mid-June to September (Fig. 7a) and summer temperatures were much higher than normal (Fig. 10). In higher flow years like 2018, cool, wet conditions supplemented irrigation so that less was needed. Exported irrigation water followed identical patterns, except for 2016, which likely represents an attempt by irrigators to preserve flow in Lolo Creek by reducing diversions. Indoor domestic use stayed nearly constant from year to year during the study period.

The month with the single highest combined use and loss was June 2018 with about 3,500 acre-ft, or 59 cfs each day for the entire month (Fig. 25a). This rate of use and loss was large compared to late summer Lolo Creek baseflow of 20-40 cfs but represented only 9% of the mean monthly discharge for June 2018. Natural losses in June 2018 were much higher than water use. Excluding natural losses, the month with the highest water was July 2017, with around 1,800 acre-ft. The month with the lowest combined use and loss was March 2017 with approximately 15 acre-ft, or 0.24 cfs each day for the entire month. In a typical year, peak water use occurred in July and August while low use occurred through the winter months December, January, and February (Fig. 25b and Table 8). Natural losses were highest in spring/early summer and consistently below 500 acre-ft per month for the rest of the year, except the winter of 2018/2019. The peaks in natural loss coincided with recession of the spring runoff and rapid growth of natural riparian plants, as well as late season rain driven floods in September and October. The only use that did not conform to the hydrologic cycle was indoor domestic use,

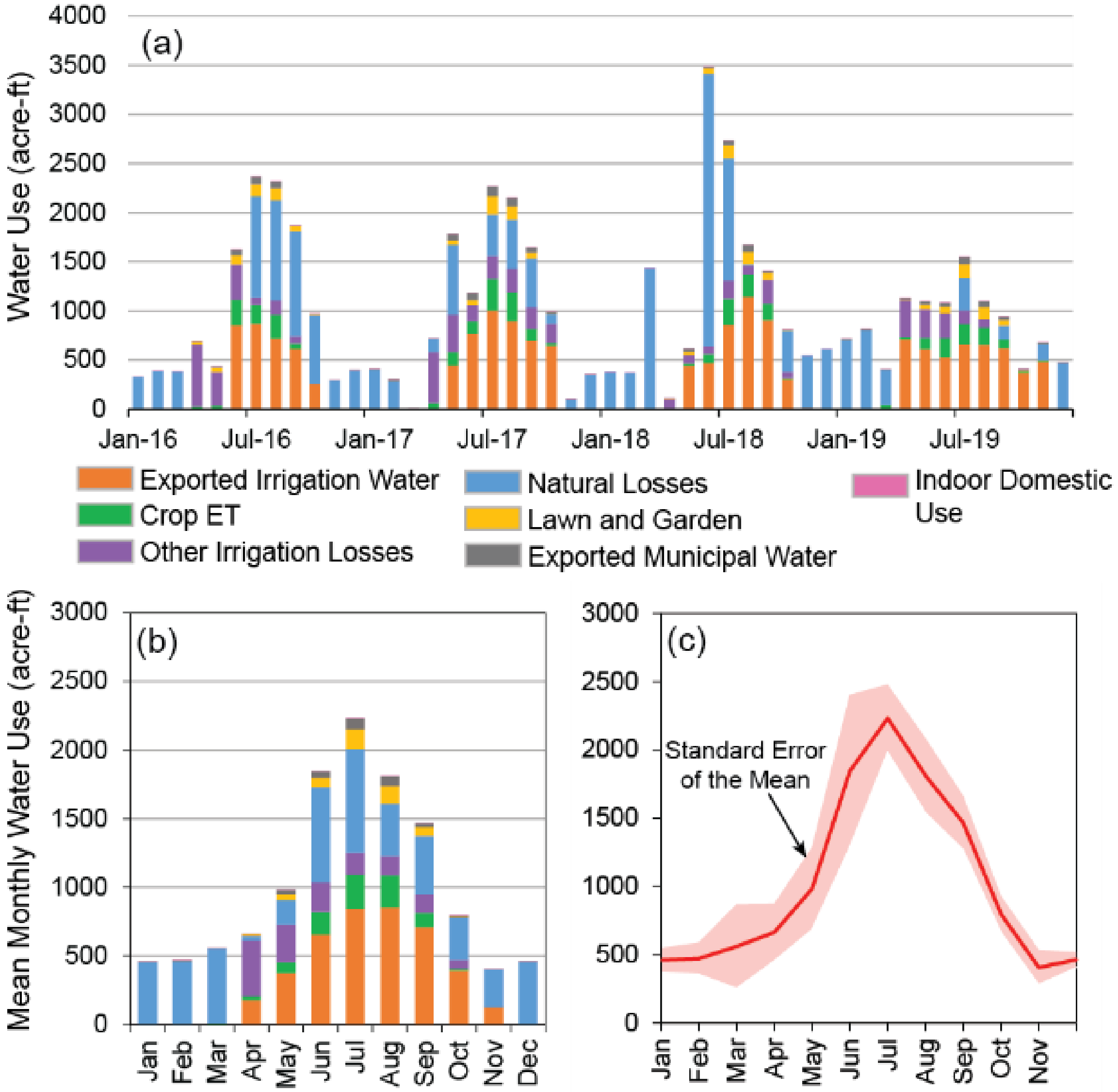


Figure 25. Graphs showing (a) monthly water use or loss for Lolo Creek watershed; (b) the 2016 – 2019 average monthly water use or loss, and (c) the inter-annual variability in average monthly water use and losses represented by the standard error (shaded region).

which remained constant throughout the year. Indoor domestic use represented a very small amount of consumption in the watershed (approximately 0.2%). Variability in water use and loss was determined by the standard error of the average-monthly combined water use and natural loss. Variability was higher in the spring/early summer (± 20 to 50% of average) and lower from August to October (± 5 to 15%) (Fig. 25c). November to February had moderately, consistent water use and natural loss.

Table 8. Lolo Creek 2016 – 2019 average monthly water use or loss by type in acre-ft.

Month	Lawn and Garden Use	Indoor Domestic Use	Crop ET	Other Irrigation Losses	Exported Irrigation Water	Exported Municipal Water	Natural Losses	Total
Jan	0.00	1.84	0.00	0.00	0.00	4.91	453.20	459.95
Feb	0.00	1.88	0.00	0.00	0.00	8.50	461.72	472.10
Mar	0.00	1.74	10.56	0.00	0.00	3.00	543.92	598.11
Apr	9.61	1.70	31.20	403.39	177.14	5.61	33.96	702.11
May	43.96	1.81	78.08	275.22	373.28	33.01	178.46	1019.93
Jun	69.68	1.76	168.60	212.23	654.22	45.11	693.25	1856.70
Jul	147.20	1.81	247.45	157.14	847.52	74.52	754.83	2263.35
Aug	128.59	1.81	236.20	138.83	852.24	71.79	382.22	1841.29
Sep	62.09	1.76	107.26	132.20	709.89	26.21	426.65	1480.99
Oct	7.68	1.81	13.12	64.96	393.63	10.55	305.40	803.86
Nov	0.00	1.68	2.97	1.50	124.44	2.73	273.59	410.90
Dec	0.00	1.73	0.00	0.00	0.00	2.81	456.87	461.42

Water Balance Regions

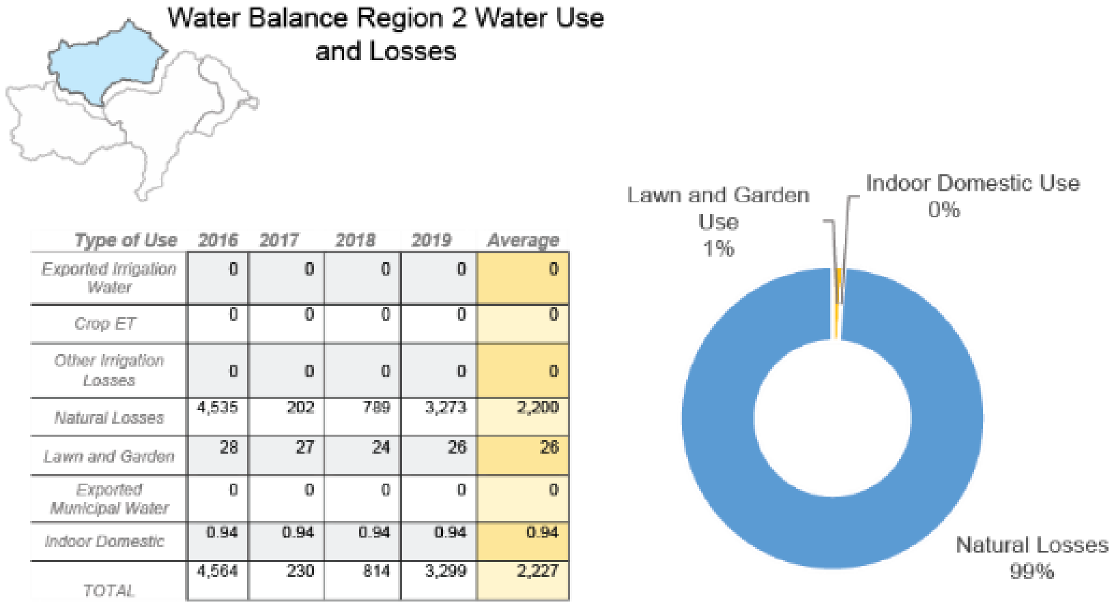
The following results provide more detail about water use and losses in each Water Balance Region. Water Balance Region 1 is considered to have no substantial use and Water Balance Region 5 was not included in the surface water balance, but water use was estimated for this region and included here for consistency.

Water Balance Region 1

No water use was calculated for Water Balance Region 1. This region encompasses the headwaters of Lolo Creek which is almost 100% National Forest land. It was assumed that water use, other than naturally occurring losses, was negligible to zero here because of the lack of significant development or irrigated lands. Outflow from this region was measured by the Lolo Creek below Granite Creek gage and was considered the natural flow produced by the headwaters.

Water Balance Region 2

There were no major irrigated lands in Water Balance Region 2 and very little housing or development. Water use and loss in this region averaged 2,227 acre-ft per year. Almost all, or 99%, of this volume was natural loss from Lolo Creek with the remaining 1% being domestic uses (Fig. 26). Natural losses from this region were not included in the total natural loss calculation for the entire watershed because much of the natural loss likely goes to groundwater that flows into Water Balance Region 3, a portion of which may resurface as streamflow. The consumption from domestic use for this region was approximately 27 acre-ft/yr, which is 0.2% of the total use for the entire



Type of Use	2016	2017	2018	2019	Average
Exported Irrigation Water	0	0	0	0	0
Crop ET	0	0	0	0	0
Other Irrigation Losses	0	0	0	0	0
Natural Losses	4,535	202	789	3,273	2,200
Lawn and Garden	28	27	24	26	26
Exported Municipal Water	0	0	0	0	0
Indoor Domestic	0.94	0.94	0.94	0.94	0.94
TOTAL	4,564	230	814	3,299	2,227

Figure 26. Summary of water use and losses for Water Balance Region 2. Average conditions (highlighted column in table) are shown proportionally by a pie-chart and annually by type of use or loss in the associated table. All values other than percentages are in acre-feet.

watershed. Domestic water use peaked in July and August depending on the year (Table 9). Natural losses occurred in most months but were highest in the winter and early spring. Some natural loss was observed in the late fall that coincided with rain driven floods. Most of the natural losses were likely seepage to groundwater that did not return to Lolo Creek within Region 2. Domestic use was dominated by lawn and garden irrigation, which peaked in July (Table 9). Indoor use was a fractional percent of the total use in Water Balance Region 2 and remained relatively constant year-round.

Water Balance Region 3

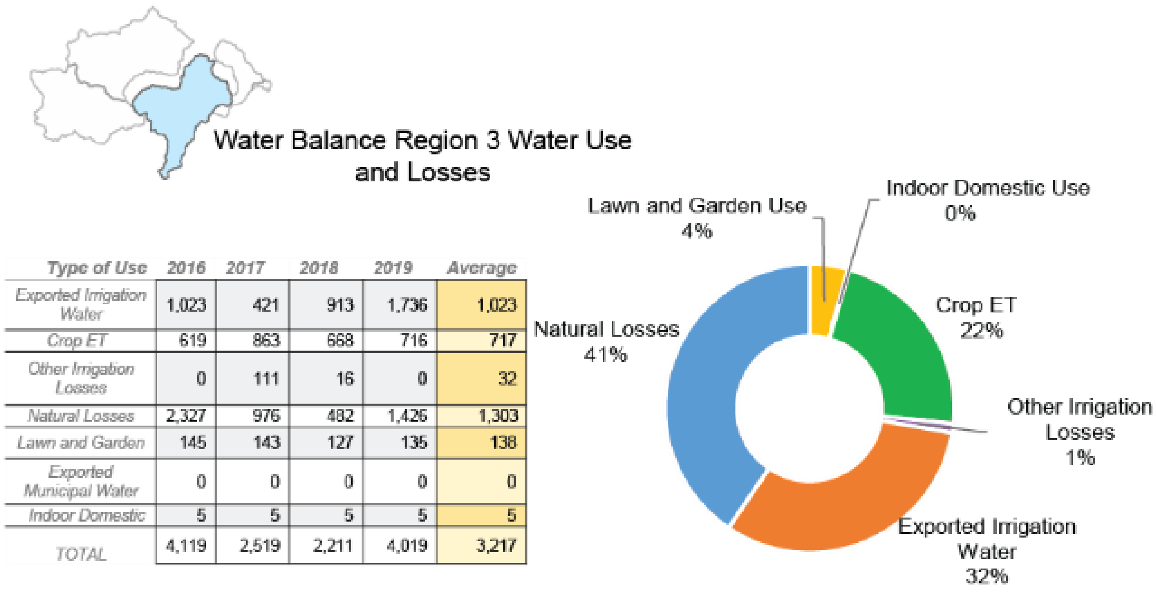
Water Balance Region 3 included the first major valley in the Lolo Creek watershed (beginning at the headwaters moving downstream). Consumptive use is centered around the valley portion of this region, which includes mostly agricultural land. Most housing exists as rural development at the downstream end of the region in the Mill Creek area. Combined water use and loss in this region averaged 3,217 acre-ft/yr. Water use was mixed here but the majority was for agricultural irrigation, which collectively accounted for 59% of water use (Fig. 27). Of the 59%, 32% was exported out of the region, 22% was consumed by crops, and 1% was from other irrigation losses. Of the remaining 24% of the total water use and loss in Region 3, 41% was lost by natural processes, 4% went to lawn and garden irrigation, and indoor

Table 9. Water Balance Region 2 average monthly water use or loss by type in acre-ft.

Month	Lawn and Garden Use	Indoor Domestic Use	Crop ET	Other Irrigation Losses	Exported Irrigation Water	Exported Municipal Water	Natural Losses	Total
Jan	0.00	0.08	0.00	0.00	0.00	0.00	403.30	403.38
Feb	0.00	0.07	0.00	0.00	0.00	0.00	486.80	486.87
Mar	0.00	0.08	0.00	0.00	0.00	0.00	472.11	472.19
Apr	0.54	0.08	0.00	0.00	0.00	0.00	233.92	234.54
May	2.46	0.08	0.00	0.00	0.00	0.00	0.00	2.54
Jun	3.89	0.08	0.00	0.00	0.00	0.00	358.88	362.85
Jul	8.22	0.08	0.00	0.00	0.00	0.00	0.00	8.30
Aug	7.18	0.08	0.00	0.00	0.00	0.00	0.00	7.26
Sep	3.47	0.08	0.00	0.00	0.00	0.00	0.00	3.55
Oct	0.43	0.08	0.00	0.00	0.00	0.00	136.11	136.62
Nov	0.00	0.08	0.00	0.00	0.00	0.00	108.70	108.78
Dec	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.08

domestic use accounted for < 0.1%. It is important to note that for individual Water Balance Regions, exported water can be water that is diverted away from the watershed entirely or to another Water Balance Region. For this region, the exported irrigation water is diverted downstream to Water Balance Region 4, staying in the watershed. Therefore, this exported irrigation water (specific to only Water Balance Region 3) was not included in the watershed total "exported" water (refer to Fig. 24b). Excluding exported water from the total use and loss in Water Balance Region 3 gave an average annual volume of 2,194 acre-ft/yr, which was 18% of the total water use for the watershed. Natural losses in Region 3 were likely overestimated because the diverted volume from the Holt Ditch was not measured for calendar year 2016 (the Holt Ditch is the diversion that exports water to Region 4). We estimated the diverted volume from the ditch based on seasonal average diversion rates for 2017 – 2019, but without measured data there was additional uncertainty for 2016. Natural losses were counted in the watershed total for this region because any loss to groundwater likely flows through Region 4 and out of the drainage as groundwater.

July 2016 had the highest combined water use and loss in the study period because of abnormally high natural losses that could be inflated by unmeasured Holt Ditch diversions (Fig. 28a). Excluding 2016, July 2017 had the highest use and loss primarily because of crop consumption. The highest annual water use and loss for Region 3 occurred in 2016, followed by 2019. The lowest water use and loss was in 2018. On average, July had the highest use and loss because of peaks in lawn and garden



Type of Use	2016	2017	2018	2019	Average
Exported Irrigation Water	1,023	421	913	1,736	1,023
Crop ET	619	863	668	716	717
Other Irrigation Losses	0	111	16	0	32
Natural Losses	2,327	976	482	1,426	1,303
Lawn and Garden	145	143	127	135	138
Exported Municipal Water	0	0	0	0	0
Indoor Domestic	5	5	5	5	5
TOTAL	4,119	2,519	2,211	4,019	3,217

Figure 27. Summary of water use and losses for Water Balance Region 3. Average conditions (highlighted column in table) are shown proportionally by a pie-chart and annually by type of use or loss in the associated table. All values other than percentages are in acre-feet.

irrigation, crop use, and exported irrigation water (Fig. 28b and Table 10). Other irrigation related losses were small in Region 3. Natural losses were highest in winter and late fall. The intra-annual variability of water use and loss in this region (Fig. 28c) was high (± 36 to 99% of average) for winter and fall months, primarily due to the anomalous patterns in 2019. During the start and peak of the irrigation season (April – August) water use and loss was consistent, fluctuating 10 to 30%, or 10 to 70 acre-ft (0.2 – 1.2 cfs) per month.

Water Balance Region 4

Water Balance Region 4 is the most downstream region used in the water balance. The southern-most part of Lolo is included in this region as well as a mixture of small agricultural properties and an increasing amount of rural development. The largest diversion in the watershed is in Region 4, which delivers irrigation water south to fields outside of the Lolo Creek watershed on the western side of the Bitterroot valley. Irrigation water from Region 3 is imported into Region 4 to water fields geographically located in Region 4. Irrigated acreage in Region 4 has declined over the decades as the population of Lolo increases, replacing former irrigated lands with housing development. Although the LWSD has one municipal well located within the region, there are a limited number of properties serviced by municipal water. Combined water use and loss in this region averaged 9,899 acre-ft/yr, or 82% of the total water use for the entire watershed. Consumptive uses were dominated by exported irrigation water, which accounted for 42% of total water use and loss (Fig. 29). Crop consumption accounted for 1% of the total water use and loss in this region; this did not include crop ET associated with imported or exported irrigation water. Other irrigation losses (primarily seepage to groundwater in this case) were 14%, exported municipal water pumped from the LWSD well was 3%, lawn and garden use accounted for 3%, and indoor domestic use was ~0.1%. Natural losses were a significant portion of the combined water use and loss in this region at 37% of the total. Most of this loss is to groundwater that then flows out of the Lolo Creek watershed into the Bitterroot Aquifer. Higher natural losses were expected in this region based on data and the current understanding of groundwater-surface water interactions (Chambers, 2016).

June 2018 had the highest combined use and loss of any month in the study period for Region 4 and is anomalous compared to the same month in other years (Fig. 30a). This anomaly was driven by natural losses and likely caused by attenuation related losses during the larger than average snowmelt flood of 2018. In general, peak water use and loss ranged from June to August, depending on the year. Average-monthly water use, excluding natural losses, shows July with the highest consumption (Fig. 30b and Table 11). Crop consumption, exported irrigation water, and lawn and garden use peaked in July and August at the same time as other regions. Natural losses were consistently observed in all months. Other irrigation losses were highest at the start of the irrigation season likely because water is being diverted and either not applied to crops or applied when crop demand is low at that time of year. This

Table 10. Water Balance Region 3 average monthly water use or loss by type in acre-ft.

Month	Lawn and Garden Use	Indoor Domestic Use	Crop ET	Other Irrigation Losses	Exported Irrigation Water	Exported Municipal Water	Natural Losses	Total
Jan	0.00	0.42	0.00	0.00	0.00	0.00	120.19	120.61
Feb	0.00	0.38	0.00	0.00	0.00	0.00	165.70	166.08
Mar	0.00	0.42	10.56	0.00	0.00	0.00	0.00	10.98
Apr	2.82	0.40	12.47	0.00	27.38	0.00	0.00	43.07
May	12.89	0.42	50.99	0.00	70.72	0.00	0.00	135.02
Jun	20.44	0.40	134.27	14.01	91.23	0.00	0.00	260.36
Jul	43.18	0.42	211.67	17.04	204.63	0.00	250.01	726.95
Aug	37.72	0.42	197.75	0.00	166.31	0.00	223.81	626.00
Sep	18.21	0.40	88.97	0.71	151.20	0.00	167.98	427.48
Oct	2.25	0.42	7.37	0.00	175.18	0.00	111.00	296.22
Nov	0.00	0.40	2.67	0.00	136.58	0.00	168.92	308.58
Dec	0.00	0.42	0.00	0.00	0.00	0.00	95.39	95.81

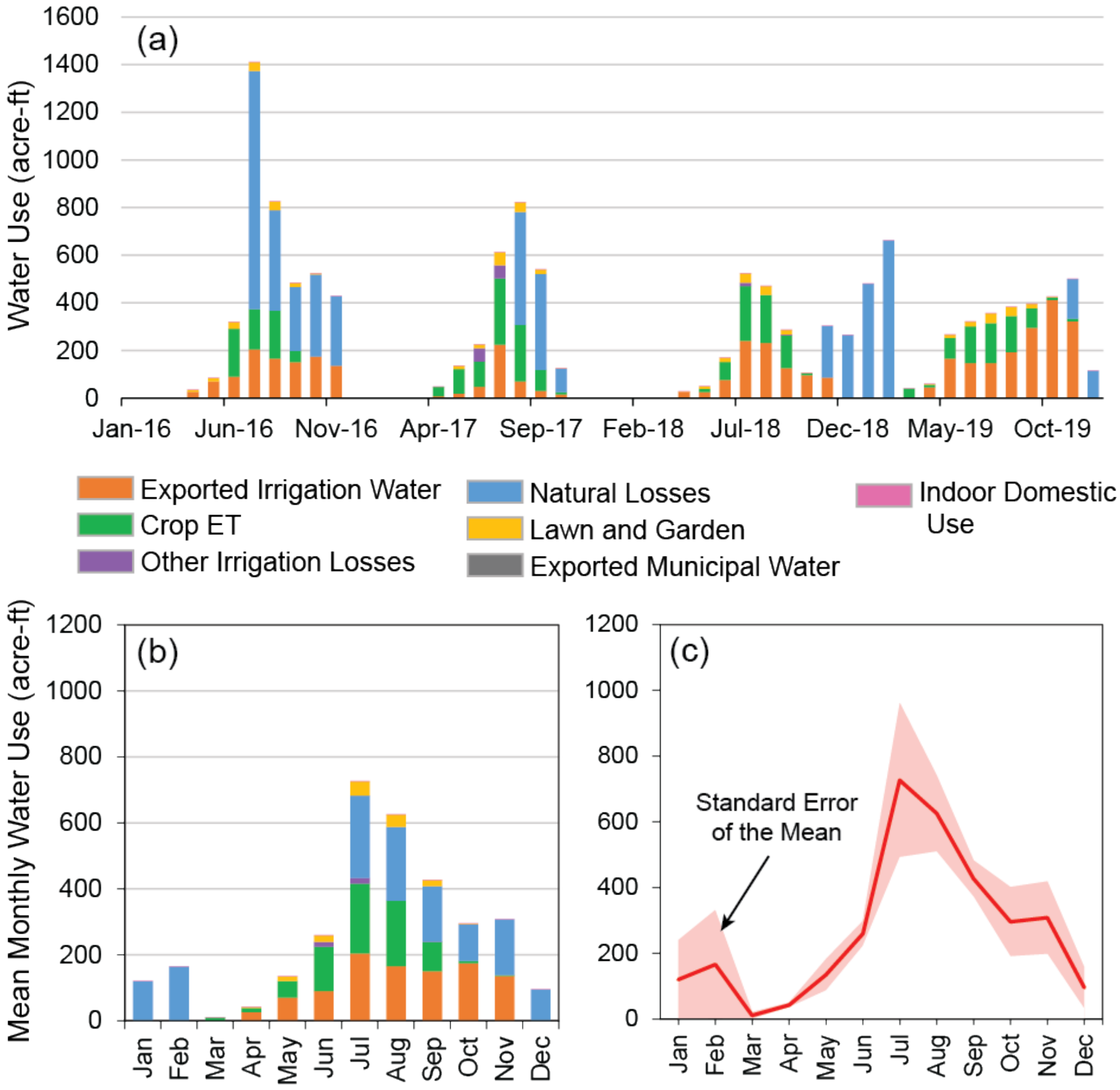
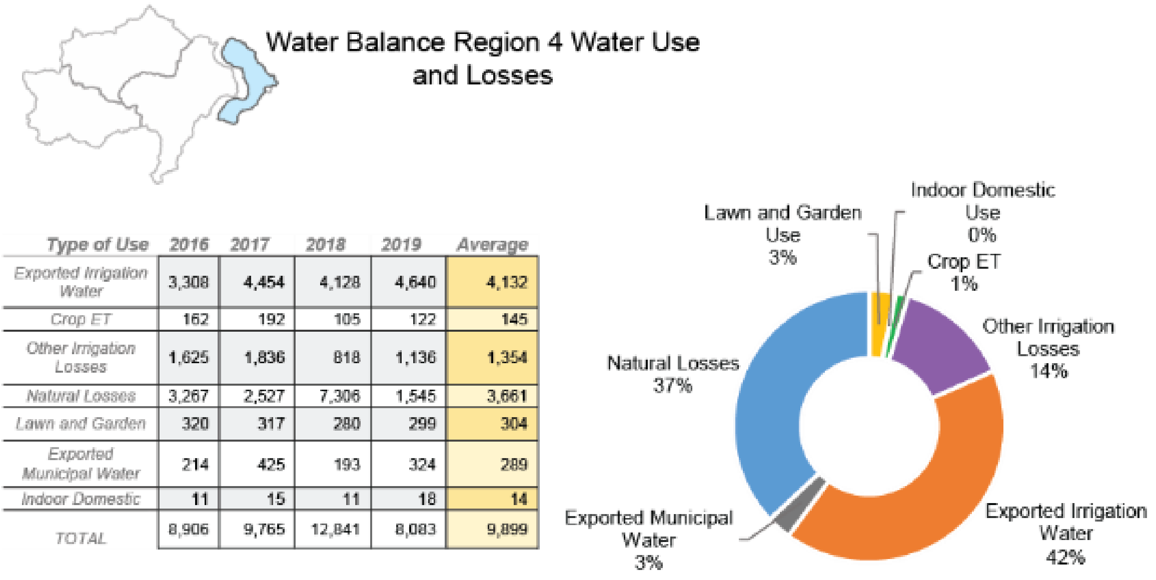


Figure 28. Graphs showing (a) monthly water use or loss for Water Balance Region 3; (b) the 2016 – 2019 average monthly water use or loss, and (c) the inter-annual variability in mean monthly use and losses represented by the standard error (shaded region).

early season water is diverted at the discretion of the irrigator and might be for maintaining water in ditches for other operational or permitted purposes (e.g., filling storage ponds, running pumps, increasing soil moisture content, or RC boat races). Exported municipal water was unique to Region 4 and followed a similar pattern as lawn and garden use, because municipal water pumped by Lolo residents was used for mostly outdoor purposes from April to November. The intra-annual variability of water use and loss in this



Type of Use	2016	2017	2018	2019	Average
Exported Irrigation Water	3,308	4,454	4,128	4,640	4,132
Crop ET	162	192	105	122	145
Other Irrigation Losses	1,625	1,836	818	1,136	1,354
Natural Losses	3,267	2,527	7,306	1,545	3,661
Lawn and Garden	320	317	280	299	304
Exported Municipal Water	214	425	193	324	289
Indoor Domestic	11	15	11	18	14
TOTAL	8,906	9,765	12,841	8,083	9,899

Figure 29. Summary of water use and losses for Water Balance Region 4. Average conditions (highlighted column in table) are shown proportionally by a pie-chart and annually by type of use or loss in the associated table. All values other than percentages are in acre-feet.

region (Fig. 30c) was consistent in winter months (± 5 to 20% of average) when use was lowest. March – June had the highest variability, fluctuating 25 to 53% or about 250 to 550 acre-ft (4-9 cfs) per month, over the 4-year study period. July – October had the most consistent water use observed for the whole study period, fluctuating 9 to 15%.

Water Balance Region 5

Water Balance Region 5 is downstream of the lower-most stream gage used in this study; therefore, natural losses were not estimated. Based on observational evidence it appears that groundwater (either from the Lolo Aquifer or the Bitterroot Aquifer) discharges to the last 0.5 – 1 mile of the creek. The exact mechanics of the interaction between the Lolo Aquifer and the Bitterroot Aquifer are complex and will be explored by MBMG's GWIP study. Domestic and irrigation water use exist in Region 5 and were estimated to provide a complete analysis of consumptive use for this study. Water use in this region was very miniscule, averaging 37 acre-ft per year or 0.3% of the total water use for the entire watershed. Almost all, or 92%, of the water use was crop consumption from irrigated land. Domestic uses accounted for the remaining 8%, with indoor use exceeding lawn and garden use (Fig. 31). Water use variability was characteristic of the other Water Balance Regions dominated by irrigation related losses, with most use occurring between April and October,

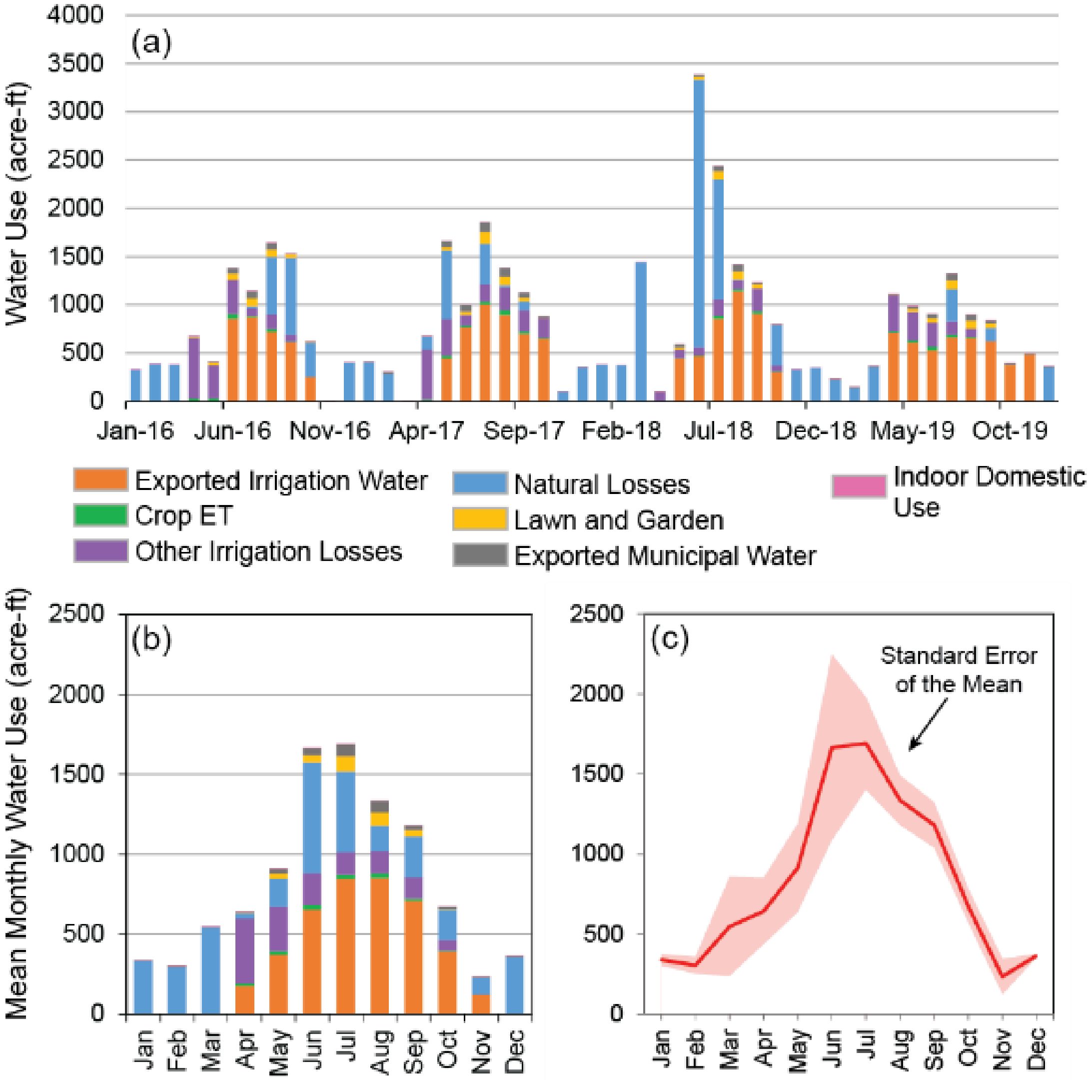


Figure 30. Graphs showing (a) monthly water use or loss for Water Balance Region 4; (b) the 2016 – 2019 average monthly water use or loss, and (c) the inter-annual variability in average monthly use and losses represented by the standard error (shaded region).

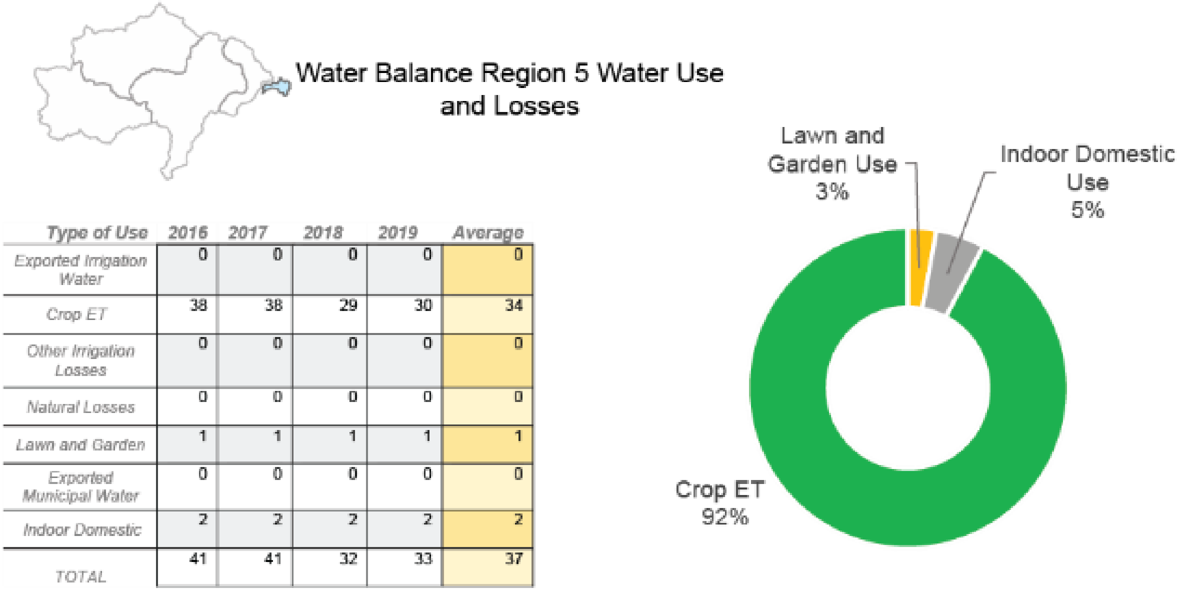
peaking in July (Table 12). The water use in this region had very little influence over water use patterns for the entire watershed, however, its proximity to the community of Lolo could mean increased domestic use in Region 5 as more development occurs.

Patterns of Water Use and Available Water Supply

It is important to understand the magnitude of water use, its variability, and potential causes for variations. Water use in the Lolo Creek watershed, relative to available water supply, is largely dependent on irrigation water use patterns and natural losses. As discussed previously, natural losses during high flows are more dependent on flood dynamics while low flow natural losses are better correlated with lower groundwater levels and water supply (i.e., dry years have higher losses, wet years have lower losses). Other water uses, while not completely detached from the natural hydrologic cycle, conform to more specific management decisions. At the regulatory level, management of agricultural irrigation is determined by the prior appropriation doctrine and Montana’s Water User Act. Within the period of use of their water rights, an irrigator decides their own management of appropriated water. These decisions are primarily motivated by economics, and therefore, water use would be expected to increase during dry years and decrease during wet years, as observed in Water Balance Regions 3 and 4. However, irrigation related uses can also be influenced by social, environmental, or conservation concerns as observed in summer of 2016 on Lolo Creek, when irrigation consumption decreased in response to dewatering, despite dry conditions. In contrast, domestic and municipal use is population driven and does not have as much year-to-year variation as irrigation use. Patterns in lawn and garden irrigation are like agricultural irrigation but are driven by landscaping aesthetics instead of crop yields. While local restrictions can be enacted for specific municipalities, there is no state law or regulation in Montana that

Table 11. Water Balance Region 4 average monthly water use or loss by type in acre-ft.

Month	Lawn and Garden Use	Indoor Domestic Use	Crop ET	Other Irrigation Losses	Exported Irrigation Water	Exported Municipal Water	Natural Losses	Total
Jan	0.00	1.19	0.00	0.00	0.00	4.91	333.00	339.10
Feb	0.00	1.28	0.00	0.00	0.00	8.50	296.03	305.81
Mar	0.00	1.09	0.00	0.00	0.00	3.00	543.92	586.90
Apr	6.24	1.07	16.34	403.39	177.14	5.61	33.96	683.24
May	28.51	1.16	23.34	275.22	373.28	33.01	178.46	949.10
Jun	45.19	1.13	29.57	198.22	654.22	45.11	693.25	1678.54
Jul	95.47	1.16	26.81	140.09	847.52	74.52	504.83	1723.27
Aug	83.40	1.16	30.08	138.83	852.24	71.79	158.41	1365.53
Sep	40.27	1.13	14.42	131.49	709.89	26.21	258.67	1197.01
Oct	4.98	1.16	4.44	64.96	393.63	10.55	194.41	680.82
Nov	0.00	1.05	0.10	1.50	124.44	2.73	104.66	238.49
Dec	0.00	1.08	0.00	0.00	0.00	2.81	361.48	365.38



Type of Use	2016	2017	2018	2019	Average
Exported Irrigation Water	0	0	0	0	0
Crop ET	38	38	29	30	34
Other Irrigation Losses	0	0	0	0	0
Natural Losses	0	0	0	0	0
Lawn and Garden	1	1	1	1	1
Exported Municipal Water	0	0	0	0	0
Indoor Domestic	2	2	2	2	2
TOTAL	41	41	32	33	37

Figure 31. Summary of water use and losses for Water Balance Region 5. Average conditions (highlighted column in table) are shown proportionally by a pie-chart and annually by type of use in the associated table. All values other than percentages are in acre-feet.

mandates conservation of domestic uses in times of drought.

Over-appropriation of a source is a condition when the permitted volume of water available for diversion, or withdrawal, exceeds the physical availability of water on that source. Given the semi-arid to arid climate of most of the western US, determining if a source is over-appropriated is important because of legal complications and the potential for conflict between water users. A primary question of this report is whether Lolo Creek is over-appropriated, or not. In Montana, the state has the authority to close river basins or aquifers to new appropriations of water due to availability, contamination, or existing water rights concerns (MT DNRC 2016). Effective March 29, 1999, the Montana Legislature voted to close the Bitterroot River Basin, including Lolo Creek, to new appropriations of water except for 1) new groundwater use, 2) municipal water supply, 3) temporary emergency appropriations as outlined in Montana Code Annotated (MCA) 85-2-113(3), and 4) to store water during high flows. The decision to close the Bitterroot Basin is evidence that water availability, in relation to expected or documented uses, is in question. Additional evidence to support over-appropriation is dewatering of the creek, which clearly shows there is not enough streamflow in some years to keep Lolo Creek

Table 12. Water Balance Region 5 average monthly water use or loss by type in acre-ft.

Month	Lawn and Garden Use	Household Use	Crop Use	Other Irrigation Losses	Exported Irrigation Water	Exported Domestic Water	Natural Losses	Total
Jan	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.15
Feb	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.14
Mar	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.15
Apr	0.02	0.15	2.40	0.00	0.00	0.00	0.00	2.56
May	0.10	0.15	3.75	0.00	0.00	0.00	0.00	4.00
Jun	0.15	0.15	4.76	0.00	0.00	0.00	0.00	5.06
Jul	0.33	0.15	8.98	0.00	0.00	0.00	0.00	9.45
Aug	0.29	0.15	8.37	0.00	0.00	0.00	0.00	8.81
Sep	0.14	0.15	3.87	0.00	0.00	0.00	0.00	4.15
Oct	0.02	0.15	1.31	0.00	0.00	0.00	0.00	1.48
Nov	0.00	0.15	0.19	0.00	0.00	0.00	0.00	0.34
Dec	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.15

connected to the Bitterroot River. However, the primary question raised by the LWG and stakeholders, and the focus of this report, is whether dewatering is fundamentally caused by over-use or is a natural phenomenon that occurred regardless of water use.

Natural losses were considered in determining over-appropriation on Lolo Creek, such that natural losses were considered an immutable water balance component that decreased available water supply. Total annual water use and loss in the Lolo Creek watershed was between 6% and 11% of the naturally available annual water supply. Using only the annual values, water use in the watershed does not appear to be greater than availability. This is usually the case in most western Montana watersheds; however, DNRC evaluates legal availability of surface water on a monthly scale in its Beneficial Water Use Permit adverse effect criteria analysis. Comparison of average annual conditions and average monthly conditions shows that the relation between water use and supply is more spatially and temporally nuanced. Over-appropriation is easily distinguished when analyzing monthly ratios of water demand versus supply. Average monthly water use and loss for the months August and September nearly equaled water supply, particularly in 2016 and 2017 (Fig. 32a). It is important to note that not all the water use in August or September was diverted directly from Lolo Creek, and that groundwater withdrawals may have a delayed effect on streamflow. Pumping groundwater can alter the vertical gradient between surface water and groundwater causing more loss. Because this report considers irretrievable loss to groundwater a "natural loss," some of the natural losses reported for Water Balance Region 4 could potentially be enhanced by groundwater

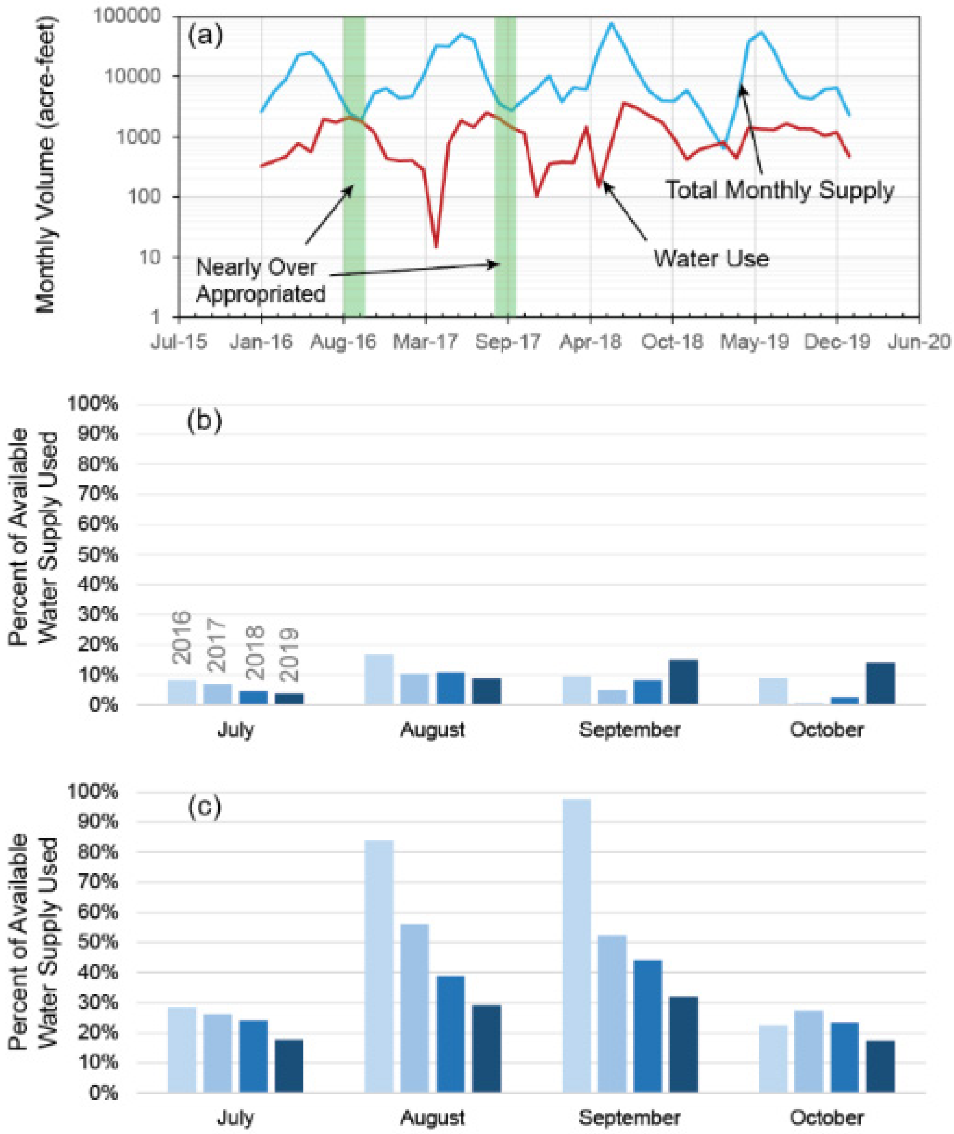


Figure 32. Graph showing (a) monthly time-series of water supply and water use for Lolo Creek with logarithmic y-axis. Green shaded regions are periods when water use was close to exceeding water supply. The remaining plots compare (b) percent of monthly water supply used during low flow months for Water Balance Region 3 and (c) the same graph for Water Balance Region 4.

pumping. This study and past studies (Chambers 2016) observed a hydraulic connection between the aquifer and Lolo Creek. Quantifying the degree of alteration to streamflow from pumped groundwater was beyond the scope of this study but will be addressed in more detail by MBMG's GWIP study. There was one anomaly where water use was greater than supply in February 2019. During the winter, there were no surface water diversions, so all water withdrawal was from groundwater. Although flows were very low in February 2019, according to the DNRC gage below US Highway 93, the creek did not go dry. The cause of this event is unclear but is most likely caused by ice damming.

Over-appropriation may also depend on location. Comparing the same low flow period at different locations shows that water use and loss is a much smaller fraction of water supply for Water Balance Region 3 (Fig. 32b) than for Water Balance Region 4 (Fig. 32c). However, this does not necessarily indicate excess water supply because flow from Water Balance Region 3 is a crucial component of overcoming the natural losses in Water Balance Region 4 and maintaining flow. Thus, increased use in upstream regions has the potential to exacerbate issues downstream because all Water Balance Regions are connected.

A comparison of natural losses among years, for August and September, showed an inter-annual variability that is likely caused by factors beyond the scope of this report. While the future GWIP study will address these factors using a numerical groundwater model, some simple conclusions can be made by comparing daily average discharge at DNRC's gages above Sleeman Creek, below Highway 93, and surface water diversions. The average daily streamflow loss for the lower reach of Lolo Creek was determined by correcting the downstream discharge for all surface water diversions. In 2016, zero flow was measured for approximately 10 days at Highway 93 from August 21 to August 31 (Fig. 33a). Streamflow losses to groundwater were between 13 and 16 cfs for those 10 days (Fig. 33c). On average, streamflow losses in 2016 were between 10 and 15 cfs for the months of August and

September. In contrast, during wet year like 2018, streamflow losses were significantly less for the same months (Fig. 33b and 33c). Streamflow losses in 2019 were very similar to 2018, and 2017 had slightly higher loss than those two years, primarily in August. The mean annual flow of each year was compared with the long-term mean annual flow from combined DNRC and historic USGS gage data to determine the deviation from normal, or average, conditions. 2017 was slightly higher than average, 2018 was average, and 2019 was slightly lower than average; however, 2016 was notably lower than average with a mean annual flow 58% of the long-term average. Therefore, while the specific mechanisms of streamflow loss are beyond the scope of this report, the magnitude of loss is clearly greater in dry years and less in wet years. This was a stronger driving factor than domestic or municipal pumping, which showed no anomalous increases in 2016 that would explain the high streamflow loss.

Water use in the Lolo Creek watershed is undoubtedly contributing to dewatering events, and in dry years there are periods when use may exceed available supply. Streamflow loss to the aquifer in the lower reaches of the creek may be increased by groundwater pumping but is ultimately a product of the geologic and geomorphological setting. Therefore, when considering managing water use and supply, this loss should not be ignored. Nor should it be

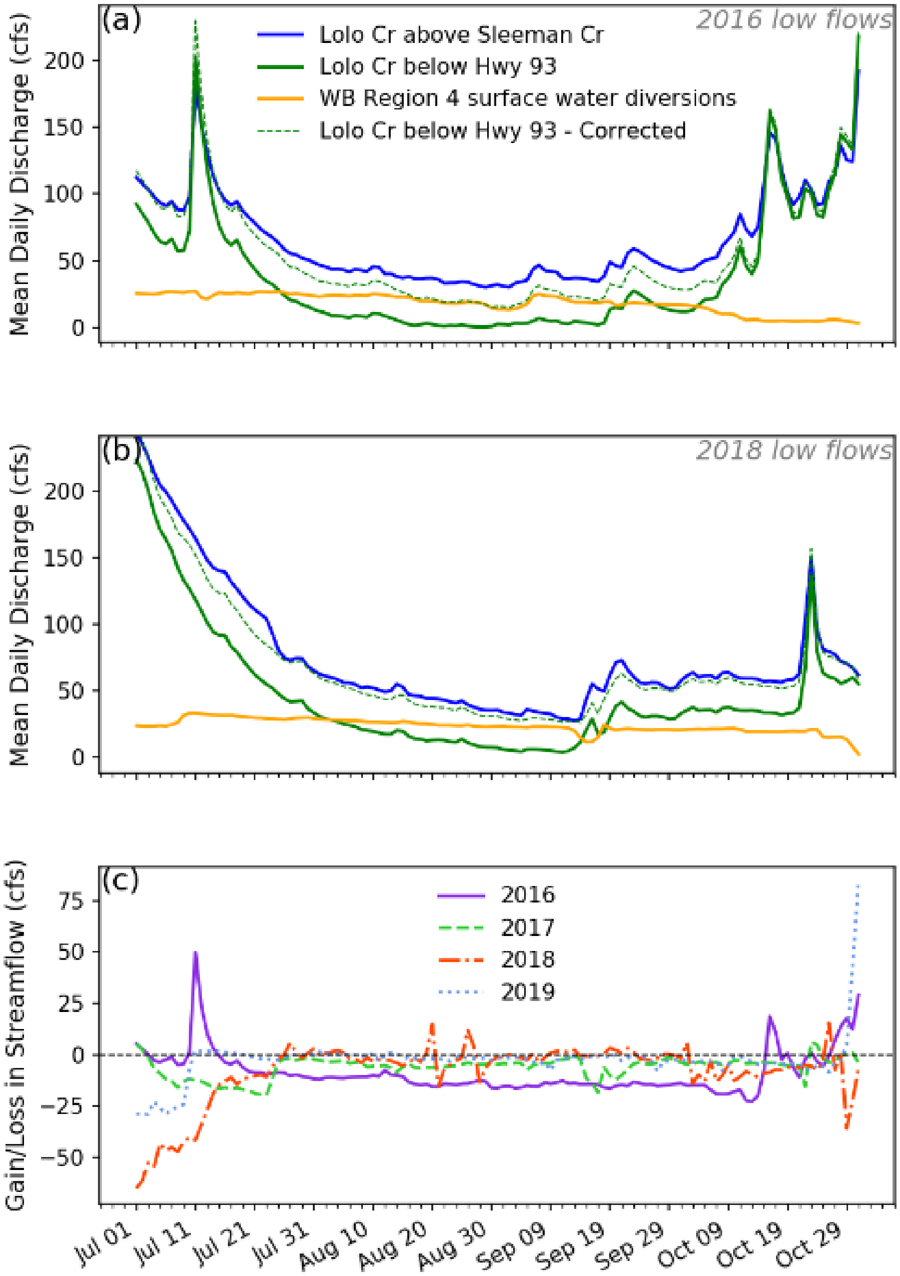


Figure 33. Graphs showing (a) mean daily discharges at lower Lolo Creek stream gages and Water Balance Region 4 surface water diversions for July 1 to October 31, 2016; (b) mean daily discharges at lower Lolo Creek stream gages and Water Balance Region 4 surface water diversions for July 1 to October 31, 2018; and (c) Region 4 mean daily streamflow loss for all years in the study period.

blamed, exclusively, for dewatering events. Years like 2016 are relatively rare based on the measured 18-year streamflow record. In fact, 2016 was the lowest recorded year in those 18 years, with similar conditions observed in only twice in 1950 and 1953. During the dewatering event, streamflow at the above Sleeman DNRC stream gage hovered around 30 cfs. Discharges of 30 cfs or less at this location were uncommon, occurring approximately 6 to 7% of the time over the 18-year record (Fig. 13b).

Before 2016, recorded streamflow was not readily available until 1960, which is why Part II of this study will use modeling to extend streamflow estimates and analyze the frequency of low water supply years. This will be an important component of understanding the effects of the Turn-of-the-Century drought on Lolo Creek dewatering, and how climate change and increased domestic use may alter the frequency of such events into the future. In turn, this information can help determine if dewatering was and will continue to be isolated to droughts that occur once a century, if they are likely to continue being more frequent, and if specific action for conserving water is of interest to stakeholders.

Recommendations for Water Management

The final objective of Part I of this PBS was to recommend solutions to water related problems in the Lolo Creek watershed based on the quantification of hydrologic processes and water use. Specifically, for Lolo Creek, the problem is a seasonal imbalance of water supply and demand leading to dewatering events that affect water users, recreation, and endangered species habitat. The following recommendations are organized by categories from Montana's 2015 State Water Plan (MT DNRC 2015), which were identified as important components of current and future water management in the state. As with recommendations from the State Water Plan, the following recommendations are subject to the existing institutional and legal framework for water use in Montana as provided for by the Montana Constitution, prior appropriation doctrine, and Montana Water Use Act. We have noted any recommendations whose implementation would require alteration of this legal framework.

Water Supply and Demand

Based on the results outlined in this report, Lolo Creek has adequate water supply for all existing uses for most of the year. However, there are water supply imbalances during drought years and risks to future water supplies, including increasing domestic demand and climate change. Increasing temperatures and changes in precipitation type and timing have altered water supply dynamics over the last 40 years. Annual precipitation amount has not changed in the Lolo Creek watershed. Minimum and mean daily temperatures have risen since 1983 and remained above average after 2000. The rising temperatures have increased the amount of fall and early winter rain as well as increased the rate of snowmelt in the spring. Higher temperatures also increased evapotranspiration across the landscape, decreasing the fraction of precipitation that became streamflow and contributing to the persistent drought conditions observed from 2000 to present. The effects of increased temperatures on the timing and quantity of water are likely to continue or worsen into the future (Whitlock et al. 2017). While new surface water appropriations are not allowed under the Bitterroot River Basin Closure, new groundwater appropriations greater than 10 acre-ft/year (or 35 gpm) require a mitigation plan or aquifer recharge plan to offset net depletion (§ 85-2-344, MCA). Thus, development of groundwater for domestic or municipal use is still possible and likely to happen as population increases in and around the community of Lolo. Part II of this study will provide more detail about long-term climate, water use patterns, and associated changes in water supply. The following recommendations discuss some immediate solutions to existing water scarcity problems that can be explored.

Our first recommendation for water supply and demand is to collaborate amongst water users and plan for when drought conditions arise. Drought preparedness and planning efforts can help residents of the watershed respond to and even lessen the impacts of drought events. The data and information from this study can inform collaborative discussions among watershed stakeholders and provide a foundation for the development of a drought management plan. Voluntary drought management plans of varying scope, detail, and formality have been successful in several other watersheds in Montana (e.g., Big Hole River and Blackfoot River). Strategies from these plans can be tailored to the needs of Lolo Creek water users. The key for most drought planning is collaboration, and, fortunately, LWG already has a well-developed network of diverse stakeholders and water users.

A common challenge in drought planning efforts is going beyond reactive measures, like attempting to respond after drought conditions develop. Proactive measures reduce the severity or lessen the impacts of drought. These programs, activities, and strategies are most successful when done in tandem with a vulnerability assessment that evaluates the risks to critical resources. The collaborative development and implementation of a drought plan, including response, vulnerability, and adaptation components, will be most effective at mitigating future drought events affecting the Lolo Creek watershed.

As with all snowmelt driven systems, snowpack is an integral part of annual water storage in the Lolo Creek watershed. As the snowpack melts, the bulk of the annual water supply is released during a relatively short runoff season. Conventional water storage projects make use of this timing to store flood water during runoff season for use during low flows, when demand may approach or exceed available supply. Conventional storage in the form of on-channel reservoirs is not a viable option for mitigating current or future water supply shortages in the watershed because of existing transportation infrastructure and housing. On-channel storage would also be counterproductive to other conservation goals (e.g., increasing aquatic habitat connectivity) in the watershed. However, as our understanding of hydrologic processes advances, so does our ability to quantify a watershed's natural storage reservoirs (e.g., shallow groundwater, hyporheic zones, snowpack, and soil/floodplains). Natural storage reservoirs in the Lolo Creek watershed could potentially be managed like an impounded reservoir to capture and store runoff that later becomes streamflow.

Flow regime alterations caused by reservoir construction and transboundary diversions (i.e., transporting water from its place of origin to another basin) have obvious impacts on streamflow. However, there are other alterations and land use practices that have unforeseen effects on watershed runoff patterns. The most common changes in riverscapes are channelization, levee construction, or other development that inhibits a stream from interacting with its floodplain on a regular interval. These alterations are usually intended to lessen flood related damages to cities, homes, and agricultural lands. Disconnecting a stream channel from its floodplain decreases the volume of water that interacts with the soil and shallow aquifer resulting in less water retention in the basin. Segments of Lolo Creek were channelized for the construction of US Highway 12 and to protect property from flooding and erosion. The LWG's WRP lists concerns such as loss of meanders and lack of woody debris, but it does not specifically address floodplain connectivity. We recommend exploring projects that would increase floodplain connectivity, where necessary and practical, as a solution to changes in water supply patterns. These types of projects can require significant excavation and engineering, which is expensive. Future assessments to quantify the degree of channel modification in the Lolo Creek watershed, the associated effects on floodplain interaction, and the water supply benefits of restoring certain areas will help identify the most impactful projects.

The flow regime of small streams across the western US can also be influenced, to some degree, by other living organisms. The role of North American beaver in altering stream hydrology and geomorphology has recently been acknowledged by scientists, policymakers, and restoration practitioners (Goldfarb 2018). Beaver dams increase surface and groundwater storage, alter channel morphology, and change the flow regime of small streams (Nyssen et al. 2011; Puttock et al. 2017; Westbrook et al. 2006). When constructed at sufficient densities across a watershed, they may be an effective tool for mitigate declining snowpack (Hafen 2017). Beaver populations in North America today are a fraction of their historical abundance (Dolan 2010, Parker et al. 1985). Consequently, beaver dam densities in stream networks across the continent are much lower (Macfarlane et al. 2017). Centuries ago, Lolo Creek was likely heavily influenced by the presence of beaver. The route of the Lolo Trail, a passageway across the Bitterroot Mountains used by the Salish and Nez Perce peoples, did not follow the valley of Lolo Creek. As documented by Lewis and Clark during their travel along the Lolo Trail in 1805, the middle and upper valleys of Lolo Creek were choked with beaver dams and downed trees. The Lolo WRP (LWG 2013) states that there is minimal presence of beaver today, however, there is no quantitative information provided on the decline of beaver populations in the watershed.

We recommend exploring the feasibility of using beaver, or beaver mimicry, to augment late season flows in Lolo Creek. There are significant areas of the Lolo Creek Watershed that can and do support naturally reproducing beaver populations. The use of natural beaver populations to create headwaters' storage and augment late season streamflow is encouraged where possible. It is understood that beavers can create problems for irrigators and other infrastructure by blocking and redirecting surface water; therefore, any strategy that includes living beaver should be accompanied by mapping of conflict zones where targeted trapping can be used to manage beaver populations or control migration. In agricultural areas and regions of the watershed with high population or housing density, the benefits of beaver dams can still be attained by employing "beaver mimicry" in and around these areas where beaver may not be desirable. "Beaver mimicry" is the construction of Beaver Dam Analogs (BDA's) that consist of posts pounded into the stream bed and native vegetation (e.g., willow branches) woven between posts. These man-made structures are cheap and easy to install with minimal equipment, while replicating the hydrologic benefits of beaver dams without the physical presence of the beavers. There has been considerable research on the hydrologic and water quality benefits of beaver dams in stream networks, as well as aquatic habitat enhancement. However, there is less information on how habitat enhancement may favor non-native fishes over some native species. This is an active area of debate and something that should be considered when using beaver or beaver mimicry as a restoration solution.

There are two things we recommend doing before pursuing beaver as a natural storage solution on Lolo Creek and its tributaries. First is to inventory existing beaver activity and assess the potential for additional beaver dams throughout the watershed. Then assess what density of beaver dams would be required to meaningfully enhance water supply/storage at the watershed scale. These analyses can be conducted using useful remote sensing tools such as the Montana Beaver Restoration Assessment Tool (2019) and methods outlined in by Hafen (2017) to calculate water supply benefits of adding beaver dams.

Like most rivers and streams in Montana, water supply in Lolo Creek is lowest near the end of summer, when the demand for irrigation water is the highest. In the Lolo Creek watershed, the largest volume of diverted water occurs just upstream of where the creek loses streamflow to the aquifer. This creates a scenario in which water supply is more than sufficient at the point of diversion (POD) but can be less than the downstream loss rate downstream of the POD. Due to the hydraulic connection between the Lolo Aquifer and Lolo Creek, pumping from domestic and municipal wells has an impact on the streamflow loss rate from Lolo Creek. Our water balance results do not show an anomalous increase in pumping rates that would suggest domestic use was the cause of the abnormally high loss rate to the aquifer in 2016. Comparable domestic use was observed in all other years (2017 – 2019) with much lower streamflow loss to the aquifer in Region 4, suggesting that losses to groundwater here are more strongly controlled by other factors (e.g., low groundwater inflow from upstream in the watershed, groundwater levels, or water level in the Bitterroot River). According to DNRC’s stream gage records, Lolo Creek likely would have remained connected to the Bitterroot River in August of 2016 if there were no surface water diversions in Water Balance Region 4 (based on comparison of loss rate to the aquifer and diversion rate; Fig. 33a). However, it is important to note that it is completely legal and within the irrigators’ water rights to divert their claimed or permitted volume and flow rate regardless of downstream conditions. Thus, all solutions to mitigate dewatering of Lolo Creek that involve reduced surface water diversions must be collaboratively approached with the recognition that any action by irrigators, incentivized or not, is voluntary. There are, however, a few approaches that could decrease the rate of surface water diversion when streamflow in Lolo Creek is critically low.

One exception to the Bitterroot Basin Closure is the ability to store water during spring runoff for use later in the season. As discussed earlier, traditional on-channel reservoirs are not a suitable option for Lolo Creek but off-channel storage, particularly in Region 4, could reduce direct flow diversions during the months of August and September. This solution may be especially beneficial for water users on the McClay ditch. The McClay ditch delivers water to multiple water users outside the Lolo Watershed. Small individual, or shared, storage ponds constructed near the place of use (POU) could be filled during high flows using the McClay ditch. The cumulative capacity of multiple small storage ponds could be designed to meet 3 – 6 weeks’ worth of irrigation and stock water needs, plus an additional amount to account for evaporative loss. We recommend analyzing the feasibility of off-channel, high flow storage to determine if it is possible given current infrastructure, potential storage pond sites, and if the footprint could be minimized while meeting water user needs. A second option to decrease surface water diversions during low streamflow is the transfer, or addition, of the legal POD to the higher volume Bitterroot River. This option is explained in the Water Use Administration section below.

The primary water supply concern for domestic and municipal use is population growth and new appropriations of groundwater. Part II of this study will explore population related impacts, or potential impacts, on overall water supply. The impact of many low volume individual domestic wells versus high volume concentrated PWS wells on groundwater levels and Lolo Creek streamflow depletion is crucial to understanding the best management path for domestic use. Local restrictions on landscape irrigation during drought conditions would mitigate the impacts of growing domestic demand. Another option would be to expand the LWSD service area to incorporate more of the rural development in the Lolo Watershed. If more new and existing homes were serviced by PWS, then high volume municipal wells could be concentrated in the Bitterroot floodplain instead of near Lolo Creek. Functionally this just shifts the problem to the Bitterroot Valley aquifer; however, there is more water in the Bitterroot River, and probably the aquifer, and more opportunities to acquire mitigation water than on Lolo Creek.

Summary of Water Supply and Demand Recommendations

- Develop a drought plan.
- Use "natural storage" reservoirs (such as floodplains, shallow or deep aquifers, wetlands, etc.) where practical and possible to store water that is released slowly back to Lolo Creek.
- Assess historical alteration of floodplains in the watershed and if there are water supply benefits to enhancing floodplain connection to Lolo Creek channel.
- Conduct a comprehensive feasibility study to see if beaver activity and/or beaver mimicry can have a positive effect on late summer water supply and if so, develop implementation strategies.
- Assess the feasibility of using small off-channel storage reservoirs/ponds to decrease surface water diversions during low-flows.
- Expand the Lolo Water and Sewer District service area to encompass future growth while concentrating associated municipal wells in the Bitterroot aquifer.

Water Use Administration

The results of this study show the limited physical availability of surface water in the Lolo Creek Watershed. We do not list specific recommendations for limiting new appropriations of water because limitations (with exceptions) are already in place under the Bitterroot Basin Closure. Existing water rights holders can still change components of their water right, depending on the proposed changes and how they do or do not affect other water rights. Certain types of water rights changes are not permittable under current state laws and rules. One example that would be useful for water scarcity issues on Lolo Creek, is moving or adding an additional POD to a nearby source with greater volume relative to appropriated water. This is defined as "source switching" (sometimes "water exchange") and would require changes to Montana Water Use law but is used effectively in other states to maintain tributary connection where exported water is an issue.

We recommend exploring, or analyzing, source switching as a solution to dewatering of Lolo Creek and other streams across the state that experience similar problems. The McClay ditch exports water to irrigated land outside the Lolo Watershed (i.e., not hydrologically connected). This exported water can be problematic for maintaining flow in lower Lolo Creek during late summer low flows. If the POD for McClay ditch water rights was moved to the higher volume Bitterroot River, or a secondary POD added with a period of diversion limited to July – October, this would allow water users to curtail their allocated water on Lolo Creek to maintain streamflow. This would require a feasibility analysis to determine if it is possible and cost effective to move Bitterroot River water to the POU, an administrative path to altering laws or rules that would allow this change, and adverse effects on the new source.

An assessment of possible complications, exploitations, and consequences following this sort of change, relative to the Montana water rights framework, would be necessary as part of implementing this solution. One possible complication is new appropriations and junior water rights on the original source. An addition of new water rights or rights junior to the water right(s) being changed have the potential to negate the instream flow benefits by diverting curtailed water or reducing flows upstream of the original POD. Implementing source switching in the Bitterroot Basin would eliminate any complications caused by new appropriations, due to the closed basin. However, these types of problems should be addressed to ensure the outcomes of source switching are what was intended. We make this recommendation because source switching is used in other western states to protect instream flows for fisheries and recreation with little to no impact on the irrigators.

New groundwater uses in the Lolo Watershed require a mitigation or recharge plan if greater than 10 acre-ft/year (35gpm). Appropriations less than 10 acre-ft/year are exempt from the permit process and therefore do not require mitigation. Currently, individual wells are the largest source of domestic water in the Lolo Watershed. These single household wells are generally exempt from the permit process while subdivisions or developments with more than one household per source are considered PWS, or multiple domestic, and must obtain a permit if they have a centralized water distribution system. There is a concern that developers may take advantage of using permit-exempt wells, instead of developing a PWS, to provide water for subdivisions without going through the more rigorous permitting process. One recommendation is to identify possible ways, within the existing laws and rules, that exempt-wells may be abused and if there are any administrative loopholes that could be closed. The effects of un-mitigated groundwater appropriation could be analyzed in the Lolo Watershed by modeling increases in domestic use and applying various scenarios of mitigation or no mitigation to the water balance. This analysis would quantify the impacts of unmitigated groundwater use and provide direction on whether to pursue further administrative action.

Summary of Water Use Administration Recommendations

- DNRC – Explore the legality, consequences, and benefits of "source switching" as a solution to decreasing exported irrigation water during low flows and maintaining flow in Lolo Creek.
- DNRC – Review of current rules for permit-exempt wells (i.e., wells with a maximum use of 35 gpm not to exceed 10 acre-ft/year), promote the best practices for their use in water resource development, and encourage further study of their potential impacts to senior water right users.

Water Information

The measurement of water information at stream gages and monitoring wells was a key objective of this study. The resulting water balance and quantification of water use would not have been possible without this information. DNRC Water Management Bureau's Stream Gage Program will continue to operate two non-real-time stream gages, two real-time stream gages, and one real-time well in the Lolo Creek watershed beyond the completion of this study. Information from these sites could be used to implement some of the other recommendations in this report and are actively used by water rights holders for distribution of water or instream flows. We recommend that future management be informed by the stream gage data and consider the advantages of using an "adaptive management" framework for decision making using the real-time infrastructure. The real-time gages allow stakeholders to know the discharge of Lolo Creek and adjust based on the conditions, rather than relying on statistically derived volumes that may not account for extreme years (wet or dry). This type of water distribution is employed in other basins throughout Montana and provides more accurate water distribution or reporting. Discharge data collected by stream gages is crucial for quantifying concentrations of pollutants, sediment loads, aquatic habitat, and geomorphic changes in a river system. Water temperature is also collected at the Lolo Creek gaging stations, which is valuable for fisheries management by providing an early warning for stressful temperature conditions for fish species. Additional benefits of real-time stream gages include alerts for flooding during snowmelt and during the design and evaluation stages of stream restoration projects.

The cost of operating this infrastructure is currently incurred by DNRC, which has benefits and drawbacks. The primary benefit is the data product – quality instantaneous (15-minute) and daily streamflow and temperature data that is produced and distributed to the public, at no cost. The main drawback is that funding for this measuring infrastructure is subject to departmental budgetary fluctuations. While the chances of these fluctuations affecting the operation of Lolo Creek gages are low, it is possible that future legislative budget decisions will cause DNRC to prioritize externally, or cooperatively, funded gages. Therefore, the benefits come with the disclaimer that the future operation of Lolo Creek gages is subject to changes in DNRC resources (both time and material) with a "worst case" being gaps in real-time data or discontinuation of a gage.

Summary of Water Information Recommendations

- Use data produced by DNRC's Stream Gage Program for water management, restoration projects, or early warnings on Lolo Creek.
- Consider developing an "adaptive management" framework for water distribution based on real-time flows.
- Explore opportunities for cost-sharing with DNRC to ensure the longevity of the Lolo Creek real-time stream gages.

Ecological Health and Environment

For several decades, conservation work in the Lolo Creek Watershed has addressed documented impairments to water quality and fish and wildlife habitat. Impairments to the watershed and conservation goals are defined in the LWG's WRP (LWG 2013). We recommend continuation of efforts by local organizations (LWG and CFC) to improve the ecological health of Lolo Creek including protecting instream flow, stream rehabilitation, improving water quality, and increasing habitat connectivity through better fish passage.

Streamflow is the most important component of Lolo Creek's aquatic ecosystem. Montana's legal framework for water marketing, in which water rights are temporarily leased for different uses, is currently being used on Lolo Creek. The CFC leases three water rights on Lolo Creek totaling a protected flow rate of 4.37 cfs with priority dates ranging from 1884 to 1890. These leased rights are beneficial to streamflow in lower Lolo Creek, but they are still junior to some of the larger irrigation rights on the creek. Although urban expansion and continued development in the Lolo Watershed brings a different set of water resource challenges, the potential loss of irrigated land presents an opportunity to protect greater volumes of instream flow. In some areas, conversion of agricultural lands to housing or commercial development increases runoff while reducing recharge from irrigation. Given the hydrogeological character of the Lower Lolo Valley, and the presence of exported irrigation water, there are minimal benefits from irrigation recharge in Region 4. We recommend the continued practice of Montana's water marketing laws to lease water rights for instream flow protection, especially where irrigated lands are being retired.

The CFC recently implemented a fish screen project on the McClay ditch to mitigate fish entrainment (when a fish enters a ditch and becomes trapped) and mortality. We recommend pursuing additional projects to screen direct flow diversions and pump intakes, as well as community outreach on fish screening and entrainment to increase the visibility of this often-overlooked issue. Previous recommendations for natural water storage projects would also have an ecological benefit as well. BDA's increase habitat diversity and have been shown to improve downstream water quality. Rehabilitation projects that allow the creek to access more of its floodplain attenuate floods, increase aquatic habitat availability, and expand riparian areas and wetlands.

Summary of Ecological Health and Environment Recommendations

- Continue conservation work being done by local organizations.
- Continue using Montana's available laws for leasing water rights for instream flow protection.
- Continue screening diversions to mitigate fish mortality in ditches and conduct public outreach about this issue.

Collaborative Water Planning and Coordination

The Lolo Creek watershed is fortunate to have an active watershed group and many other engaged stakeholders. LWG serves as a central hub of communication and coordination, and the group fosters inter-agency collaboration across ownership boundaries. Other, larger, groups, such as Trout Unlimited and the Clark Fork Coalition, have greater capacity to implement large projects, but collaborating with LWG can increase their effectiveness in the watershed. The Missoula Conservation District is also well-positioned to collaborate with LWG on restoration projects and public outreach.

Many of the watershed restoration efforts to date have been guided by the WRP developed by LWG (LWG 2013), which provided a detailed overview of the issues and strategies for restoration. The WRP enables access to Montana DEQ 319 project funding and offers justification for projects that could be funded through other sources. Although LWG developed it, other groups working in the watershed can use it to leverage grant funds.

The success of any efforts to enhance water quality and quantity largely depends on capacity. Watershed coordinators are key to building partnerships and coordinating projects, and they can also lead water management planning and updates to the WRP. Capacity funding is often in short supply but is well worth the investment for these community "keystones."

DNRC will continue to provide technical and planning support to LWG and other interested stakeholders as resources allow. The agency can provide training on groundwater well measurements using existing monitoring wells and help establish monitoring infrastructure to ensure groundwater levels are tracked in the future. DNRC can also provide training for the University of Montana Geosciences Department annual Hydrogeology Field Camp and Advanced Hydrogeology course in the Lolo Watershed. Finally, DNRC may convene a Basin Advisory Council for the Clark Fork and Kootenai River Basins to evaluate and implement the State Water Plan (MT DNRC 2015), as well as provide recommendations for future updates. A representative from LWG or another engaged watershed stakeholder should have a place on the Council to ensure the local and regional water management issues are captured and addressed in the next Plan.

Summary of Collaborative Water Planning and Coordination Recommendations

- Maintain the LWG as a central body for agency/other organization collaboration on watershed projects.
- Continue to leverage the LWG and Lolo WRP for grant funding for water and restoration projects.
- Make use of DNRC's technical and planning resources to continue educational opportunities and outreach for issues related to Lolo Creek.

Future Studies

DNRC will produce a Part II to the Lolo Pilot Basin Study following this report. Part II will focus more on existing and modeled watershed conditions that affect water supply and demand. This will include analysis of modeled historic natural flows and assessment of future impacts due to population growth and climate change.

MBMG's GWIP is studying groundwater-surface water interactions in the Lower Lolo Valley and Bitterroot floodplain using field measurements and numerical modeling. Their research will assess various scenarios that could dewater Lolo Creek and includes a more sophisticated look at the effects of well pumping than this study. The GWIP study will compliment aspects of this report.

DNRC Standards of Review Statement

This document has been reviewed in accordance with Category 1 standards set forth by DNRC's Water Management Bureau Standards for Review (MT DNRC 2021).

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Appendices

Appendix A can be downloaded in digital format (.pdf) from DNRC Water Management Bureau's website (http://dnrc.mt.gov/divisions/water/management) or in print by contacting DNRC Water Resources Division, 1424 9th Ave; Helena, MT 59601, 406-444-6601.

Appendix A: Extended methods for data analysis and water balance calculations

Supplementary Information and Digital Data

All original data produced as part of this study are included as digital datasets of spatial and tabular data. The complete Digital Data Release is available on DNRC Water Management Bureau's website (http://dnrc.mt.gov/divisions/water/management) or in an alternative format by request (please contact DNRC Water Resources Division, 1424 9th Ave; Helena, MT 59601, 406-444-6601).

Suggested citation for Digital Datasets…

Blythe TL, Folnagy AJB, Ketchum DG. 2022. Lolo Creek Pilot Basin Study Part I: Hydrology and Water Use 2016 – 2019 Digital Data. Helena (MT): Montana Department of Natural Resources and Conservation, Water Management Bureau. Digital Dataset DD220218-WMB.

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Publishing information:

[Not Applicable for this document]

Back Cover: Ice dam on Lolo Creek near Lolo, Montana, January 2022. Photo by Troy Lechman, MT Department of Natural Resources and Conservation.