Upper Salmon Basin
Hydrologic Monitoring and Analyses

Prepared by

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PROJECT OVERVIEW

DOC, Award Number:	NA20NMF4380252 and NA21NMF4380463
CFDA Number:	11.438
CFDA Project Title:	Salmon Restoration, State of Idaho
Geographic Area:	Salmon River, above the Middle Fork Salmon River, Idaho
OSC Project Number:	003 21 SA
Project Sub-Grantee:	Idaho Department of Water Resources
Project Contact Information:	Ryan McCutcheon Hydrogeologist 322 E. Front Street, P.O. Box 83720 Boise, ID 83720-0098
Grant Period:	04/01/2022 – 06/30/2023
Total PCSRF Funds:	$218,076.00
Total Non-Federal Match:	$110,800.00
Primary PCSRF Objectives:	Salmon Research, Monitoring, and Evaluation (SRME)

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INTRODUCTION

The Upper Salmon Basin (USB) and its tributaries have historically hosted large populations of anadromous fish (salmonids) such as Chinook salmon, sockeye salmon, and steelhead trout (USBWP, 2019). However, spawning returns to the USB have been greatly reduced over the past 150 years due to the placement of physical barriers (e.g., dams), alteration of in-stream habitat, water quality degradation, and other factors (ISCC, 1995). A persistent decrease in the returns of salmonids has led to spring/summer Chinook salmon, fall Chinook salmon, sockeye salmon, and steelhead trout being listed under the Endangered Species Act (ESA).

In response to decreased returns of salmonids, many stakeholders in the USB seek to improve streamflow conditions and in-stream habitat in the hopes of improving the abundance and health of these populations. A group of such individuals came together to form the Upper Salmon Basin Watershed Program (USBWP) in 1992, and this group still operates today. The mission statement of the USBWP is "to protect and restore habitat for ecologically- and socially-important fish species in the Lemhi, Pahsimeroi, and East Fork Salmon Rivers while respecting and balancing the needs of irrigated agriculture and strengthening the local economy" (USBWP, 2018).

The USBWP consists of two focused working groups that employ their own unique sets of expertise in service of USBWP objectives. The Advisory Committee is composed of local landowners and stakeholders with a vested interest in the health of the salmonid runs. Members of this committee convey the wishes of the local community, provide local knowledge and expertise, and are often willing to allow for implementation of habitat improvement projects (HIPs) on their private property. The group that implements HIPs is known as the Technical Team (Tech Team), which is a diverse group of federal, state, and nonprofit agency personnel that cooperates to design, review, prioritize, and evaluate proposed and ongoing HIPs.

Development and evaluation of HIPs relies on a detailed understanding of the hydrogeology of the Upper Salmon Basin, as well as predictions on how both salmonid habitat and water users might be impacted by changes to water management, land use, climate, etc. As a member of the Tech Team, it is a goal of the Idaho Department of Water Resources (IDWR) to provide that expertise. Although IDWR is committed to advising projects throughout the Upper Salmon Basin, the primary focus of this report is the Lemhi River Basin (LRB), which hosts many HIPs requiring further development and evaluation.

In support of the USBWP, this report details collected hydrologic data, analyses, and numerical modeling activities conducted during the Upper Salmon Basin Hydrologic Monitoring and Analyses Study. All data and products resulting from this study have been made available to the public within this report or via IDWR web portal.

OBJECTIVES

The following objectives were copied from the research proposal submitted to the Idaho Pacific Coastal Salmon Recovery Fund (2021, Round 24). All modifications to tasks, as well as the degree to which each task was completed, is detailed in the subsequent results section.

Task 1: Stream Gaging

Streamflow data has been and will continue to be critical for project planning and evaluation in the Upper Salmon Basin. The current streamflow monitoring network was created in 2005, with Idaho Power Company installing and operating the gages, the locations of which were determined through discussions with the USBWP Technical Team and collaborators. The network has changed periodically since 2005, reflecting Upper Salmon Basin Watershed Program (USBWP) and collaborator needs, as well as transfers of gages between agencies. However, since January 1, 2020, IDWR has operated nine stream gages via PCSRF funds, while managing an additional five through a subcontractor. All 14 gages are important reference points for fish passage and habitat health and should continue to be operated through 2023 barring any requests for changes to the network by the USBWP Tech Team. IDWR also proposes adding two subcontracted gages on Hawley Creek, which are valuable for monitoring the impacts of in-stream habitat projects including beaver dam analogues. Finalized streamflow data for each gage can be accessed via IDWR web portal (Aqua Info) and will be updated on an annual basis. More recent data may be made available upon request.

Task 2: Groundwater Level Measurements

A groundwater level monitoring network of 21 wells was established in May 2011 based on review of the water level monitoring efforts conducted in the late 1990's by Spinazola (1998). Until May 2015, continuous water level measurements were recorded using electronic pressure transducers in nine wells and biweekly manual measurements were made in the additional 12 wells. In May 2015, the network was expanded to 41 wells; 24 continuously monitored by IDWR and 17 manually measured bi-weekly by Water District 74 (WD74) through a subcontract.

IDWR proposes discontinuing the 17 manually measured wells that are visited biweekly, reducing the network to the 24 wells that are continuously measured using dataloggers during this project phase. Six years of data have now been collected from the bi-weekly measured wells, which, when combined with similar data from the Donato (1998) study, and the continuous groundwater level data, is enough to conduct a thorough spatiotemporal analysis of groundwater levels. Nevertheless, IDWR proposes that the continuous groundwater level network continue to be maintained, as these wells still contain data loggers that will continue to provide valuable data for years to come. Furthermore, the remaining groundwater level network may serve to improve the response functions of the Lemhi River Basin Model, and maybe one day create a more robust groundwater model. Under this task, IDWR will continue to monitor and maintain the continuous groundwater level network. New data will be collected from the wells on a bi-annual basis and all new data will be made available to the public annually through a groundwater level database (in development). More recent data may be made available upon request.

Task 3: Soil Moisture Tension Measurements

From 2014 to present, eight soil moisture monitoring sites, each containing sensors at multiple depths, were installed to continuously monitor soil moisture storage and to better characterize infiltration and groundwater recharge in the basin. Six sites were installed in agricultural fields where irrigation was changed from flooding to sprinkler irrigation. In these locations, the soil moisture data allows IDWR to evaluate the hydrologic effects of changes to irrigation practice. The seventh and eighth sites were placed adjacent to Hawley Creek, next to a series of beaver dam analogues (BDAs) installed as part of a salmonid habitat improvement project. At these locations, the soil moisture sensors allow IDWR to assess the hydrologic impact of BDAs by indirectly observing overbank flows and hyporheic exchange.

Four soil moisture sites are still operational today, two in an agricultural field that has converted from flood to sprinkler, and two adjacent to the Hawley Creek BDAs. Data is collected on a bi-annual basis and should continue to be collected through this project phase, as the changes made to these systems may slowly change soil water dynamics at these locations over time. IDWR will post the recorded soil moisture data to the project website on an annual basis at https://idwr.idaho.gov/water-data/projects/upper-salmon/references/. More recent data may be made available upon request.

Task 4: Surface Water Quality Measurements

The impetus for surface water quality data collection was a report by the Idaho Department of Environmental Quality (IDEQ) that concluded several reaches of the Lemhi River and its major tributaries contain “Impaired Waters”, with listed pollutants including temperature, sedimentation/siltation, fecal coliform, and nutrients (IDEQ, 1999, 2012). Furthermore, limiting factors to salmonid habitat suitability in the Lemhi River and its tributaries include elevated summer water temperatures and winter freezing, as well as excess fine sediment (OSC et al., 2019; Mike Edmonson, personal communication, 8/7/2019). Additional water quality metrics of concern include pH and dissolved oxygen (DO), as unsuitable concentrations of H+ or DO can result in diminished production, or even mortality of salmonids (Carter, 2008). However, despite these concerns, there were no long-term, coordinated water quality monitoring programs in the basin as of late 2019 (Todd Blythe, USBWP, personal communication, 9/11/2019).

IDWR began monitoring Lemhi Basin surface water quality in 2020 and has continued to do so through 2021. Temperature sensors were deployed, and continuous surface water temperature data were collected at all 21 IDWR managed gages in the Upper Salmon Basin. In addition, the Lemhi River, its return flows, and Lemhi River tributaries were analyzed using multiparameter water quality sondes that recorded pH, DO, turbidity, specific conductivity, temperature, etc. Water quality samples were also collected from the Lemhi River and select return flows and sent to the lab to analyze a suite of analytes that included metals, nutrients, and pH (IDWR, 2021). After reviewing the data collected thus far, IDWR recommends additional water quality assessment as part of a more long-term surface water quality monitoring program.

Continuous Surface Water Temperature Data:

All IDWR managed gages in the Upper Salmon Basin (this project and the Water Transactions Program led by Amy Cassel) were outfitted with continuously-recording temperature sensors by mid-2021. It is recommended that this data collection continue through 2023. All collected data will be uploaded to the project website (https://idwr.idaho.gov/water-data/projects/upper-salmon/references/) annually and more recent data can be made available upon request. Additional water temperature sensors may be deployed at specific project sites or other locations if requested from members of the USBWP Tech Team or collaborators.

Data collected thus far shows that temperatures in many reaches of the Lemhi River are above the optimal salmon spawning temperatures of 54°F - 59°F during the summer, and some stretches of fish-bearing tributaries become warmer than the Lemhi River in the summer and can even freeze over in the winter. Further research is needed to evaluate the impacts of habitat and water transaction projects on surface water temperature, as well as to better predict the impacts of climate change. As such, a long-term water temperature monitoring network should prove invaluable to planning and development efforts for both project managers and water managers.

Discrete Surface Water Quality Data:

From 2020 to 2021, this task involved recording water quality sonde measurements of temperature, specific conductivity, turbidity, pH, and dissolved oxygen levels at over 30 sites along the Lemhi River and its tributaries approximately every six weeks (weather permitting). Monitoring sites included all stream gaging locations monitored by IDWR for this study, all lower stream gages on Lemhi River tributaries managed by IDWR (for this study and the water transactions program led by Amy Cassel), and several sites on the Lemhi River itself. A full water year of this data has been collected and will be characterized in the final project report entitled Upper Salmon Basin Groundwater and Surface Water Interactions V (publication pending).

As part of a more long-term water quality monitoring effort, it is recommended that IDWR continue recording water quality sonde measurements on the Lemhi River and tributaries containing ESA-listed fish. If water quality is found to be unhealthy, additional monitoring of irrigation return flows or smaller tributaries may be conducted. The data can be used to alert landowners, the USBWP Tech Team, and if necessary, IDEQ of water quality degradation more quickly, giving stakeholders a better chance to address issues before salmonids are negatively impacted.

Due to instances of waters being impaired via sedimentation/siltation, nutrients, and fecal coliform (Idaho DEQ, 1999, 2012), IDWR recommends also collecting grab samples and conducting laboratory analyses on waters from the Lemhi River and tributaries containing ESA-listed fish. The suggested analytes include ammonium as N, nitrogen nitrite-nitrate, total phosphorous, total coliforms, and E.coli. Samples should be collected three times per year, ideally prior to the irrigation season (March) as a control, in the early irrigation season (June), and in the late irrigation season (September). Proposed sampling sites are detailed in the map attached to this application.

__Hydrologic Modelling__

IDWR has been responsible for developing, maintaining, and running the Lemhi River Basin Model (LRBM) for hydrologic analyses and predictions from 2008 to present. The model has included the entire Lemhi River Basin since 2013 and is regularly updated and recalibrated with new data and hydrologic information to reflect the current state of the basin. Under this task, the LRBM will be updated with data and irrigation system configuration information through water year 2022. All hydrologic modeling activities are and will continue to be performed by IDWR with assistance from a Mike Hydro Basin Consultant on an as-needed basis. Specific modelling goals are detailed below.

Task 5: LRBM Model and Public Tool Updates and Improvements

A) The LRBM groundwater recharge functions will be updated and improved using multiple sources and analyses.

B) The LRBM Habitat Tool will be updated with recent monitoring data and expanded to include the University of Idaho CER Bioenergetic Model.

Task 6: LRBM Scenarios

A) The LRBM will be used to estimate Lemhi Basin streamflow under both the current natural flow conditions (no anthropogenic influence) and variable climate futures defined by the USFS (see below) in the Resources and Planning Act Assessments (Joyce & Coulson 2020). Characterizing water resources available at present and in the future using a variety of plausible future climate projections will help project managers, water managers, and water rights holders to prepare for potential future changes to basin hydrology.

B) The LRBM will be used to run scenarios submitted by the USBWP Tech Team via the Public Graphical Interface (developed by IDWR for the Upper Salmon Basin Groundwater and Surface Water Interactions V project). The model output data will then be analyzed to evaluate the efficacy of habitat and water transactions projects.

__Hydrologic Analyses__

A significant amount of hydrologic data have been collected in the Upper Salmon Basin, and especially within the Lemhi Basin, over the past twenty years. As such, it is important to mine and analyze this data to better characterize the hydrology of the region. Below is a list of analyses that will be completed during this project period, though additional analyses may be completed following discussions with the USBWP Tech Team.

Task 7: Lemhi Basin Stable Isotope Analysis

Surface water and groundwater stable isotope data (δ^{2}H and δ^{18}O) were collected from the Lemhi River, its tributaries, and Lemhi Basin wells during the Upper Salmon Basin Groundwater and Surface Water Interactions, Phase 3 study (IDWR, 2019). The data were plotted in the report, and basic descriptive statistics were calculated; however, more information can be gleaned from this data. IDWR will perform additional statistical analyses on this dataset similar to those performed by McCutcheon et. al. (2017) to determine if there is isotopic distinction between these waters. A discussion piece will also be added to detail interpretation of the statistical analysis, including potential source waters and hydrologic pathways for the sampled bodies of water.

Task 8: Lemhi Basin Water Quality Analysis

All surface water and groundwater quality data that have been collected in the Lemhi Basin will be aggregated and analyzed to characterize spatiotemporal trends, determine what surface water bodies are areas of concern for each water quality analyte, and develop an optimal long-term monitoring strategy. The results will be presented to the USBWP Tech Team to inform future habitat and water transactions project development.

Task 9: Develop a plan for an intensely monitored study site near the confluence of the Mainstem Lemhi and Lower Hayden Creek

A large number of projects are set to be developed on both Hayden Creek and the Lemhi River near the confluence over the next several years. The goal of this task is to coordinate with project managers, the University of Idaho (who is developing a monitoring project there), and other parties to develop an intensely monitored study site at this location. The purpose of establishing this site is to characterize the local hydrogeology, sediment transport, and water quality before, during, and after implementation of these projects. Since most of these projects are still in development and conversations are on-going, a plan for monitoring will be built out over the next year, culminating in an application for additional funds next year that would be used to purchase the necessary monitoring equipment.

RESULTS

Task 1 – Stream Gaging

Streamflow data were collected and used to support the USBWP in planning, implementation, and monitoring of streamflow enhancement and in-stream habitat improvement projects, as well as to calibrate the Lemhi River Basin Model (LRBM). The data and LRBM have also been used to plan for minimum streamflow provisions (including coordinated high flows designed to flush excess streambed sediment and increase salmonid habitat diversity) mandated by the Lemhi River Basin Comprehensive Settlement Agreement, which was signed on February 2, 2022. As a result of the agreement, IDWR-managed gages are now being used to enforce minimum streamflow provisions at the Lemhi River at McFarland, Lemhi River below L5 Diversion, Big Timber Creek Lower, Bohannon Creek Lower, Canyon Creek, and Hayden Creek gaging stations.

With funding from the Pacific Coast Salmon Recovery Fund (PCSRF) and Idaho Water Transactions Program (WTP), which includes the Columbia Basin Water Transactions Program and the Bonneville Power Association Idaho Accord, IDWR has collected streamflow data from 1997 to present (Table 1). Between these programs, IDWR actively manages 35 stream gages, 16 of which are managed through this project using PCSRF funds (Table 1, Figure 1). As a focal point of salmonid habitat improvement efforts, the Lemhi Basin contains 22 of the 35 total active gages (Figure 2).

Each gage records stage data using a pressure transducer or bubbler. On-site streamflow measurements were made at each gage every six weeks (conditions permitting) using an Acoustic Doppler Velocimeter, an acoustic Doppler current profiler, or dilution gaging techniques. The stage and streamflow data were then used to develop stage-discharge rating tables and compute daily mean streamflow values.
All PCSRF and WTP streamflow data (Table 1, Figure 1) collected through September 30, 2022 has been posted to the web portal (Aqua Info). Data from water year 2022 (October 1, 2021, to September 30, 2022) and prior may be considered finalized, while data from water year 2023 should be considered preliminary until 12/31/2023 unless otherwise specified by IDWR. Additional Upper Salmon Basin streamflow data funded through other IDWR programs and the Shoshone Bannock Tribes can be found in the USGS web portal (NWIS). Please refer to IDWR (2022b) for long-term streamflow trend analyses at gages with more than ten years of data.

Table 1. IDWR Stream Gages within the Upper Salmon Basin

Gage Name	Latitude	Longitude	Data Range	Status	Funding
Agency Creek	44.949	-113.568	2005 - present	Operated by HDR	PCSRF
Alturas Lake Creek	43.982	-114.846	2006 - 2015	Discontinued	None
Bayhorse Creek	44.378	-114.257	2013 - present	Operated by IDWR	PCSRF
Beaver Creek	43.919	-114.814	2004 - present	Operated by HDR	WTP
Big Eightmile Creek, Lower	44.694	-113.482	2008 - present	Operated by IDWR	PCSRF
Big Eightmile Creek, Upper	44.644	-113.529	2005 - present	Operated by IDWR	PCSRF
Big Hat Creek	44.818	-114.111	2004 - 2005	Discontinued	None
Big Springs Creek, Lower	44.728	-113.433	2005 - present	Operated by HDR	WTP
Big Springs Creek, Upper	44.711	-113.409	2008 - present	Operated by HDR	PCSRF
Big Timber Creek, Lower	44.689	-113.370	2004 - present	Operated by USGS	WTP
Big Timber Creek, Upper	44.614	-113.397	2005 - present	Operated by IDWR	PCSRF
Bohannon Creek, Lower	45.122	-113.732	2008 - present	Operated by HDR	WTP
Bohannon Creek, Upper	45.191	-113.691	2013 - present	Operated by IDWR	PCSRF
Canyon Creek	44.691	-113.364	2008 - present	Operated by HDR	WTP
Canyon Creek blw CC2 Div	44.697	-113.337	2022 – present	Operated by IDWR	WTP
Carmen Creek, Lower	45.246	-113.893	2005 - present	Operated by HDR	WTP
Carmen Creek, Upper	45.345	-113.789	2005 - 2018	Discontinued	None
Challis Creek, Lower	44.569	-114.194	2005 - present	Transferred to BOR	None
Challis Creek, Upper	44.572	-114.305	2005 - 2019	Discontinued	None
East Fork Salmon River	44.267	-114.325	2004 – 2018, 2022	Discontinued	None
Eighteenmile Creek	44.668	-113.314	2006 - present	Operated by HDR	PCSRF
Eighteenmile Creek Mouth	44.683	-113.352	2008 - 2009	Discontinued	None
Falls Creek	44.583	-113.766	2005 - 2007	Discontinued	None
Fourth of July Creek	44.030	-114.834	2004 - present	Operated by HDR	WTP
Garden Creek	44.511	-114.203	2005 - 2007	Discontinued	None
Goat Creek	44.219	-114.952	2018 - present	Operated by HDR	WTP
Hawley Creek Lower	44.672	-113.302	2020 - present	Operated by HDR	PCSRF
Hawley Creek Middle	44.659	-113.216	2020 - present	Operated by HDR	PCSRF
Hawley Creek Upper	44.667	-113.192	2008 - present	Operated by IDWR	PCSRF

Hayden Creek	44.870	-113.627	1997 - present	Operated by HDR	PCSRF
Herd Creek	44.117	-114.262	2005 - 2007	Discontinued	None
Iron Creek	44.888	-113.971	2006 - present	Operated by HDR	WTP
Kenney Creek	45.027	-113.654	2004 - present	Operated by HDR	WTP
Knapp Creek	44.368	-115.126	2023	Operated by IDWR	WTP
Lee Creek	44.746	-113.476	2009 - present	Operated by IDWR	PCSRF
Lemhi River above Big Springs	44.729	-113.433	2005 - present	Operated by HDR	PCSRF
Lemhi River above Hayden Creek	44.867	-113.625	2004 - 2009	Discontinued	None
Lemhi River above L-63	44.682	-113.356	2008 - 2019	Discontinued	None
Lemhi River at Baker	45.098	-113.722	2004 - 2009	Discontinued	None
Lemhi River at Cottom Lane	44.749	-113.476	2005 - present	Operated by HDR	PCSRF
Lemhi River at L-1	45.177	-113.886	1997 - present	Operated by IDWR	Other
Lemhi River at McFarland	44.803	-113.566	1997 - present	Operated by USGS	IDWR
Lemhi River nr Lemhi	44.940	-113.639	1938 – present	Operated by USGS	IDWR
Little Morgan Creek	44.653	-113.932	2005 - 2007	Discontinued	None
Little Springs Creek, Lower	44.779	-113.544	2008 - present	Operated by IDWR	WTP
Little Springs Creek, Upper	44.773	-113.528	2008 - 2016	Discontinued	None
Meadow Creek	44.218	-114.944	2018 - present	Operated by HDR	WTP
Morgan Creek	44.612	-114.170	2006 - 2021	Discontinued	None
North Fork Salmon River	45.406	-113.994	2005 - 2007	Discontinued	None
Pahsimeroi at Ellis	44.692	-114.047	1984 – present	Operated by USGS	IDWR
Pahsimeroi at Furey Lane	44.526	-113.848	2004 - present	Transferred to BOR	None
Pahsimeroi River below P-9	44.597	-113.953	2005 - present	Operated by HDR	WTP
Patterson - Big Springs, Lower	44.606	-113.951	2009	Discontinued	None
Patterson - Big Springs, Upper	44.596	-113.938	2008 - present	Operated by HDR	WTP
Pole Creek	43.909	-114.759	2005 - present	Operated by HDR	WTP
Pratt Creek	45.078	-113.699	2017 - present	Operated by IDWR	WTP
Salmon River near Obsidian	44.001	-114.833	2004 - 2009	Discontinued	None
Salmon River near Stanley	44.257	-114.833	2004 - 2009	Discontinued	None
Texas Creek	44.636	-113.323	2008 - present	Operated by IDWR	PCSRF

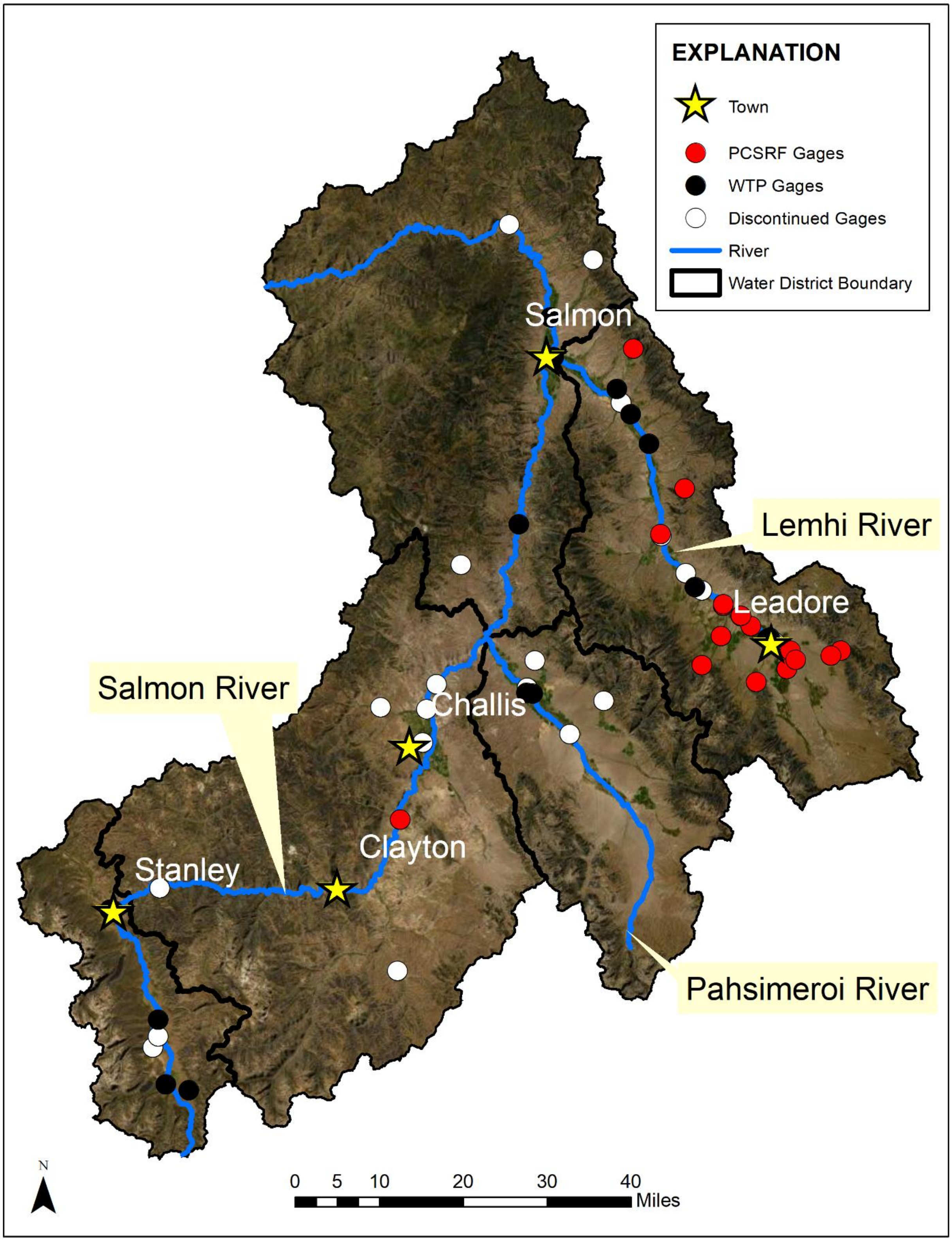


Figure 1. Upper Salmon Basin Streamflow Monitoring Network

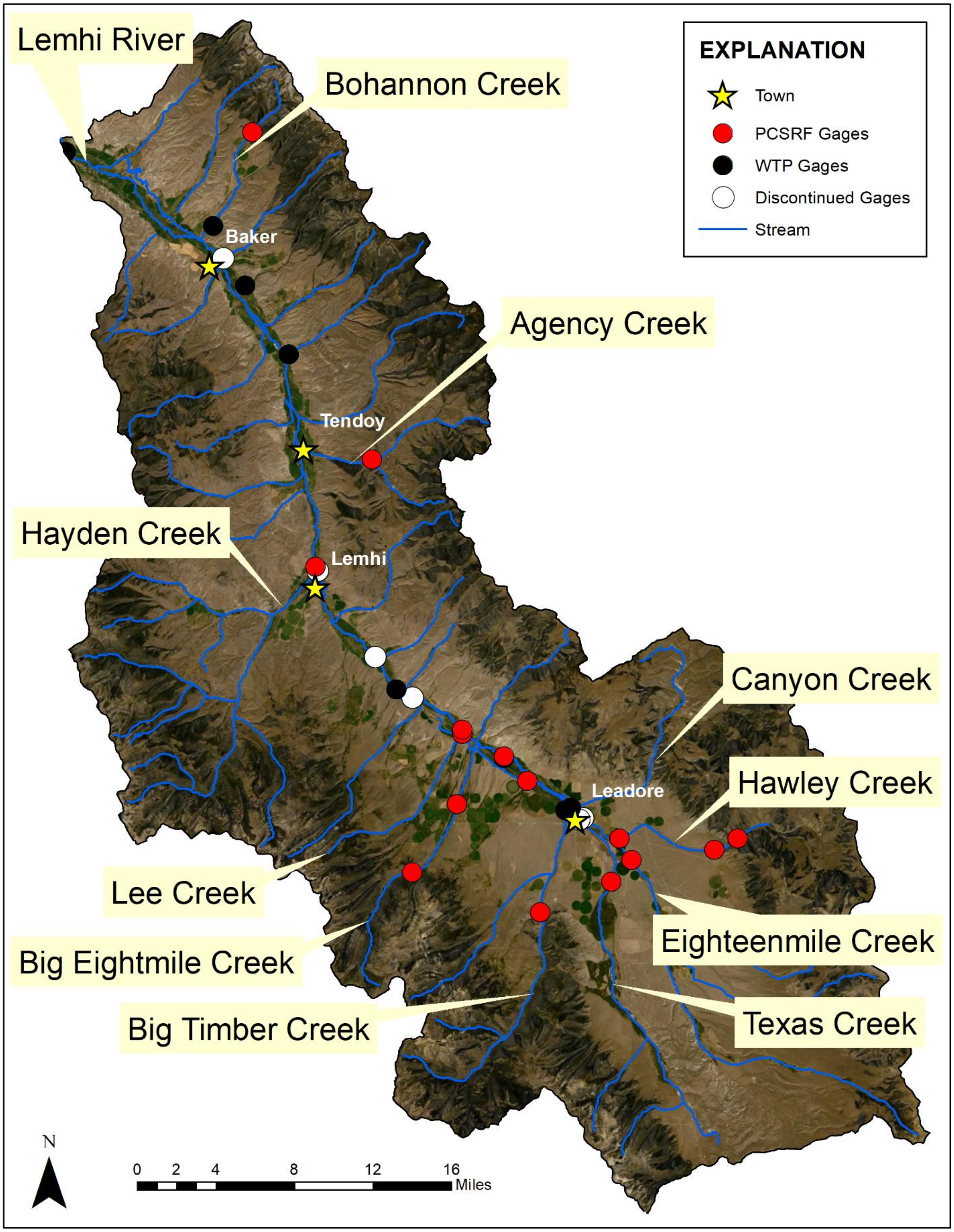


Figure 2. Lemhi River Basin Streamflow Monitoring Network

Task 2 – Groundwater Level Measurements

The collection of groundwater level data is necessary to determine how changes to land use, stream channels, water management, and climate impact both groundwater and surface water availability and quality in the Lemhi Basin. Understanding interactions between groundwater and surface water is especially important in Idaho where water resources are subject to conjunctive management. As such, groundwater levels and streamflow data have been used to characterize these interactions and to help managers of water and habitat improvement projects to make informed decisions when considering alterations to the land surface or water use patterns.

The Lemhi River Basin Groundwater Monitoring Network currently consists of 23 instrumented wells. Each actively monitored well has a period of record between 7 and 12 years (Table 2). IDWR equipped the 23 wells with non-vented In-Situ Level Troll data loggers (Figure 3), which recorded water levels and temperature every twelve hours, year-round. A calibrated electric tape was used to manually measure groundwater levels at the instrumented wells on a bi-annual basis and ensure the accuracy of the pressure transducer data.

All groundwater level data collected through April 2023 has been posted to the IDWR web portal (Groundwater Data Portal), and all published data may be considered finalized. Please refer to IDWR (2022b) for Mann-Whitney Tests comparing modern (2011 – present) water levels to 1997 and 1998 water levels measured by Donato (1998).

Table 2. IDWR Groundwater Level Monitoring Sites within the Lemhi River Basin

Well Number	Latitude	Longitude	Instrumentation	Data Range	Status
21N 22E 10ACD2[1]	45.16505	-113.83914	Non-Instrumented	2011 - 2021	Discontinued
21N 22E 09DAB1	45.16368	-113.85635	Non-Instrumented	2011 – 2021	Discontinued
21N 22E 10CCA1	45.15980	-113.84790	Instrumented	2011 - present	Operated by IDWR
21N 22E 09DDB1[1]	45.15888	-113.85682	Instrumented	2011 - present	Operated by IDWR
21N 22E 14CDD1[1]	45.14410	-113.82265	Non-Instrumented	2015 – 2021	Discontinued
21N 22E 24DCA1[1]	45.13138	-113.79678	Non-Instrumented	2015 – 2021	Discontinued
21N 23E 30ABC1	45.12622	-113.77948	Non-Instrumented	2013 – 2021	Discontinued
21N 23E 30DAC1[1]	45.11773	-113.77499	Instrumented	2013 - present	Operated by IDWR
20N 23E 03CBA2[1]	45.09077	-113.72743	Instrumented	2011 - present	Operated by IDWR
20N 23E 10ABA1[1]	45.08403	-113.71750	Non-Instrumented	2015 – 2021	Discontinued
20N 23E 11ADD1	45.07869	-113.69151	Instrumented	2016 - present	Operated by IDWR
20N 23E 11ADD2	45.07869	-113.69151	Instrumented	2016 - present	Operated by IDWR
20N 23E 11DBB1	45.07641	-113.69766	Instrumented	2016 - present	Operated by IDWR
20N 23E 11DBB2	45.07689	-113.69850	Instrumented	2016 - present	Operated by IDWR
20N 23E 14DDB1[1]	45.05836	-113.69347	Instrumented	2015 - present	Operated by IDWR
20N 23E 24CDD1[1]	45.04268	-113.68028	Non-Instrumented	2015 – 2021	Discontinued
20N 23E 25DAB1	45.03343	-113.67259	Non-Instrumented	2015 – 2021	Discontinued
20N 24E 31DDC1	45.01276	-113.65267	Instrumented	2013 - present	Operated by IDWR
19N 24E 17BBB1[1]	44.98321	-113.64745	Non-Instrumented	2015 – 2021	Discontinued

19N 24E 30AAA2[1]	44.95454	-113.64964	Instrumented	2015 - present	Operated by IDWR
19N 24E 28ABB2[1]	44.95342	-113.61718	Non-Instrumented	2015 – 2021	Discontinued
19N 24E 29BDA1[1]	44.95087	-113.63946	Instrumented	2015 - present	Operated by IDWR
19N 24E 32ADC1[1]	44.93372	-113.63255	Instrumented	2013 - present	Operated by IDWR
18N 24E 16BBB1[1]	44.89499	-113.62826	Non-Instrumented	2011 – 2021	Discontinued
18N 24E 20ADD1	44.87690	-113.62498	Instrumented	2011 - present	Operated by IDWR
18N 24E 21BCD1[1]	44.87607	-113.62916	Instrumented	2011 - present	Operated by IDWR
18N 24E 28DCC3[1]	44.85399	-113.61804	Non-Instrumented	2015 – 2021	Discontinued
18N 24E 31ACD1[1]	44.84654	-113.64959	Instrumented	2015 - present	Operated by IDWR
18N 24E 33ACB1[1]	44.83354	-113.60230	Instrumented	2013 - present	Operated by IDWR
17N 24E 04ADC1[1]	44.84722	-113.61015	Instrumented	2015 - present	Operated by IDWR
17N 24E 13CBD1[1]	44.80042	-113.55596	Instrumented	2015 - present	Operated by IDWR
16N 25E 03BCC1[1]	44.74601	-113.47765	Instrumented	2011 - present	Operated by IDWR
16N 25E 18BBC1[1]	44.72115	-113.53810	Instrumented	2011 - 2019	Discontinued
16N 26E 21ACA1[1]	44.70572	-113.35900	Non-Instrumented	2015 - present	Operated by WD74
16N 25E 20BDD1[1]	44.70349	-113.51018	Instrumented	2015 - 2021	Discontinued
16N 26E 21CAC1[1]	44.69963	-113.36721	Instrumented	2011 - present	Operated by IDWR
16N 26E 20CDD1	44.69631	-113.38594	Instrumented	2013 - present	Operated by IDWR
16N 26E 26ABB1[1]	44.69349	-113.32314	Non-Instrumented	2015 – 2021	Discontinued
16N 26E 26DBB1[1]	44.68739	-113.32330	Non-Instrumented	2015 – 2021	Discontinued
16N 26E 26CBC1	44.68470	-113.33335	Non-Instrumented	2018 – 2021	Discontinued
16N 26E 27CAC1[1]	44.68399	-113.34880	Non-Instrumented	2012 – 2021	Discontinued
16N 26E 27CCB1[1]	44.68380	-113.35352	Instrumented	2015 - present	Operated by IDWR
15N 26E 09ADD2[1]	44.64458	-113.35482	Non-Instrumented	2015 - 2016	Discontinued

[1] Data set includes 1997 - 1998 measurements from Donato (1998) study.

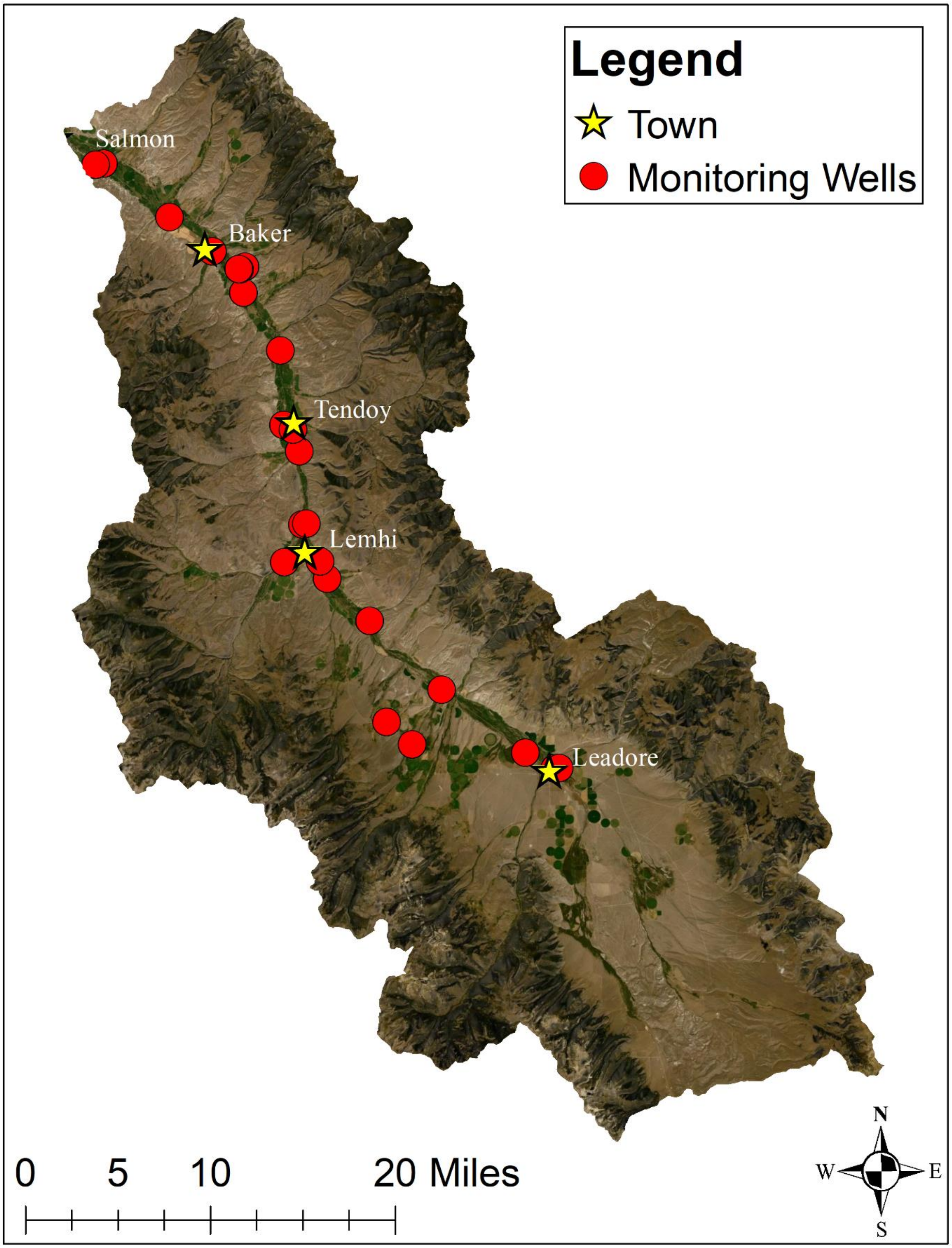


Figure 3. Lemhi River Basin Groundwater Level Monitoring Network

Task 3 – Soil Moisture Tension Measurements

IDWR installed soil moisture stations at eight locations within the Lemhi Basin between 2012 and 2017 (Table 3, Figure 4). Each station contains tensiometers (soil moisture sensors) placed at multiple depths (and sometimes multiple locations) within the soil column. This design allows for analyses of infiltration and potential for groundwater recharge, in addition to providing soil moisture tension data. For example, groundwater recharge may be occurring in instances where deep soil moisture sensors (e.g. 5 feet deep) in agricultural fields show saturated conditions. Conversely, groundwater recharge is much less likely when only the first couple feet of soil wet up, while deeper soil remains unsaturated.

Each station was installed on irrigated land or near salmonid habitat improvement projects, as data from these locations provide information about the hydrologic impacts of human activities. The data can also be used to ground truth satellite-based soil moisture estimates (e.g. Zhang et al., 2022), which are often used as hydrologic model inputs when projecting future water supply (e.g. National Weather Service, 2023).

The Lemhi Basin Soil Moisture Monitoring Network consists of four active soil moisture monitoring stations and four discontinued stations (Table 3, Figure 4). Two of the active Stations are located near agricultural fields in the Pratt Creek drainage, while the other two are located adjacent to beaver dam analogues (BDAs) on Hawley Creek. The agricultural stations contain one soil moisture pit each, while both BDA stations contain two soil moisture pits (one in the ephemerally inundated portion of the stream channel and one above the stream bank). Each Station was visited biannually to download data and maintain the equipment. All recorded data has been posted to the project website at https://idwr.idaho.gov/water-data/projects/upper-salmon/references/. Soil moisture data from two of the active soil moisture stations are discussed in the following sections.

Table 3. IDWR Soil Moisture Stations within the Lemhi River Basin

Soil Moisture Stations	Latitude	Longitude	Data Range	Status	Sensor Depths (ft)
Hawley Creek BDA5	44.65845	-113.22092	2017 - present	Active	1, 3, 5
Hawley Creek BDA4	44.65838	-113.22190	2017 - present	Active	1, 3, 5
SnookF1	45.08319	-113.68627	2016 - present	Active	0.5, 1, 2, 3, 4, 5
SnookF2	45.07860	-113.69111	2016 - present	Active	0.5, 1, 2, 3, 4, 5
TylerK	44.69187	-113.39346	2012 - 2018	Discontinued	0.5, 1, 2, 3, 4, 5
SnookQ	45.03385	-113.67143	2014 - 2018	Discontinued	0.5, 1, 2, 3, 4, 5
Mulkey1	45.07788	-113.70005	2016 - 2018	Discontinued	0.5, 1, 2, 3, 4, 5
Mulkey2	45.07818	-113.70452	2016 - 2018	Discontinued	0.5, 1, 2, 3, 4, 5

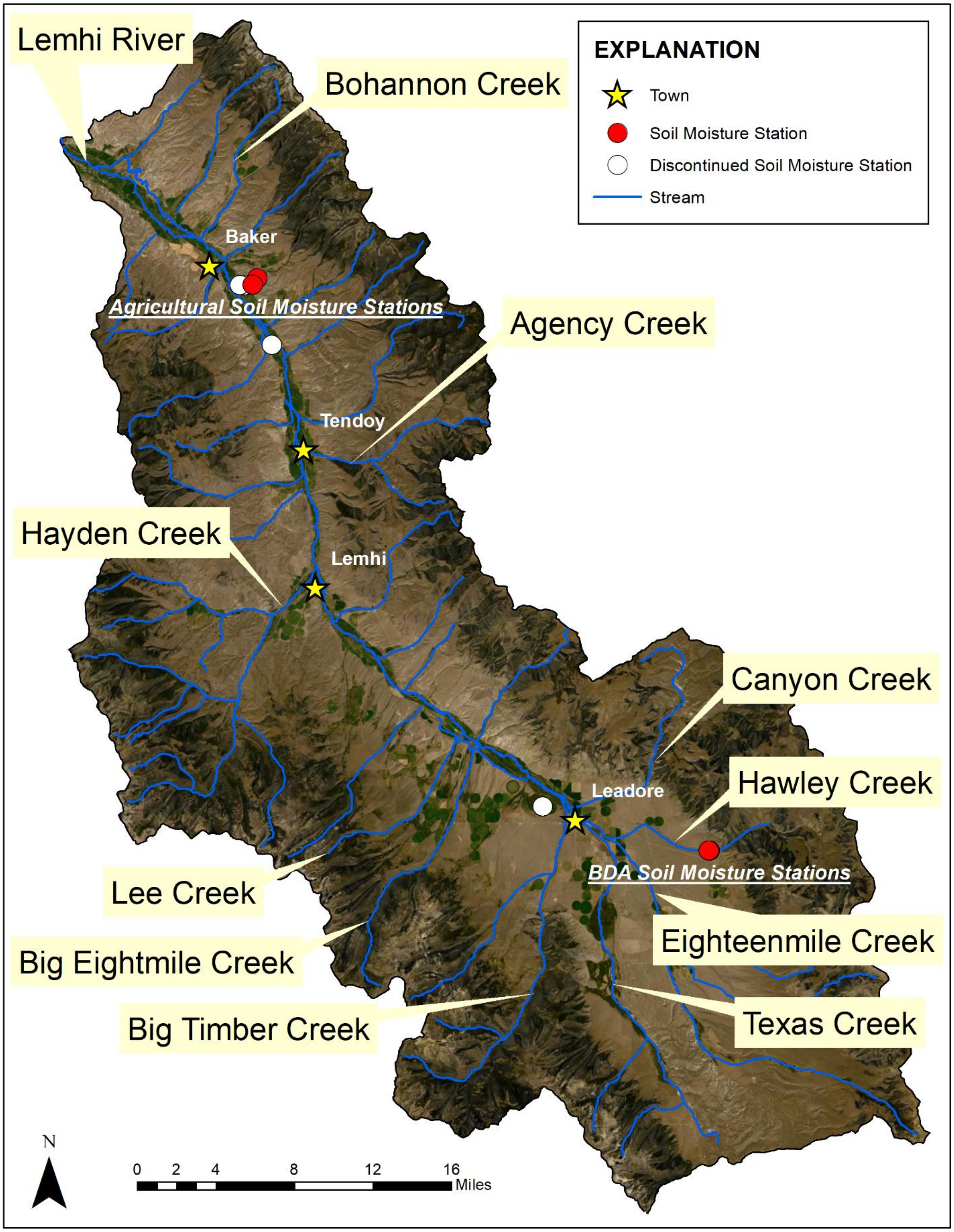


Figure 4. Lemhi River Basin Soil Moisture Monitoring Network

Analysis of soil moisture trends near a Beaver Dam Analogue on Hawley Creek

Beaver Dam Analogue (BDA) 4 was installed along Hawley Creek in September 2017 as one of a series of BDAs that were installed to improve salmonid habitat. Potential benefits of the BDAs include the addition of new in-stream pools, as well as wetter stream-adjacent soils that can lead to increased riparian vegetation growth. The additional riparian vegetation provides essential coverage for salmonids, as well as habitat for other endangered wildlife like Sage Grouse. The increased shade provided by riparian willows and other trees reduces the magnitude of daily streamwater temperature fluctuations, while the roots stabilize streambank soils (reducing sediment erosion) and absorb excess nutrients (e.g. from irrigated agriculture). Increased riparian vegetation also allows for natural placement of woody debris (increases in-stream habitat diversity), and slows the velocity of over-bank flow during flooding events, causing greater deposition of fine soils within the floodplain, and reducing downstream sedimentation. Following completion of the BDA, soil moisture sites were installed to evaluate local soil moisture retention and detect overbank flow events.

Two soil moisture pits were dug, one in an often-inundated area, and one on top of the streambank (IDWR, 2019). In each pit, soil moisture sensors were installed at 1, 3, and 5 feet below the ground surface, along with a temperature sensor 1 foot below ground surface. The sensors record water tension in centibars. All else being equal (e.g. consistent soil texture), the higher the tension, the less water is contained in the soil pores, and the less water is available for usage by plants and other organisms.

Monthly mean soil moisture tension timeseries were plotted (Figure 5, Figure 6), and lines were included to indicate the thresholds at which point soil has likely reached the wilting point (when soil water is held too tightly within the soil for plants roots to extract water), field capacity (when excess soil moisture has drained away and the rate of water movement has decreased to near zero), and saturation (when soil pores are full of water).

Reviewing soil moisture data at the inundated and streambank sites (Figure 5, Figure 6), an annual cycle of rising and falling soil moisture tension is observed in most years. The magnitude and timing of spikes and troughs in soil moisture tension were especially consistent from 2017 through 2020. Tension at both sites and at all depths typically spiked to its highest levels at some point in July through September, and fell to its lowest levels October through May. The timing of the tension spikes aligns with the dates when soils were driest throughout the basin (Zhang et al., 2022) as well as the receding limb of the streamflow hydrograph in Hawley Creek (Aqua Info). The inundated site showed stable average annual tension levels from 2017 through 2020, while the streambank site showed a trend of increasing average tension levels. This trend could have resulted from changes to the BDA structure following its installation, decreased annual peak streamflow in Hawley Creek, and/or fine sediments deposited during floods decreasing the permeability of the soil in the near bank floodplain area.

In 2021, soil at the inundated site (Figure 6) saw an unusual spike, recording high tension levels November through February. This occurred while the temperature sensor at the 1 ft depth had readings below 0°C. It is unknown whether there was streamwater over top of the site during this spike in tension; however, the temperature data suggests that any streamwater at this location would have been frozen at this time. The second unusual phenomenon in 2021 was that every sensor at the streambank site showed very dry soil throughout the entire year. This was likely a result of the extreme drought conditions in the basin (e.g. NOAA, 2023) resulting in less soil moisture and lower streamflow in Hawley Creek.

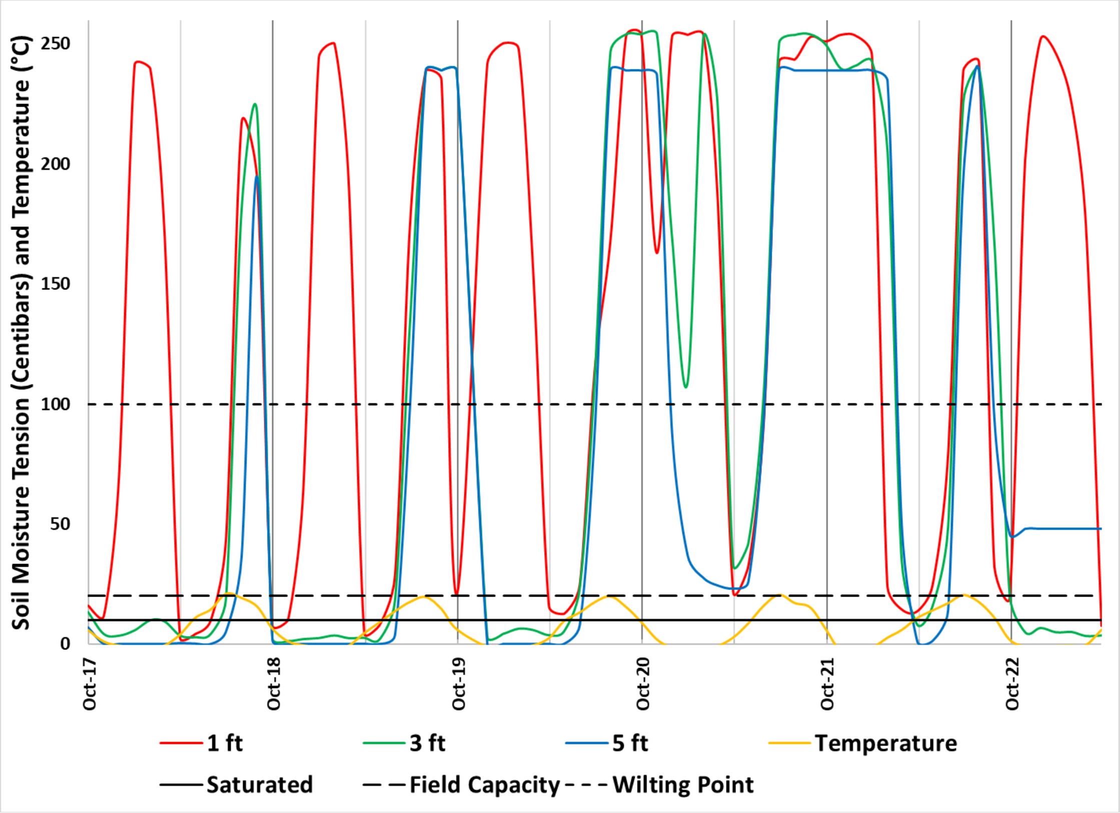


Figure 5. Average Monthly Soil Moisture Tension at Beaver Dam Analogue 4 – Inundated Site

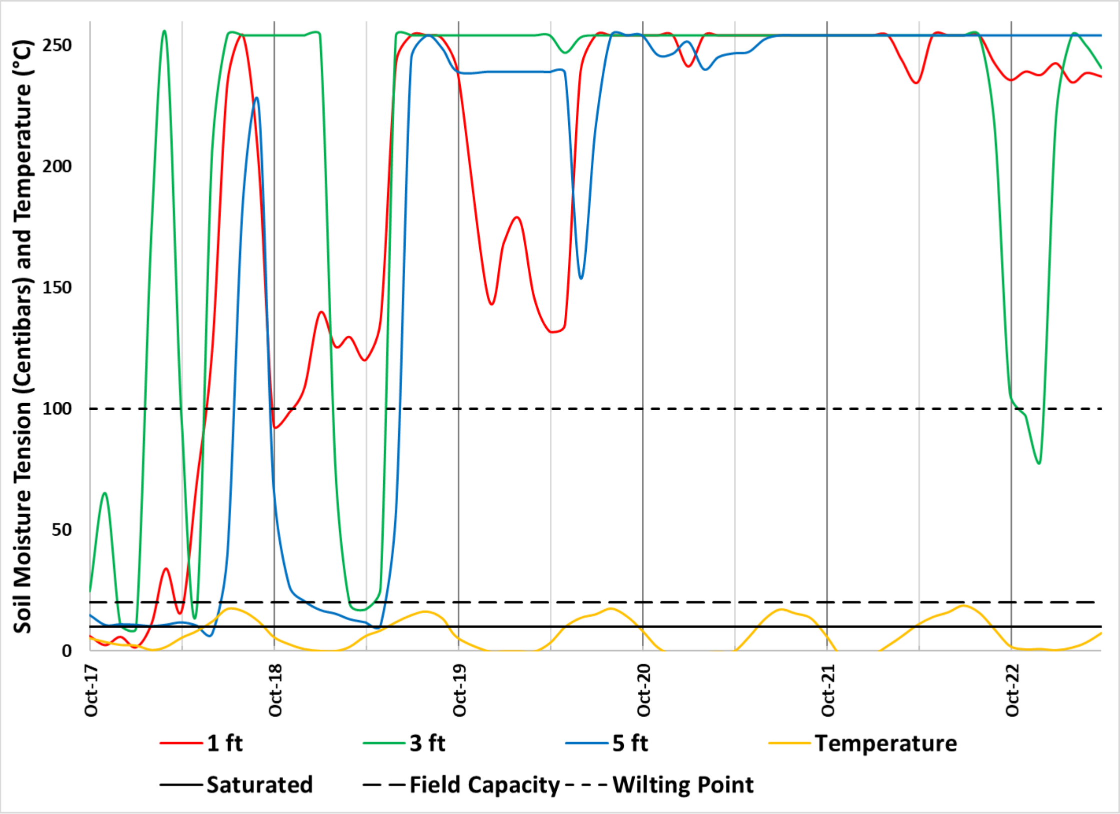


Figure 6. Average Monthly Soil Moisture Tension at Beaver Dam Analogue 4 – Streambank Site

There was very little precipitation to wet the soil, and the peak flow in Hawley Creek was significantly less than average (Aqua Info). As a result, Hawley Creek may never have flooded its banks near this location in 2021.

In 2022, both the inundated and streambank sites had soil moisture characteristics closer to those seen in 2017 through 2020, suggesting at least partial recovery from drought conditions at both sites. The saturated site reached near saturated levels at every sensor, albeit for a much lesser duration than the average year, and the streambank site saw slightly wetter conditions at 1 ft depth and significantly wetter conditions at 3 ft depth. Late 2022 and early 2023 also show saturated conditions at 5 ft depth at the inundated site, more similar to the period of 2017 through 2020 than 2021 through early 2022.

Analysis of soil moisture trends after conversion from flood to wheel-line sprinkler irrigation

Two soil moisture stations were installed in an agricultural field adjacent to Pratt Creek. SnookF1 Station was installed further upstream, and SnookF2 Station roughly ½ mile down-gradient in the same field. SnookF1 is displayed here (Figure 7) because both soil moisture pits displayed similar trends and there were less data gaps in the SnookF1 dataset. The irrigation method for this agricultural field was changed from flooding to wheel-line sprinklers prior to the start of the 2018 irrigation season. When interpreting Figure 7, it is important to note that this Station is placed within the area that was previously flood irrigated, but slightly downslope of where the wheel line sprinklers have typically irrigated from 2018 to present.

Visual inspection of Figure 7 shows that there is an abrupt change to average annual soil moisture after the transition from flood to wheel-line sprinkler irrigation in early 2018. Average annual tension at all depths has increased, and has been trending upwards since sprinkler irrigation began. Prior to 2018, only the tension at the 1 ft depth sensor had ever exceeded field capacity. However, beginning in 2018, tension at all depths began exceeding field capacity on occasion. By the non-irrigation season of 2019, tension at all depths exceeded field capacity for multiple months. By 2020, peak tension levels neared the wilting point at all depths.

As mentioned previously, there was a significant drought period from 2021 through 2022, so soil moisture levels were unusually dry throughout the basin. Between August 2021 and April 2022, soil moisture tension was above wilting point at all depths. Similar soil dryness was observed in August 2022 through March 2023, though, for unknown reasons, the soil was even drier than in 2021.

Tension levels at this site often exceeded field capacity even during the irrigation seasons of 2021 and 2022. Note that this may have been due, at least in part, to the location of the soil moisture site being slightly downslope of where the wheel-line typically irrigates. Nevertheless, by April 2023 soil at 1 ft depth was wetter than it ever was in 2021 or 2022, indicating that shallow soils were nearing saturation after above average snowfall and spring rain (NRCS NWCC), and the Lemhi Basin exiting drought after two years of dry conditions.

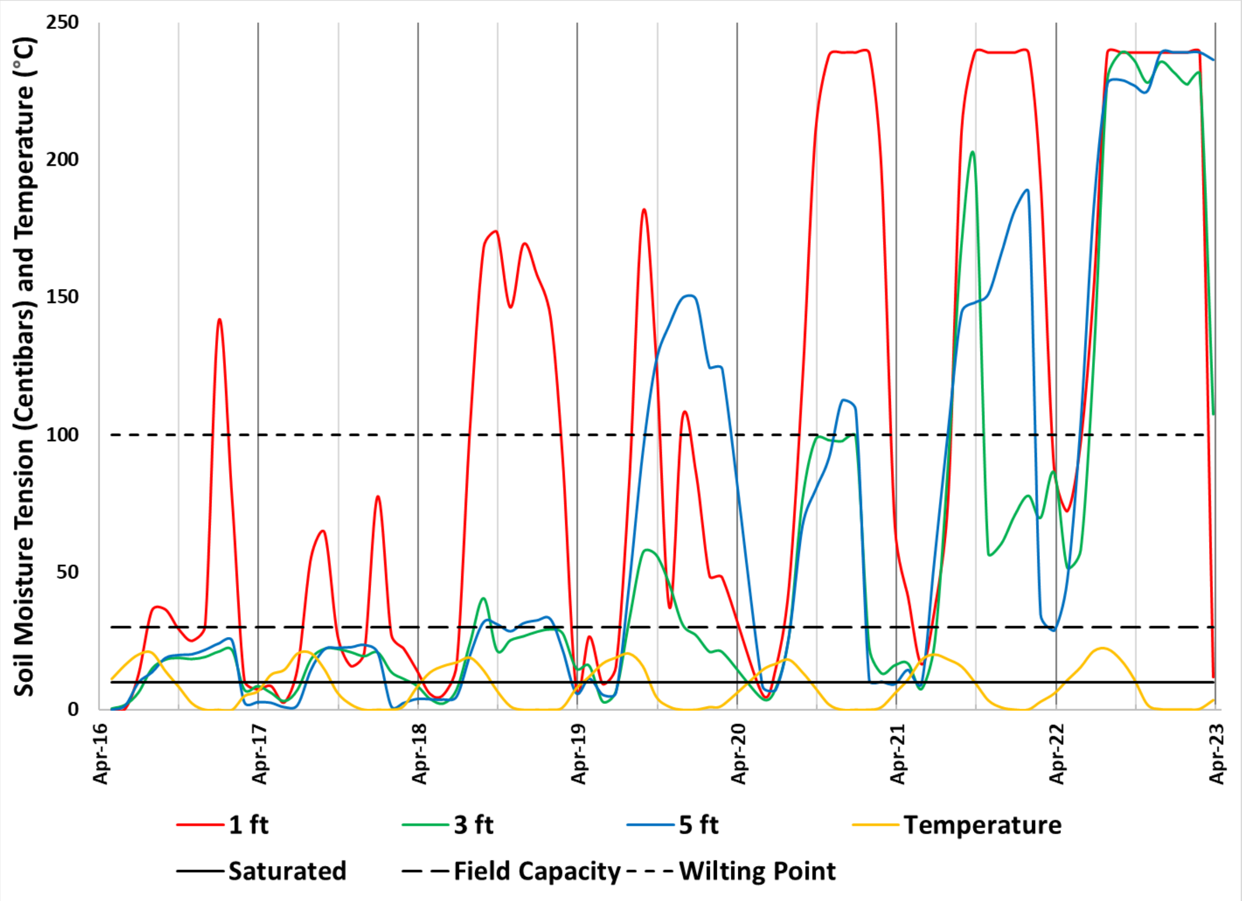


Figure 7. Average Monthly Soil Moisture Tension in an agricultural field (SnookF1)

Looking at the entire timeseries (Figure 7), there is a gradual trend of decreasing soil moisture at all depths since the field converted from flood to sprinkler irrigation. Of particular note is the soil at 5 ft depth. Groundwater is quite shallow in the area (Groundwater Data Portal), so saturated soil at 5 ft depth would typically be indicative of groundwater recharge; however, soils are becoming drier at this depth over time, as they were saturated for shorter than average durations during the 2020 and 2021 irrigation seasons, and never saturated in 2022. In fact, soil at 5 ft depth only wetted up beyond the wilting point during April of 2022, while the rest of the year showed tension levels above the wilting point.

These trends of drying soil are unsurprising, as sprinkler irrigation is typically more efficient than flood irrigation from a water usage perspective. Given this trend in declining soil moisture with the transition from flood to sprinkler irrigation, a common question amongst water users, managers, and conservationists is whether this transition causes a net decrease to groundwater levels or streamflow in nearby streams. Groundwater level data from the three monitoring wells downgradient of the soil moisture station (SnookF1) have shown declining groundwater levels since 2018 (Groundwater Data Portal – wells 20N 23E 11ADD2, 20N 23E 11DBB1, and 20N 23E 11DBB2). However, additional data is required to discern whether this trend is primarily driven by the conversion from flood to sprinkler irrigation or other factors. For example, 2017 and 2018 were particularly wet years, whereas 2021 and 2022 were particularly dry years, and these differences in precipitation may have caused changes to groundwater levels. IDWR hopes to continue monitoring these sites until longer longer-term trends can be analyzed.

Task 4 – Surface Water Quality Measurements

IDWR began a water quality study in 2020, and the data collection effort is still ongoing today. The goal of this study is to measure water quality field parameters and collect grab samples throughout the Lemhi Basin, and use the data to identify areas where salmonid habitat may be degraded due to poor water quality. The data provides baseline water quality information and can be used to aid the design and evaluation of salmonid habitat improvement projects.

Much of the proposed monitoring was put on hold during 2022 due to time constraints, water quality sonde issues, and a desire by IDWR and members of the USBWP to ensure that the water quality program provides data that can be used by IDEQ in their determinations of whether streams are impaired for sediment, temperature, bacteria, or other factors. Note that sections of the Lemhi River and its tributaries have been characterized as impaired in the past (EPA, 2023). As a result, IDWR is meeting with members of the USBWP in July 2023 to discuss the most effective path forward for the water quality monitoring program. These discussions should lead to development of a monitoring strategy that implements IDEQ accepted sampling, lab testing, and quality assurance protocols to ensure that all IDWR collected data can be applied towards IDEQ determinations of impaired waters. The locations of monitoring sites may be modified from those in the project proposal, depending on the needs of the USBWP.

The last discrete measurements of water quality field parameters were taken on the first week of May 2022 when IDWR deployed a multiparameter water quality sonde at several stream gaging sites. In addition to this data, streamwater temperature is still being continuously recorded at all IDWR gage sites. Given the limited scope of these water quality datasets, the data is not characterized within this report. Instead, it will be included in the next report, along with data collected in 2023 and 2024. For an in-depth analysis of water quality data collected in 2020 and 2021, please see the IDWR (2022b) report. For reference, the sites where IDWR has measured water quality parameters from 2020 through early 2023 are included in Table 4 and Figure 8.

Table 4. Lemhi Basin Surface Water Quality Monitoring Sites

Water Quality Measurement Site	Latitude	Longitude	Measurements
Agency Creek at Old 28	44.959	-113.644	8
Bayhorse Creek Gage	44.379	-114.257	9
Big Eightmile Creek Lower Gage	44.694	-113.482	8
Big Eightmile Creek Upper Gage	44.644	-113.529	7
Big Springs Creek Lower Gage	44.728	-113.433	7
Big Springs Creek Upper Gage	44.712	-113.411	1
Big Timber Creek Lower Gage	44.687	-113.367	6
Big Timber Creek Upper Gage	44.614	-113.397	7
Bohannon Creek at Lemhi Rd	45.114	-113.744	7
Bohannon Creek Upper Gage	45.191	-113.691	7

Canyon Creek at Old 28	44.692	-113.354	7
Eighteenmile Creek at Old 28	44.683	-113.355	7
Eighteenmile Creek Gage	44.668	-113.313	6
Hawley Creek BDA4	44.658	-113.221	4
Hawley Creek BDA5	44.658	-113.222	4
Hawley Creek Upper Gage	44.667	-113.192	9
Hawley Creek Middle Gage	44.659	-113.216	4
Hayden Creek Gage	44.868	-113.628	6
Haynes Creek at Price Creek Rd	45.030	-113.679	3
Kenney Creek at Back Rd	45.027	-113.654	7
Kirtley Creek at Old 28	45.165	-113.841	5
Lee Creek Gage	44.746	-113.476	11
Lemhi above Big Springs Gage	44.729	-113.433	8
Lemhi above Hayden	44.868	-113.624	6
Lemhi above L-63 Gage	44.682	-113.356	8
Lemhi at Baker Gage	45.097	-113.721	8
Lemhi at Cottom Ln Gage	44.749	-113.476	7
Lemhi at L-1 Gage	45.178	-113.887	7
Lemhi at McFarland Gage	44.803	-113.566	8
Lemhi River nr Lemhi USGS Gage	44.940	-113.639	8
Little Eightmile Creek at Old 28	44.743	-113.459	4
Little Sawmill Creek at 28	44.849	-113.620	8
Little Springs Creek Lower Gage	44.780	-113.544	8
McDevitt Creek at Mabey Ln	44.933	-113.640	2
Mill Creek at 28	44.767	-113.516	5
Muddy Creek at McDevitt Creek Rd	44.933	-113.638	3
Pattee Creek at Lemhi Rd	44.981	-113.640	6
Pratt Creek at Lemhi Rd	45.076	-113.697	8
Sandy Creek at Lemhi Rd	45.050	-113.670	7
Texas Creek Gage	44.632	-113.325	10
Wimpey Creek at Old 28	45.098	-113.720	8
Withington Creek at 28	45.092	-113.724	3

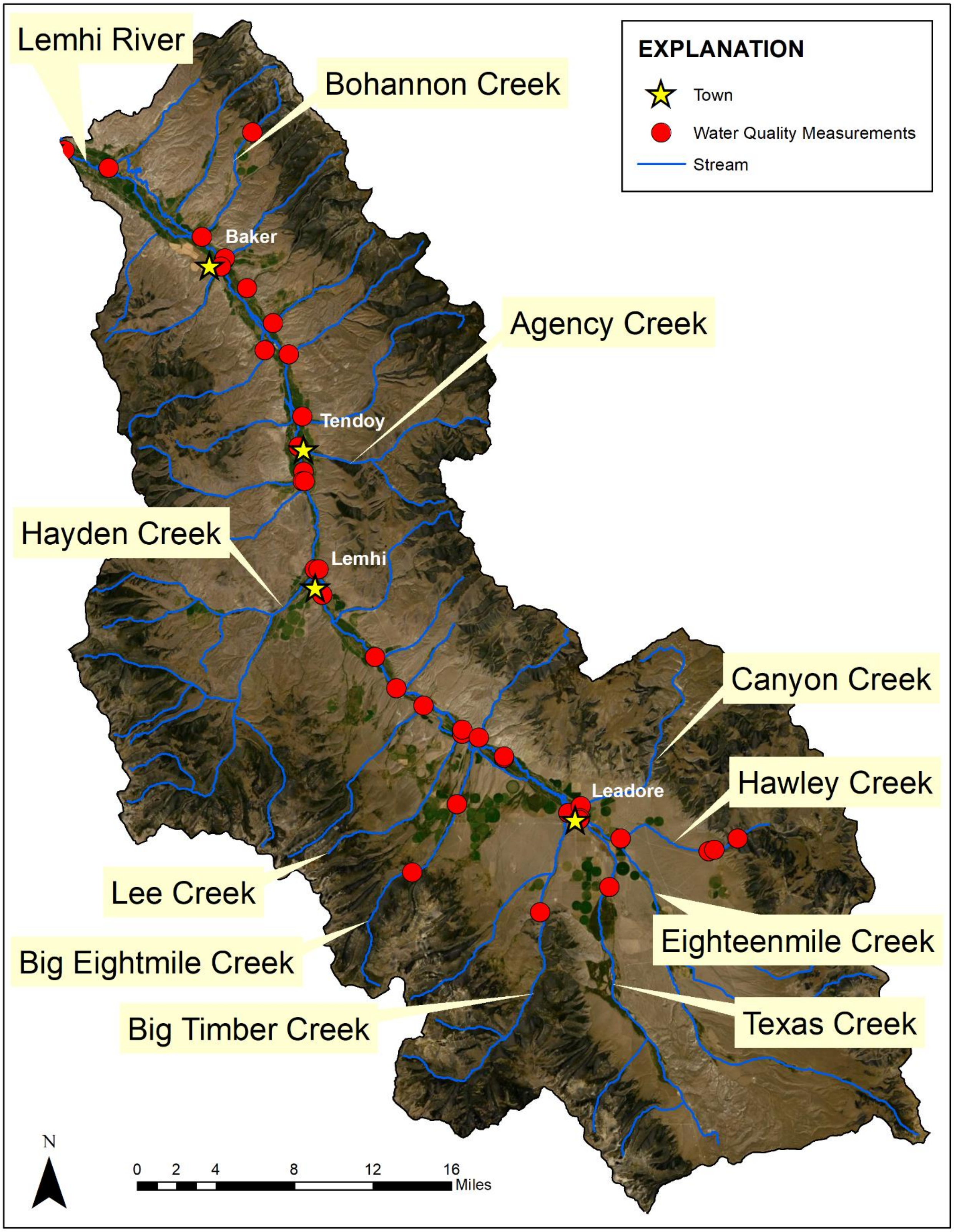


Figure 8. Lemhi River Basin Surface Water Quality Monitoring Sites

Task 5 – Lemhi River Basin Model and Public Tool Updates and Improvements

Please refer to IDWR (2022b) for additional background information on the Lemhi River Basin Model (LRBM), as the general structure and function of the model remains unchanged.

Updates

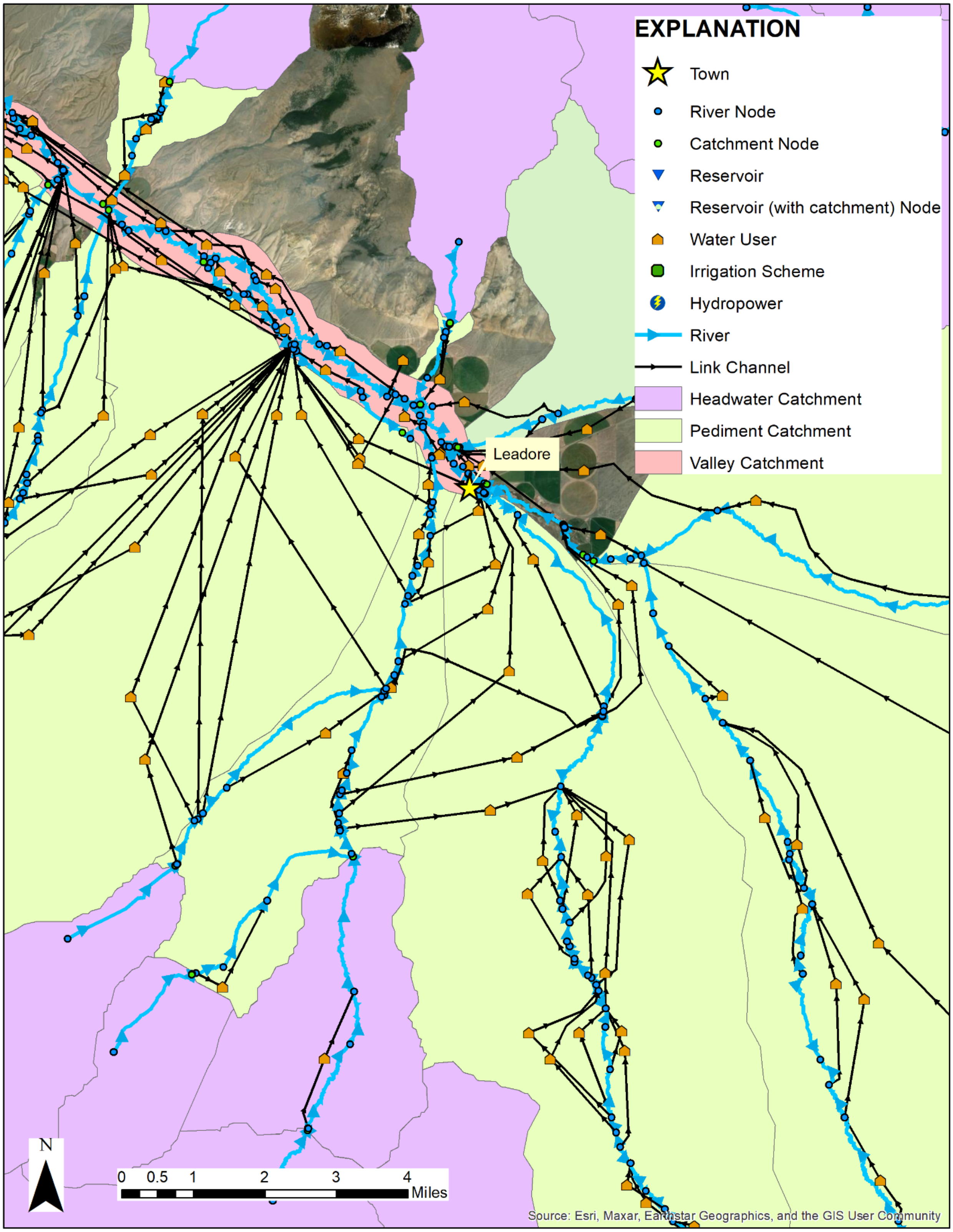
It was anticipated that IDWR would upgrade the groundwater recharge functions during this project period. However, due to other model upgrades being deemed more beneficial in the short-term, this effort was pushed back to the next project period. In total, four model upgrades were completed during this project period.

1. Reconstructed the LRBM network in MIKE HYDRO BASIN v2022 (MHB)
2. Updated and recalibrated the NAM Rainfall-Runoff Model
3. Updated LRBM input data and the supporting data pre-processing files
4. Updated and recalibrated the LRBM and post-processing files

1. Reconstruction of the LRBM network in MIKE HYDRO BASIN v2022 (MHB)

The LRBM has been migrated from the MIKE BASIN software, DHI's extension in ArcGIS, to the stand-alone MHB software package. Due to model complexity from the previous iteration of the LRBM in MIKE BASIN, only the river network was able to be directly loaded into MHB. Therefore, catchments, water user nodes, diversion nodes, connecting arcs, stream gages, and reach gain locations were all manually recreated, connected, and labeled. A section of the LRBM near Leadore, ID is provided as an example of details included in the model (Figure 9).

LRBM details other than the river network, including input timeseries files for the catchment inflow, water demand, water return fraction, and reach gains were recreated and connected to the relevant model elements (e.g., water user nodes, catchments, river branches, etc.). The resulting river basin model network included 77 catchments, 69 branches, 857 river nodes (e.g., diversions, catchment pour points, gages, etc.), 321 water user nodes representing irrigation, and 1 water user node representing the inter-basin water transfer from Wimpey Creek to Bohannon Creek. The entire LRBM, including all of these components, is visualized for reference in Figure 10. Input timeseries files (DFS0s) created and attached include 77 catchment runoff timeseries, 322 water demand timeseries, 317 return fraction timeseries, and 24 river reach gain timeseries.



Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

Figure 9. LRBM catchments, tributaries, and irrigation water use nodes near Leadore, ID

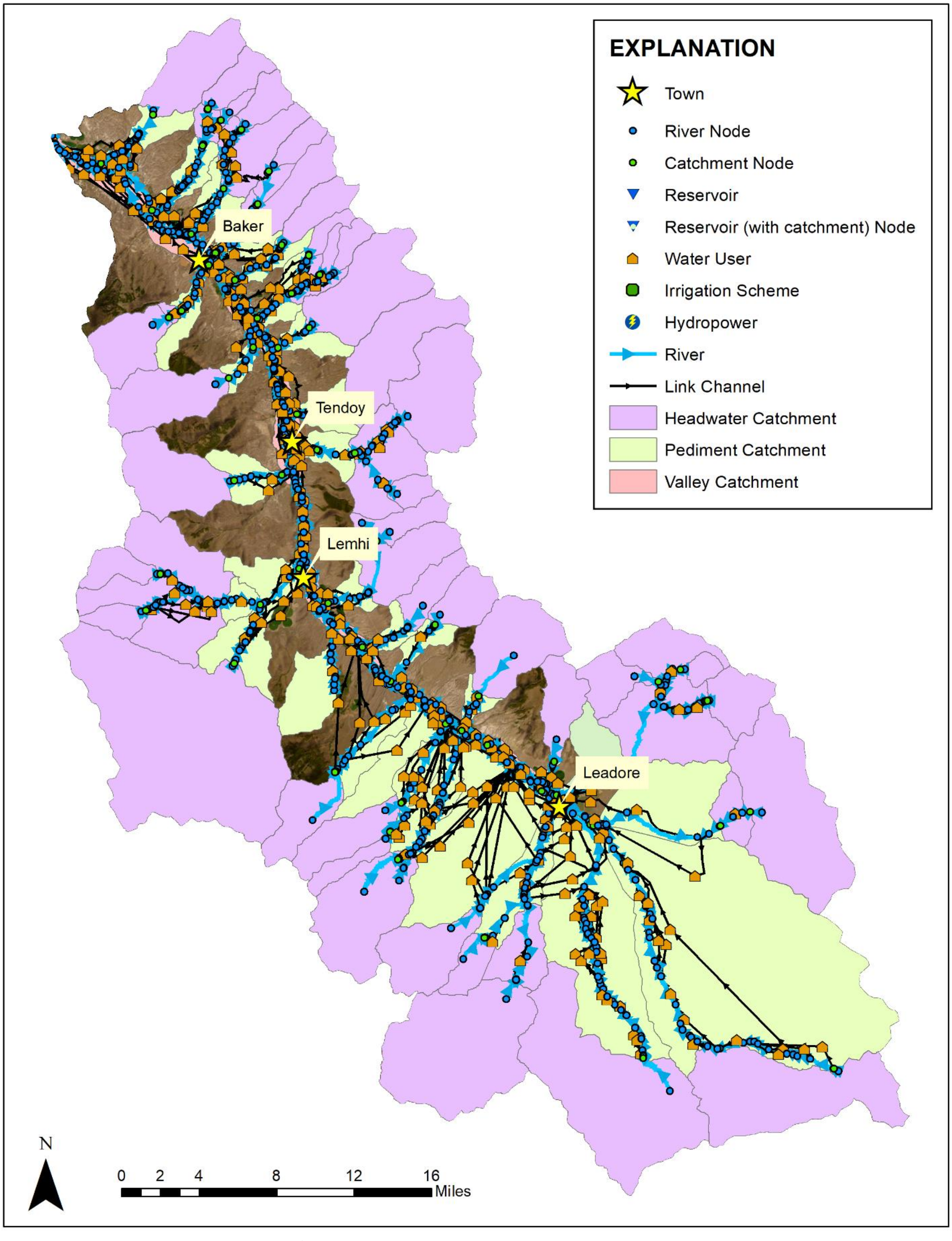


Figure 10. LRBM network of catchments, tributaries, and irrigation water use nodes

2. Updating and recalibrating the NAM Rainfall-Runoff Model

The NAM Rainfall-Runoff Model (NAM) is used to generate inflow data for each Lemhi Basin subcatchment in the LRBM. NAM was updated and recalibrated to include data from water years 2021 and 2022. NAM inputs have been created and loaded into the NAM model for the years 1981 through 2022. As a result, NAM is now capable of computing unaltered streamflow in the Lemhi Basin from 1981 through 2022.

Climate data inputs to the NAM rainfall-runoff model were acquired by downloading daily mean PRISM data for all 77 catchments (Figure 10) from Climate Engine (Huntington et al., 2017). Input data included precipitation, temperature, and potential evapotranspiration, while a snowmelt coefficient input dataset was computed using the method outlined in IDWR (2012).

Following completion of the NAM input datasets, the model had to be calibrated. Subcatchments that contained stream gages upstream of all diversions were used for calibration, as these gages record natural runoff. The adjustable model parameters that yielded modelled streamflow values nearest to observed streamflow were then applied to nearby ungaged subcatchments. The final product is a timeseries of estimated daily mean runoff for each subcatchment within the Lemhi Basin. This dataset is first checked for quality assurance and quality control, including comparative analyses between the computed NAM rainfall-runoff and the USGS StreamStats model. The final NAM streamflow values are then fed into the LRBM, which routes the runoff through streams, diversions, return flows, etc., ultimately providing estimates of daily mean streamflow at locations throughout the Lemhi Basin.

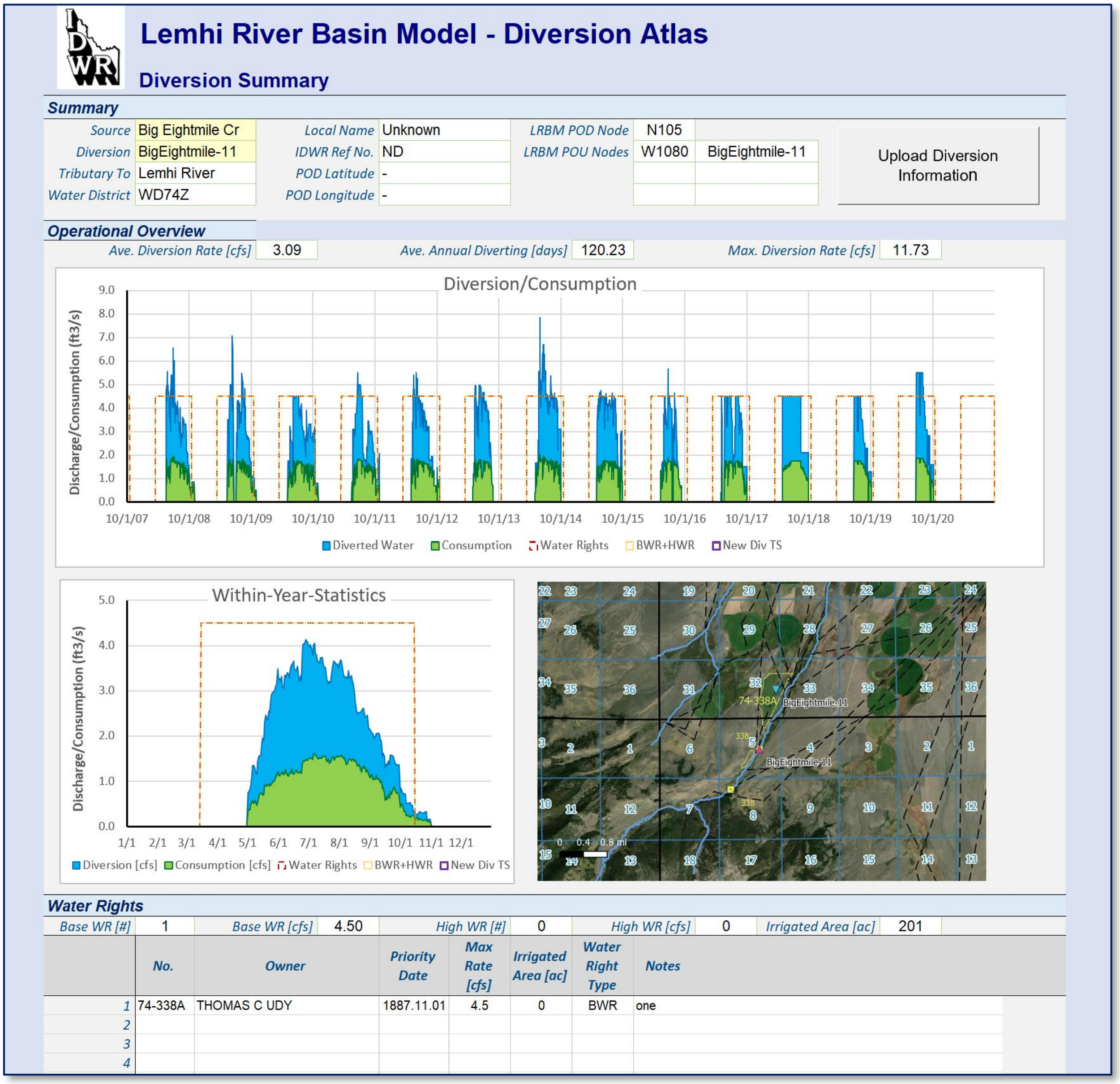
3. Updating input data and the supporting data pre-processing files

This portion of the LRBM update process involved obtaining, preparing, and loading the input timeseries information into the DFS0 files. This pre-processing step was largely conducted by updating and enhancing supporting pre-processing Excel files including *Data Atlas.xlsm, CatchmentInflowTS.xlsm,* and *LRBM Catchment_RG_InputTS_v04.xlsm*. Specific updates that were completed include:

- The irrigation demand timeseries for the 322 water user nodes have been updated through 10/1/2021 from the water master records submitted to IWDR. Once compiled and gap filled, each time series was reviewed, and errors were corrected for the period 10/1/2007 -10/1/2021.
- The Data Atlas structure was modified, and macros were written to expedite reviewing, modifying, and updating demand timeseries.
- The consumptive equation was updated with improved methodology and recoded to expedite calculation times. The reference ET timeseries was extended through 10/1/2021 to match the irrigation period documented in the 2021 water master records. Results are now presented in the Data Atlas (Figure 11).
- The Data Atlas was improved by implementing the display of the return fractions of diverted waters and mapped images of each diversion's point of diversion and places of use. The format of the Diversion Atlas was developed using input provided by members of the USBWP.
- The updated NAM rainfall-runoff values were entered into the DFS0 files associated with each subcatchment.
- For irrigation systems with long return flow paths, as defined by CH2M Hill (2014), the return flow delay has been applied in the form of a catchment reach gain timeseries to add to shallow

groundwater return flows. These are computed exterior to the LRBM and loaded into the model as timeseries. The demand and return fractions in the Data Atlas have been connected to the *LRBM Catchment_RG_InputTS_v04.xlsm* file for computing the catchment gains.

Note, loading the timeseries into the DFSOs from Excel is time consuming and potentially error prone. Timeseries were handled programmatically in Excel for MIKE BASIN, but that method is no longer available. A python tool has been created to restore this functionality and load timeseries. However, future efforts to incorporate this tool into the Excel pre- and post-processing are still required.



Lemhi River Basin Model - Diversion Atlas

Diversion Summary

Summary

Source	Big Eightmile Cr	*Local Name*	Unknown	*LRBM POD Node*	N105	
Diversion	BigEightmile-11	*IDWR Ref No.*	ND	*LRBM POU Nodes*	W1080	BigEightmile-11
Tributary To	Lemhi River	*POD Latitude*	-			
Water District	WD74Z	*POD Longitude*	-			

Operational Overview

Ave. Diversion Rate [cfs] 3.09 *Ave. Annual Diverting [days]* 120.23 *Max. Diversion Rate [cfs]* 11.73

Water Rights

Base WR [#] 1 *Base WR [cfs]* 4.50 *High WR [#]* 0 *High WR [cfs]* 0 *Irrigated Area [ac]* 201

	No.	Owner	Priority Date	Max Rate [cfs]	Irrigated Area [ac]	Water Right Type	Notes
1	74-338A	THOMAS C UDY	1887.11.01	4.5	0	BWR	one
2							
3							
4							

Figure 11. Example of a Data Atlas diversion summary at Big Eightmile Creek - Diversion 11

4. Updated and recalibrated the LRBM and post-processing files

Once the LRBM node network was created and the input data pre-processed, the model was further calibrated by calculating reach gains at each gage location for the simulation period of 10/1/2007 through 9/30/2021. The model has been calibrated to the Lemhi River at Cottom Lane Gage, with downstream calibrations to be performed in the summer of 2023. A hydrograph of the observed flows at the Lemhi River at Cottom Lane Gage versus LRBM modelled streamflow shows the current performance level of the model (Figure 12).

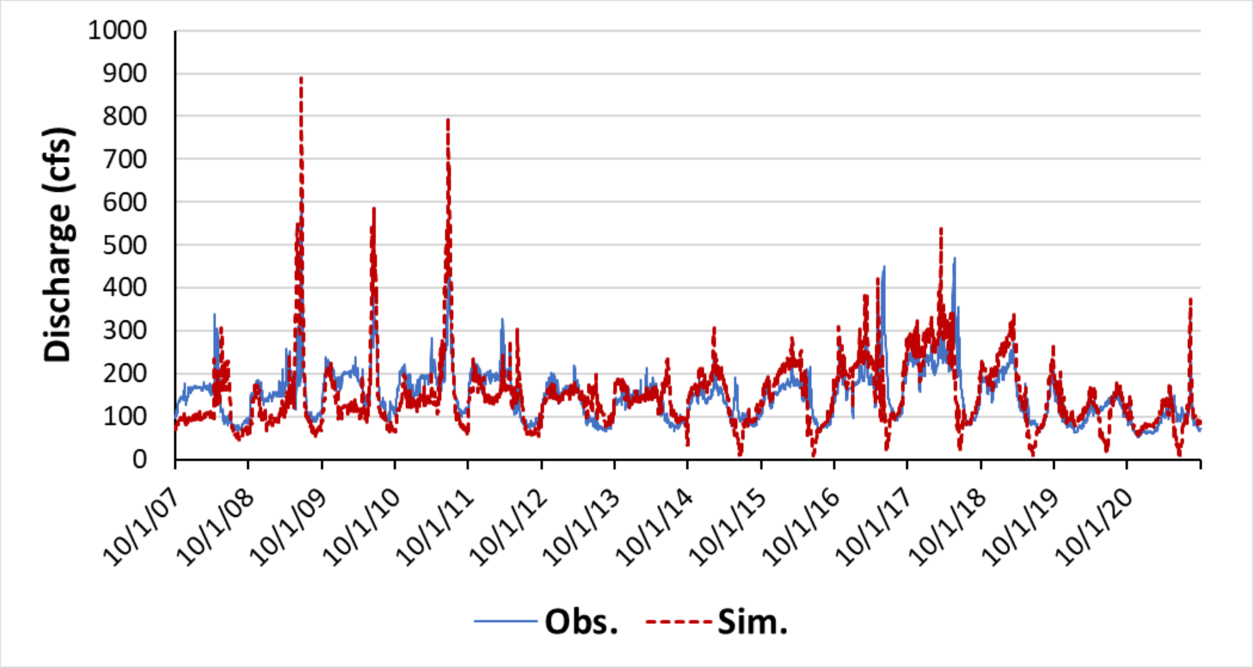


Figure 12. Lemhi River at Cottom Lane observed streamflow versus LRBM streamflow output

Task 6 – Lemhi River Basin Model Scenarios

Scenario requests submitted by Lemhi Basin stakeholders and evaluated using the LRBM

The LRBM input data and model have been used to support several projects that benefit Lemhi Basin salmonid recovery efforts and water users during this project period. The larger support efforts are listed below:

- Assessment of Big Timber Creek high water right claims.
- Lemhi Settlement Agreement Feasibility and Design: provided assessment of the quantity and timing of flow required to meet a minimum streamflow provision at the Lemhi River at McFarland Campground stream gage. This analysis was the foundation for the terms of the settlement.
- Lemhi Settlement Agreement Initiation: As the Settlement has been adopted, it is important to be able to select the proper timing to execute the event when applicable. The LRBM and

associated model input data are being used to formulate indicators that will be used to meet the agreed upon minimum streamflow targets when required.

Lemhi Basin Streamflow Estimates Under Variable Climate Projections

Estimation of future Lemhi Basin streamflow under variable climate projections was completed, though the results are still preliminary and require further quality checks before they can be considered finalized. This analysis diverged from the methods described in the research proposal as a result of data availability issues. IDWR needed to either find or compute the necessary climate futures input data for the NAM rainfall-runoff model, and could not find the necessary information within the Joyce and Coulson (2020) report. However, after seeking alternative climate change data sources, IDWR was ultimately able to estimate future unaltered runoff within the Lemhi Basin under two potential future climate scenarios.

The LRBM NAM rainfall-runoff model requires inputs of daily mean precipitation, temperature, potential evapotranspiration (PET), and a snowmelt coefficient for each subcatchment (Figure 10). A multi-step process was used to compute the input datasets needed to estimate streamflow given variable potential climate futures.

1. The Climate Explorer (NOAA, 2023) was used to estimate changes to precipitation and temperature that will occur in Lemhi County (approximates the Lemhi Basin) between the present day and 2099 under both low and high greenhouse gas emissions scenarios.
2. The Climate Explorer projected average max temperatures and annual cumulative precipitation values, which were compared to the PRISM (used in NAM) average daily max temperatures and cumulative precipitation values for the period from 2010 through 2019.
3. The percentage differences between the climate projection data and the 2010 to 2019 data were used to compute annual timescale correction factors for temperature and precipitation.
4. For temperature, the annual timescale correction factors were multiplied times the mean daily values for each day of the year for the period from 2010 through 2019, generating daily timeseries of temperature data for 2055, 2075, and 2095.
5. A similar method was used to generate the precipitation data. However, the base precipitation values to which the correction factors were applied were randomly sampled from the period of 2010 through 2019 for each day of the year. This was done to ensure that there would be a normal number of days with zero precipitation.
6. The Climate Explorer did not project future PET values. However, it is estimated that approximately 78% of climate-related changes to PET at the latitude of the Lemhi Basin are described by changes to temperature alone (Scheff and Frierson, 2014). Given this information, a regression analysis was performed on the relationship between temperature and PET using historical data. Estimates of climate-induced changes to PET were then computed using the regression equations. The low emissions estimate was a 21% increase in PET between 2022 and 2099, while the high emissions result was a 45% increase. These estimates fall within the range of projections presented in Scheff and Frierson (2014) for regions near the same latitude as the Lemhi Basin, though the high emissions result is on the higher end of the range of projections.
7. The daily snowmelt coefficients (Csnow) for 2055, 2075, and 2095 were calculated using the method described by IDWR (2012), where Csnow = 0.0614 * x + 1.519.

Following the development of the climate futures NAM input datasets, NAM was set up to estimate runoff in 2055, 2075, and 2095, given input data developed from both high and low greenhouse gas emissions scenarios. The model had already been calibrated through water year 2022 (see "Lemhi River Basin Model and Public Tool Updates and Improvements"), and the same calibration parameters were applied to each subcatchment for the climate projection model runs. The initial conditions for NAM were set by running the model for three years using the same climate futures input datasets for every year. The NAM output for the third year was then accepted as the final modelled runoff result.

As previously noted, all runoff projections presented in this report are preliminary, and require additional quality checks before being finalized. Nevertheless, the preliminary NAM results and analyses are presented below.

NAM computed runoff from every Lemhi Basin headwater subcatchment (Figure 10) was characterized in Table 5. Note that pediment and valley catchments were excluded from this analysis because very little runoff was generated at lower elevations within the Lemhi Basin (roughly 5.3% of the total runoff). Table 5 can be interpreted as follows:

- Peak Runoff = mean of peak annual streamflow from every headwater subcatchment
- Mean Total Runoff = mean total daily runoff from every headwater subcatchment
- Peak Runoff Date = mean date on which peak flow occurred in every headwater subcatchment
- Volume = total volume of runoff from every subcatchment

Table 5. Lemhi Basin Headwater Catchment Runoff Under Variable Climate Projections

Timeframe	Scenario	Peak Runoff (cfs)	Peak Runoff Date	Mean Total Runoff (cfs)	Volume (acre-ft/yr)
2010-2022	Mean	28.27	4-Jun	361	261468
2055	Low	38.91	27-May	340	245980
2055	High	39.24	2-Jun	341	247150
2075	Low	28.82	18-May	228	164917
2075	High	23.29	23-Apr	179	129901
2095	Low	22.47	15-May	176	127206
2095	High	22.2	8-May	160	115653

Table 5 shows the preliminary NAM predictions that Lemhi Basin headwater catchment runoff is likely to decrease significantly between 2022 and 2099, regardless of which emissions scenario occurs. The average total runoff from the headwater catchments was projected to decrease by 37% or more by 2075, and 50% or more by 2095. Interestingly, the annual peak runoff value is projected to increase between 2022 and 2055, before trending downward again in 2075 and 2095. This result may be due to higher temperatures and more springtime rain triggering faster and larger snowmelt events. Also of interest is the peak runoff date occurring earlier in the year as time progresses, again, regardless of the emissions scenario. The peak runoff date moves up from early June (2010-2022 average) to somewhere between mid-May and late April by the end of the century.

The projected runoff for the headwaters of Hayden Creek and Big Timber Creek were plotted to evaluate potential future changes within two streams that are focal points in recent salmonid recovery efforts (Figure 13, Figure 14). Hayden Creek is the second most prominent Chinook salmon spawning reach in the Lemhi Basin behind the Lemhi River itself, and significant work has been completed on Big Timber Creek to reconnect it to the Lemhi River and provide additional habitat for Chinook salmon and Steelhead.

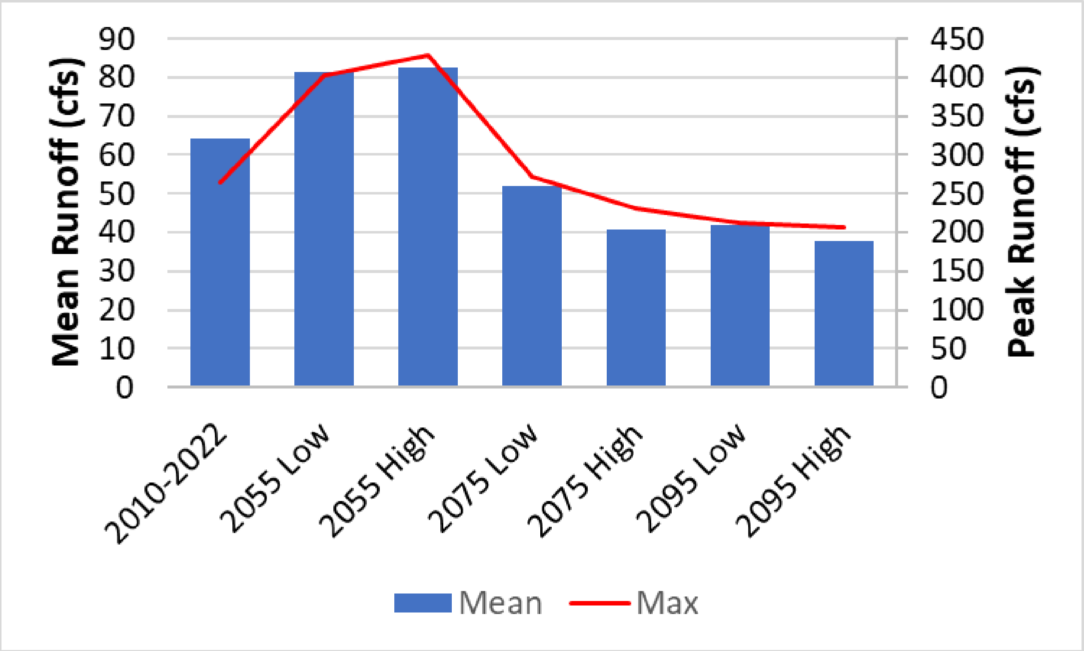


Figure 13. Projected Runoff for Hayden Creek Headwater Catchment

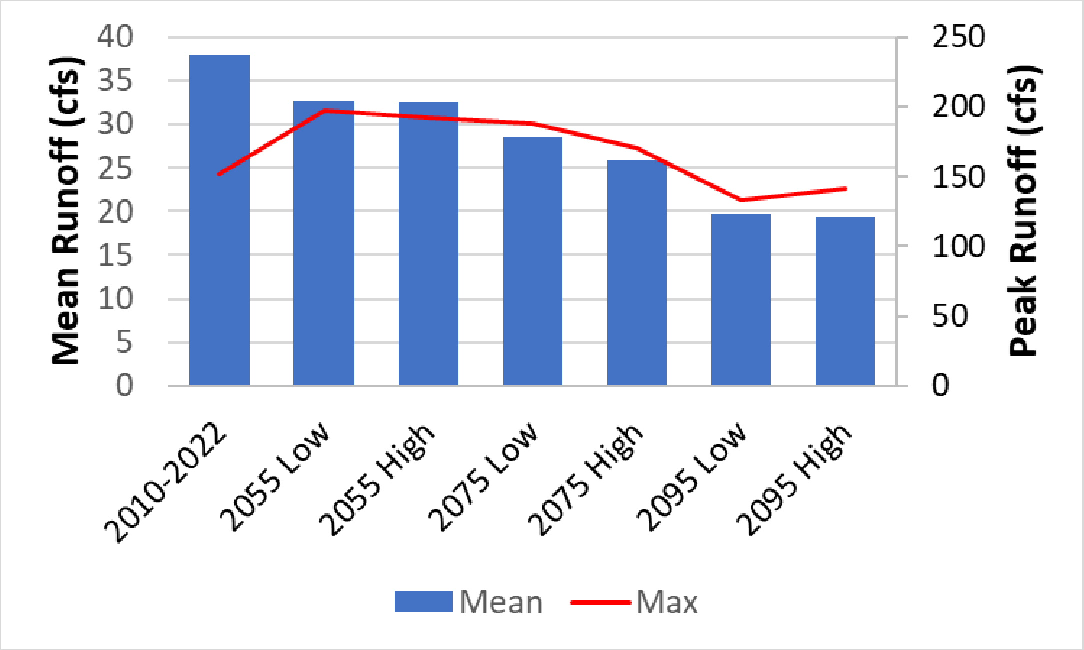


Figure 14. Projected Runoff for Big Timber Creek Headwater Catchment

Reviewing the charts, there is a notable downward trend over time in both peak and mean projected runoff for Hayden Creek and Big Timber Creek (Figure 13, Figure 14). The maximum projected decrease in mean runoff in Hayden Creek was 41%, while the maximum decrease in Big Timber Creek was 49%. Interestingly, the Hayden Creek headwaters have a projected spike in both mean and peak runoff in 2055 relative to 2022, whereas Big Timber Creek only has a projected spike in peak runoff. The spike in peak runoff in 2055 is reflective of the average behavior of subcatchments throughout the Lemhi Basin, while the spike in mean runoff is not.

The modelled decreases in mean runoff throughout the Lemhi Basin in the latter half of the 21st century are problematic for salmonid recovery efforts for multiple reasons. First, some of the tributaries that provide salmonid habitat have already had minimum streamflow levels below fish passage in recent years. Second, decreased flow volume makes the temperature of the Lemhi River and its tributaries more vulnerable to air temperature fluctuations. With temperatures estimated to increase significantly over the coming century (NOAA, 2023), and Lemhi River temperatures already warmer than optimal in the summer months (IDWR, 2022b), any increases to summer water temperatures may cause additional harm.

Task 7 – Lemhi Basin Stable Isotope Analyses

IDWR sampled surface water and groundwater throughout the Lemhi Basin from 2015 through 2018, and sent the samples to the Boise State Stable Isotope Laboratory for analysis of stable isotope ratios (δ^2H and δ^{18}O) present in each sample. Samples were collected approximately quarterly from several locations within the Lemhi River, its tributaries, one diversion, and three local wells. This data were previously reported in IDWR (2019); however, additional analyses have been performed for this report. The goal of these analyses is to determine if there is isotopic distinction between any of the sampled waters, and if so, if those unique isotopic signatures might provide information on water sources or flowpaths.

The stable isotope data used in the analyses is listed in Table 6 and Figure 15, while Figures 16, 17, and 18 show some of the newly conducted analyses. Note that the lc-excess values in the table and figures equal the line-conditioned excess, which is a measure of the distance a sample plots from the local meteoric water line (LMWL; Landwehr and Coplen, 2006). The lc-excess is computed using the equation lc-excess = [δ^2H-a δ^{18}O-b]/S, where a and b are the slope and intercept of the LMWL, and S is the combined uncertainty of δ^2H (‰) and δ^{18}O (‰). As is typical for natural water stable isotope data, δ^2H (‰) and δ^{18}O (‰) values are reported as the difference between the sampled isotope ratios (^{18}O/^{16}O and ^{2}H/^{1}H, respectively) and Vienna Standard Mean Ocean Water (VSMOW) in units of per-mille (‰). The global meteoric water line (GMWL) was included as an additional reference point beyond that of the LMWL (Figure 10).

Table 6. Lemhi Basin Stable Isotope Data

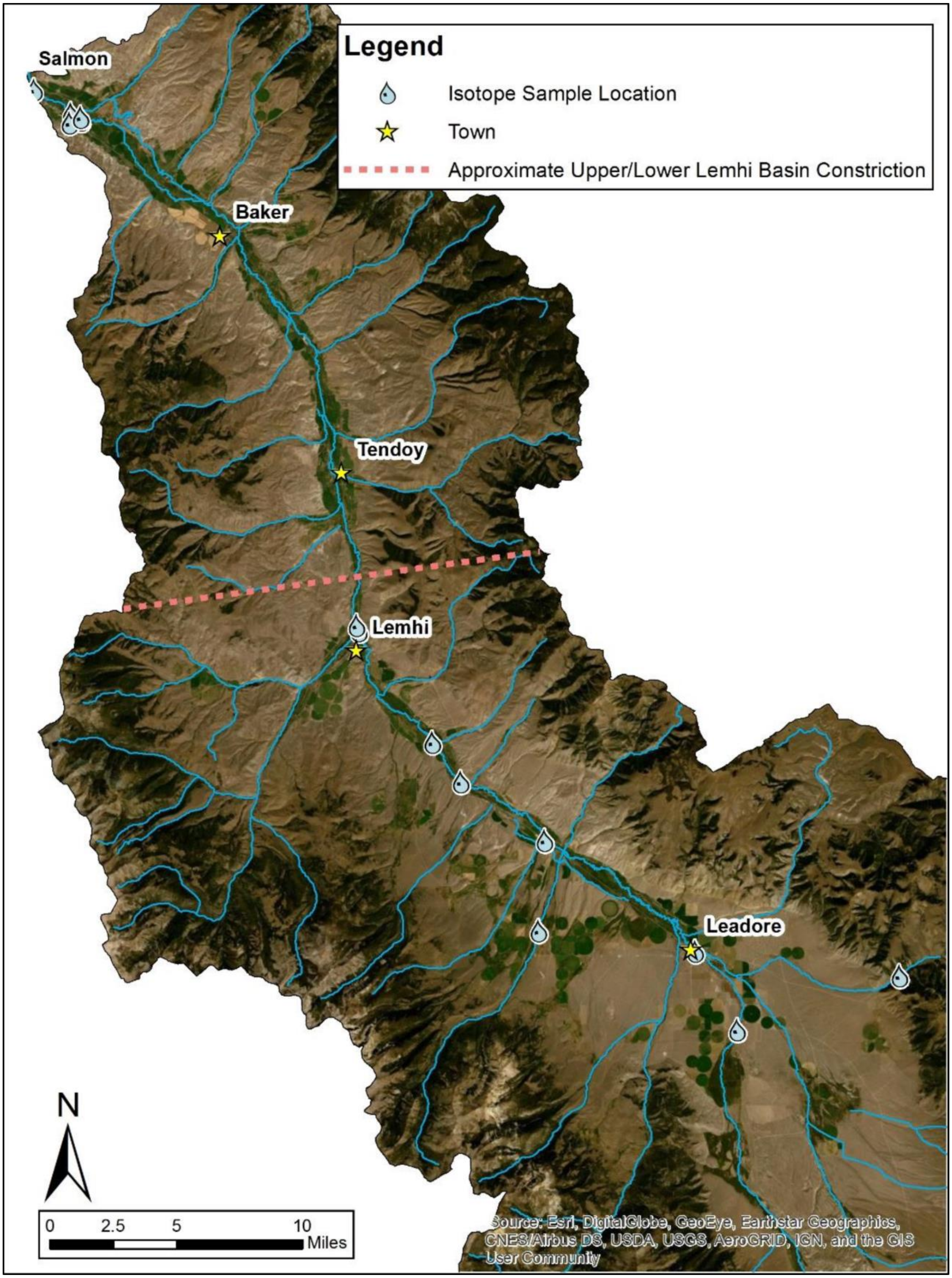
Site Name	Site Type	Date	δ18O (‰)	δ2H (‰)	lc-excess
L-7 Diversion	Diversion	06/10/2015	-17.50	-133.71	-0.08
L-7 Diversion	Diversion	08/06/2015	-17.76	-127.78	8.45
L-7 Diversion	Diversion	10/07/2015	-17.66	-128.96	6.36
L-7 Diversion	Diversion	04/06/2016	-17.25	-132.69	-1.09

L-7 Diversion	Diversion	06/03/2016	-17.52	-127.85	6.35
L-7 Diversion	Diversion	09/07/2016	-17.68	-137.11	-2.21
L-7 Diversion	Diversion	04/11/2017	-17.81	-133.11	3.16
L-7 Diversion	Diversion	06/07/2017	-18.18	-133.68	5.58
L-7 Diversion	Diversion	09/08/2017	-17.11	-133.74	-3.35
L-7 Diversion	Diversion	11/15/2017	-17.98	-130.13	7.72
L-7 Diversion	Diversion	04/10/2018	-17.49	-134.38	-0.90
L-7 Diversion	Diversion	09/06/2018	-17.46	-134.86	-1.68
Big Eightmile Creek Gage	Stream	08/04/2015	-17.68	-128.78	6.71
Big Eightmile Creek Gage	Stream	12/01/2015	-18.57	-132.32	10.32
Big Eightmile Creek Gage	Stream	04/05/2016	-18.52	-132.45	9.72
Big Eightmile Creek Gage	Stream	06/02/2016	-17.90	-129.97	7.23
Big Eightmile Creek Gage	Stream	09/08/2016	-17.94	-133.88	3.38
Big Eightmile Creek Gage	Stream	12/20/2016	-18.21	-135.23	4.14
Big Eightmile Creek Gage	Stream	04/11/2017	-17.96	-134.69	2.66
Big Eightmile Creek Gage	Stream	06/06/2017	-18.62	-133.37	9.56
Big Eightmile Creek Gage	Stream	09/07/2017	-17.76	-135.50	0.14
Big Eightmile Creek Gage	Stream	11/14/2017	-18.38	-135.35	5.45
Big Eightmile Creek Gage	Stream	04/10/2018	-18.12	-136.59	1.93
Hawley Creek Gage	Stream	08/04/2015	-18.34	-141.16	-1.14
Hawley Creek Gage	Stream	12/01/2015	-18.83	-142.86	1.12
Hawley Creek Gage	Stream	04/05/2016	-18.49	-141.68	-0.42
Hawley Creek Gage	Stream	06/02/2016	-18.02	-139.48	-1.96
Hawley Creek Gage	Stream	09/08/2016	-18.51	-140.00	1.54
Hawley Creek Gage	Stream	12/20/2016	-19.03	-139.36	6.58
Hawley Creek Gage	Stream	04/11/2017	-18.65	-146.89	-4.72
Hawley Creek Gage	Stream	06/06/2017	-18.53	-140.73	0.91
Hawley Creek Gage	Stream	09/07/2017	-18.69	-142.82	0.00
Hawley Creek Gage	Stream	11/14/2017	-18.80	-141.42	2.38
Hawley Creek Gage	Stream	04/10/2018	-18.39	-142.86	-2.55
Hayden Creek Gage	Stream	08/04/2015	-17.42	-128.86	4.47
Hayden Creek Gage	Stream	12/01/2015	-18.10	-137.41	0.87
Hayden Creek Gage	Stream	04/05/2016	-17.87	-134.31	2.32
Hayden Creek Gage	Stream	06/02/2016	-17.66	-134.08	0.88
Hayden Creek Gage	Stream	09/08/2016	-18.14	-135.06	3.75
Hayden Creek Gage	Stream	12/20/2016	-18.00	-133.24	4.54
Hayden Creek Gage	Stream	04/11/2017	-17.79	-137.98	-2.26
Hayden Creek Gage	Stream	06/06/2017	-18.40	-141.79	-1.27
Hayden Creek Gage	Stream	09/07/2017	-18.32	-133.79	6.62
Hayden Creek Gage	Stream	11/14/2017	-18.02	-129.74	8.54
Hayden Creek Gage	Stream	04/10/2018	-18.23	-137.58	1.78
Lee Creek Gage	Stream	08/04/2015	-17.93	-129.91	7.54
Lee Creek Gage	Stream	12/01/2015	-18.11	-140.07	-1.89

Lee Creek Gage	Stream	04/05/2016	-18.37	-129.14	12.02
Lee Creek Gage	Stream	06/02/2016	-17.58	-131.40	3.06
Lee Creek Gage	Stream	09/08/2016	-17.87	-136.81	-0.38
Lee Creek Gage	Stream	12/20/2016	-18.37	-135.17	5.58
Lee Creek Gage	Stream	04/11/2017	-18.25	-135.45	4.30
Lee Creek Gage	Stream	06/06/2017	-17.78	-138.27	-2.66
Lee Creek Gage	Stream	09/07/2017	-17.26	-138.22	-6.91
Lee Creek Gage	Stream	11/14/2017	-18.51	-129.63	12.67
Lee Creek Gage	Stream	04/10/2018	-17.98	-138.53	-1.30
Lemhi above Hayden Creek	Stream	08/04/2015	-18.22	-134.05	5.55
Lemhi above Hayden Creek	Stream	12/01/2015	-18.49	-143.15	-2.01
Lemhi above Hayden Creek	Stream	12/01/2015	-18.40	-135.44	5.51
Lemhi above Hayden Creek	Stream	04/05/2016	-18.41	-135.37	5.66
Lemhi above Hayden Creek	Stream	06/02/2016	-18.48	-132.80	9.06
Lemhi above Hayden Creek	Stream	09/08/2016	-18.38	-139.20	1.30
Lemhi above Hayden Creek	Stream	12/20/2016	-18.61	-135.10	7.67
Lemhi above Hayden Creek	Stream	04/11/2017	-18.43	-142.03	-1.31
Lemhi above Hayden Creek	Stream	06/06/2017	-18.45	-135.01	6.40
Lemhi above Hayden Creek	Stream	09/07/2017	-18.35	-133.03	7.72
Lemhi above Hayden Creek	Stream	11/14/2017	-18.68	-133.84	9.57
Lemhi above Hayden Creek	Stream	04/10/2018	-17.88	-138.72	-2.32
Lemhi at McFarland	Stream	08/04/2015	-18.36	-135.50	5.11
Lemhi at McFarland	Stream	12/01/2015	-18.58	-143.09	-1.20
Lemhi at McFarland	Stream	04/05/2016	-18.47	-138.80	2.46
Lemhi at McFarland	Stream	06/02/2016	-18.14	-135.47	3.29
Lemhi at McFarland	Stream	09/08/2016	-18.46	-138.21	3.06
Lemhi at McFarland	Stream	12/20/2016	-18.59	-135.67	6.83
Lemhi at McFarland	Stream	04/11/2017	-18.29	-143.00	-3.54
Lemhi at McFarland	Stream	06/06/2017	-18.35	-130.62	10.32
Lemhi at McFarland	Stream	09/07/2017	-17.50	-141.56	-8.52
Lemhi at McFarland	Stream	11/14/2017	-18.57	-130.25	12.49
Lemhi at McFarland	Stream	04/10/2018	-18.26	-139.19	0.33
Lemhi near Cheney Well	Stream	06/10/2015	-17.75	-132.74	3.03
Lemhi near Cheney Well	Stream	08/06/2015	-17.58	-130.46	4.09
Lemhi near Cheney Well	Stream	10/07/2015	-17.43	-136.02	-3.14
Lemhi near Cheney Well	Stream	12/03/2015	-18.00	-137.94	-0.50
Lemhi near Cheney Well	Stream	04/06/2016	-17.90	-137.83	-1.22
Lemhi near Cheney Well	Stream	06/03/2016	-17.59	-133.79	0.55
Lemhi near Cheney Well	Stream	09/07/2016	-17.87	-133.46	3.24
Lemhi near Cheney Well	Stream	04/11/2017	-17.24	-141.62	-10.76
Lemhi near Cheney Well	Stream	06/07/2017	-18.50	-136.07	5.66
Lemhi near Cheney Well	Stream	09/08/2017	-17.47	-130.40	3.20
Lemhi near Cheney Well	Stream	11/15/2017	-18.43	-132.69	8.72

Lemhi near Cheney Well	Stream	04/10/2018	-17.95	-137.75	-0.73
Lemhi near Cheney Well	Stream	09/06/2018	-17.55	-135.02	-1.04
Lemhi River Above L-63	Stream	08/04/2015	-18.17	-136.13	2.85
Lemhi River Above L-63	Stream	12/01/2015	-18.11	-141.38	-3.24
Lemhi River Above L-63	Stream	04/05/2016	-18.00	-136.46	1.12
Lemhi River Above L-63	Stream	06/02/2016	-18.15	-136.30	2.51
Lemhi River Above L-63	Stream	09/08/2016	-18.03	-135.68	2.17
Lemhi River Above L-63	Stream	12/20/2016	-18.57	-136.17	6.17
Lemhi River Above L-63	Stream	04/11/2017	-17.61	-136.65	-2.33
Lemhi River Above L-63	Stream	06/06/2017	-18.09	-141.55	-3.61
Lemhi River Above L-63	Stream	09/07/2017	-17.87	-137.02	-0.59
Lemhi River Above L-63	Stream	11/20/2017	-18.48	-137.97	3.46
Lemhi River Above L-63	Stream	04/10/2018	-17.96	-140.26	-3.32
Lemhi River at L-1	Stream	12/01/2015	-18.15	-133.83	5.16
Lemhi River at L-1	Stream	04/05/2016	-18.07	-131.39	7.11
Lemhi River at L-1	Stream	06/02/2016	-17.98	-134.22	3.36
Lemhi River at L-1	Stream	09/08/2016	-17.52	-134.25	-0.47
Lemhi River at L-1	Stream	12/20/2016	-18.50	-133.52	8.42
Lemhi River at L-1	Stream	04/11/2017	-17.53	-142.41	-9.16
Lemhi River at L-1	Stream	06/06/2017	-17.79	-140.02	-4.48
Lemhi River at L-1	Stream	09/07/2017	-17.80	-129.40	7.06
Lemhi River at L-1	Stream	11/15/2017	-18.72	-135.14	8.47
Lemhi River at L-1	Stream	04/10/2018	-17.87	-138.57	-2.22
Little Springs Creek Lower	Stream	12/01/2015	-18.20	-142.29	-3.47
Little Springs Creek Lower	Stream	04/05/2016	-18.11	-132.00	6.83
Little Springs Creek Lower	Stream	06/02/2016	-18.02	-137.10	0.60
Little Springs Creek Lower	Stream	09/08/2016	-18.11	-145.48	-7.71
Little Springs Creek Lower	Stream	12/20/2016	-18.21	-137.85	1.37
Little Springs Creek Lower	Stream	04/11/2017	-18.02	-137.88	-0.24
Little Springs Creek Lower	Stream	06/06/2017	-18.12	-132.71	6.11
Little Springs Creek Lower	Stream	09/07/2017	-18.61	-136.02	6.63
Little Springs Creek Lower	Stream	11/14/2017	-17.88	-138.64	-2.25
Little Springs Creek Lower	Stream	04/10/2018	-17.88	-138.31	-1.87
Texas Creek Gage	Stream	08/04/2015	-17.87	-131.84	4.97
Texas Creek Gage	Stream	12/01/2015	-18.76	-141.66	1.85
Texas Creek Gage	Stream	04/05/2016	-18.17	-131.10	8.24
Texas Creek Gage	Stream	06/02/2016	-17.51	-129.72	4.26
Texas Creek Gage	Stream	09/08/2016	-17.59	-135.53	-1.27
Texas Creek Gage	Stream	12/20/2016	-19.13	-139.71	7.03
Texas Creek Gage	Stream	04/11/2017	-17.98	-134.74	2.81
Texas Creek Gage	Stream	06/06/2017	-17.66	-140.17	-5.67
Texas Creek Gage	Stream	09/07/2017	-17.56	-128.41	6.11
Texas Creek Gage	Stream	11/14/2017	-18.49	-139.99	1.35

Texas Creek Gage	Stream	04/10/2018	-17.93	-138.33	-1.47
21N 22E 09DAB1	Well	06/10/2015	-17.67	-136.49	-1.67
21N 22E 09DAB1	Well	08/06/2015	-17.80	-126.53	10.16
21N 22E 09DAB1	Well	10/07/2015	-17.43	-135.14	-2.22
21N 22E 09DAB1	Well	12/04/2015	-17.48	-134.76	-1.39
21N 22E 09DAB1	Well	04/06/2016	-17.73	-128.90	7.03
21N 22E 09DAB1	Well	06/03/2016	-17.51	-130.26	3.72
21N 22E 09DAB1	Well	09/07/2016	-17.78	-136.90	-1.16
21N 22E 09DAB1	Well	04/11/2017	-17.20	-132.63	-1.43
21N 22E 09DAB1	Well	06/07/2017	-17.59	-140.54	-6.72
21N 22E 09DAB1	Well	09/08/2017	-17.35	-127.18	5.65
21N 22E 09DAB1	Well	11/15/2017	-18.01	-127.69	10.62
21N 22E 09DAB1	Well	04/10/2018	-17.55	-133.97	0.06
21N 22E 09DAB1	Well	09/06/2018	-17.69	-134.49	0.61
21N 22E 09DDB1	Well	06/10/2015	-18.08	-137.41	0.75
21N 22E 09DDB1	Well	08/06/2015	-17.76	-132.60	3.24
21N 22E 09DDB1	Well	10/07/2015	-17.63	-128.36	6.77
21N 22E 09DDB1	Well	12/03/2015	-17.34	-135.73	-3.58
21N 22E 09DDB1	Well	04/06/2016	-17.68	-127.64	7.93
21N 22E 09DDB1	Well	06/03/2016	-17.50	-129.59	4.34
21N 22E 09DDB1	Well	09/07/2016	-17.92	-131.92	5.31
21N 22E 09DDB1	Well	06/07/2017	-17.62	-130.39	4.48
21N 22E 09DDB1	Well	09/08/2017	-17.35	-129.09	3.66
21N 22E 09DDB1	Well	11/15/2017	-17.87	-136.37	0.12
21N 22E 09DDB1	Well	04/10/2018	-17.44	-133.12	0.08
21N 22E 09DDB1	Well	09/06/2018	-18.04	-134.21	3.83
21N 22E 10CCA1	Well	06/10/2015	-17.67	-134.61	0.37
21N 22E 10CCA1	Well	08/06/2015	-17.64	-129.43	5.71
21N 22E 10CCA1	Well	10/07/2015	-17.13	-132.36	-1.73
21N 22E 10CCA1	Well	12/03/2015	-17.48	-135.59	-2.26
21N 22E 10CCA1	Well	04/06/2016	-17.65	-129.36	5.85
21N 22E 10CCA1	Well	06/03/2016	-17.73	-133.26	2.29
21N 22E 10CCA1	Well	09/07/2016	-17.94	-136.35	0.74
21N 22E 10CCA1	Well	04/11/2017	-17.77	-141.38	-6.10
21N 22E 10CCA1	Well	06/07/2017	-17.61	-139.96	-5.91
21N 22E 10CCA1	Well	09/08/2017	-17.52	-135.61	-1.95
21N 22E 10CCA1	Well	11/15/2017	-18.08	-129.55	9.17
21N 22E 10CCA1	Well	04/10/2018	-17.64	-130.03	5.04
21N 22E 10CCA1	Well	09/06/2018	-17.58	-132.92	1.39



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

Figure 15. Lemhi Basin Water Sampling Locations for Stable Isotope Analysis

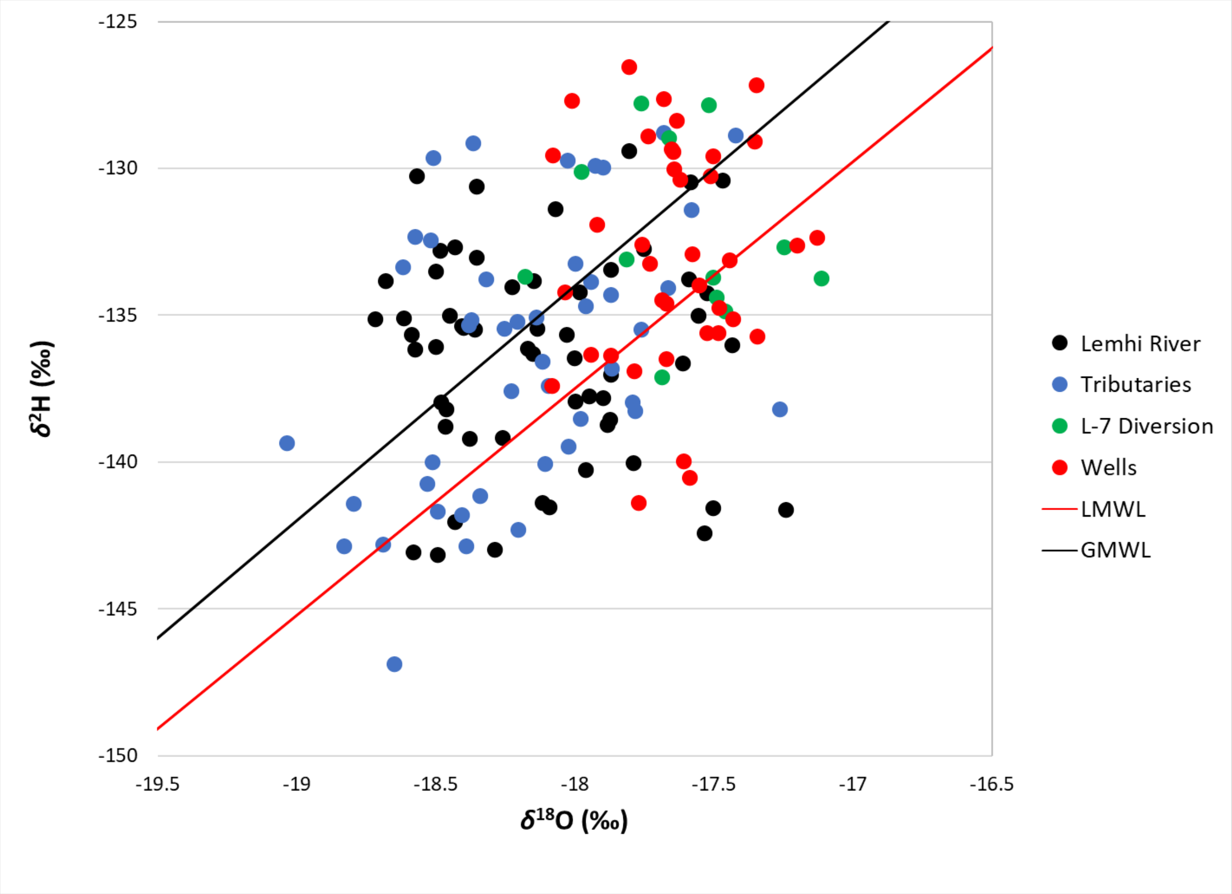


Figure 16. Lemhi Basin Stable Isotope Data Plotted Against the LMWL and GMWL

As was previously identified by IDWR (2019), the isotopic signatures of water sampled from Lemhi Basin surface water and groundwater suggest that these waters are likely well-mixed, as none of the sampled water bodies consistently plot far away from other water bodies in dual-isotope space (Figure 16). This mixing is likely the result of multiple factors. First, flood irrigation is commonly practiced in the Lemhi Basin (IDWR, 2022b). The flood irrigation demand is fed by a series of diversions and ditches running from the Lemhi River and its tributaries to agricultural places of use. Some of that diverted water is consumed by plants, some recharges the groundwater system, and some flows back into the Lemhi River and its tributaries via return flows. After return flows return to streams, the water is available to be re-diverted, and water in the basin is likely reused multiple times before exiting the basin via surface water and groundwater flowpaths (Donato, 1998). Furthermore, a constriction in the aquifer (Figure 15) surrounding the Lemhi River causes groundwater flowing down gradient through the Upper Lemhi Basin to be pushed to the surface as flow in the Lemhi River before entering the Lower Lemhi Basin.

Looking beyond the apparent frequent mixing of groundwater and surface water within the basin, there are notable differences between the isotopic signatures of the sampled wells and return flow versus the Lemhi River and its tributaries. The wells and diversion plot higher up and to the right along the LMWL on average than the Lemhi River and its tributaries. The similarity between the wells and the diversion suggests that these waters may have similar sourcing and hydrologic histories. Water that plots further up and to the right along a LMWL than other samples is typically indicative of a higher proportion of warm season precipitation. This suggests that water sampled from the wells and diversion may contain a higher percentage of warmer season precipitation than the Lemhi River and its tributaries. Conversely, the Lemhi River and its tributaries likely contain a higher percentage of cold season precipitation.

It may seem counterintuitive that the wells would contain a greater percentage of warm season precipitation than nearby streams. However, in the Lemhi Basin, many users have high flow water rights, where additional water can be diverted as long as the stream from which water is being diverted is above a certain flow target. This irrigation practice may result in a disproportionate percentage of springtime precipitation making its way into diversions and the groundwater system, especially because rain on snow events often trigger high flows within the Lemhi Basin. It is notable that the highest groundwater levels throughout much of the basin occur during the irrigation season (IDWR, 2022b), indicating that some of the irrigated water likely recharges the aquifer rather quickly. This suggests that some wells may contain a disproportionate amount of water sourced from spring rainfall relative to the ratio of total spring versus cold season precipitation in the basin.

It is difficult to detect differences between the different sample types in distance above or below the LMWL (Figure 16). However, lc-excess values were computed (Table 6) and visualized for each individual sampling site (Figure 17) in an effort to determine if any differences do exist.

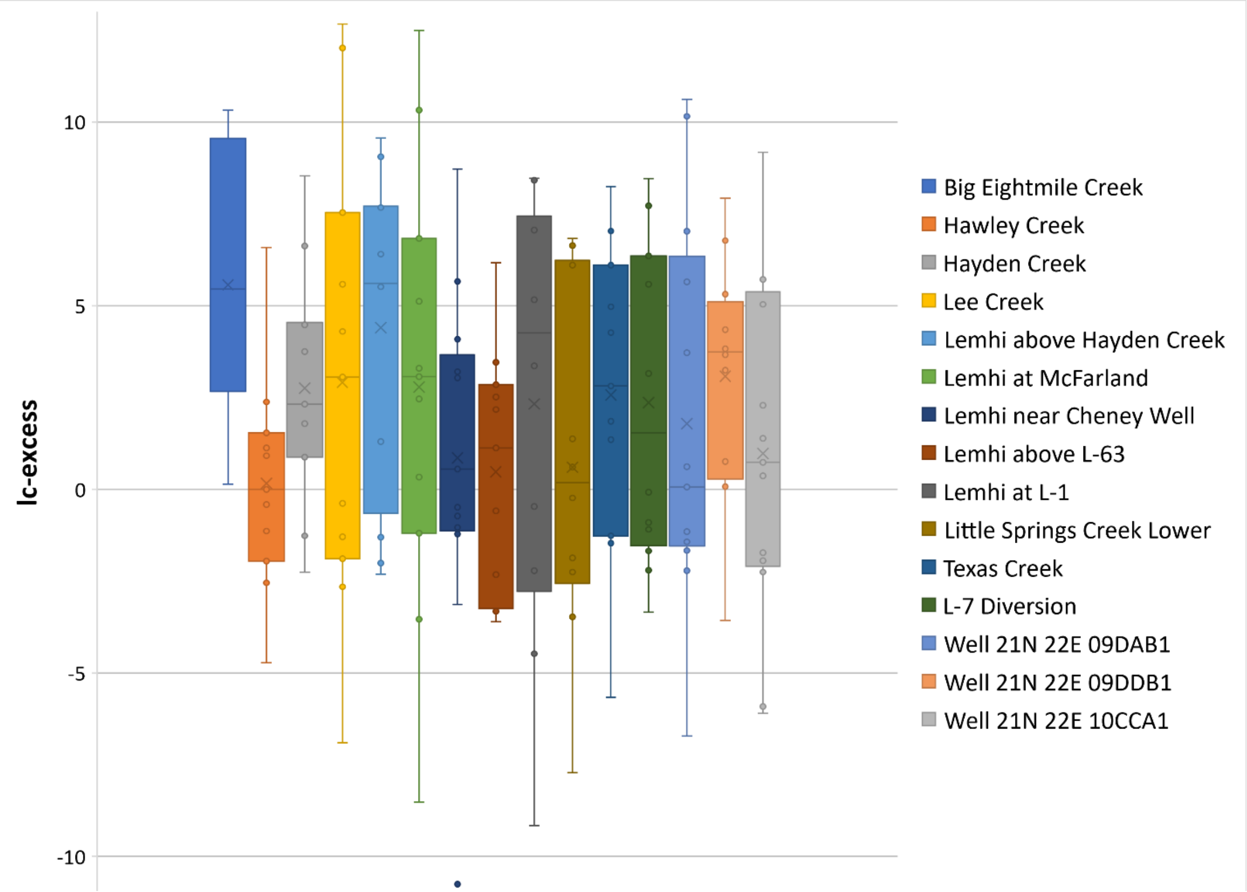


Figure 17. Lemhi River Basin Stable Isotope Data lc-excess Boxplot

Figure 17 shows that there is some overlap in the lc-excess values of every type of site sampled, including the Lemhi River, tributaries, the diversion, and the wells. As a result, no site type is statistically differentiated from another at a 95% confidence interval. There is also overlap between the vast majority of individual sites. However, it is worth noting that this a small sample size. As a result, it is possible that a larger sample size might have resulted in waters from different sites being statistically differentiated from one another. Despite this result, there are still some notable data points to discuss.

The lc-excess mean and median values for Big Eightmile Creek were both above 5, which was unique from all other sites. Big Eightmile Creek sources its water primarily from the Lemhi Range on the western side of the basin, and such positive lc-excess values are typically indicative of precipitation that originated from a more arid vapor source than most local precipitation. Though the signal was not as pronounced, the other tributaries draining the Lemhi Range (Hawley Creek and Lee Creek) also showed positive mean and median lc-excess values. Texas Creek had a less positive lc-excess value than the others, but much of the water in Texas Creek is sourced from valley bottom springs and seeps, differing from the mountain runoff dominated Big Eightmile, Hayden, and Lee Creeks. Interestingly, Hawley Creek, which drains the Beaverhead range on the eastern side of the basin, had a mean lc-excess of near zero, and was the only site where the quartile box did not overlap the quartile box of Big Eightmile Creek (Figure 17). Again, this is a small dataset, but this result suggests that a larger dataset could possibly allow for detection of distinct isotopic signatures between waters draining the east and west sides of the basin.

Examining the Lemhi River, it appears as though the Upper Lemhi Basin sites have lower mean lc-excess values than the Lower Lemhi Basin sites. Lemhi above L-63 has the lowest mean lc-excess value of any Lemhi River sampling site. Moving downstream from L-63, samples from the Lemhi at McFarland and above Hayden Creek sites had increasingly large lc-excess values. It is possible that the addition of Hayden Creek waters lowered Lemhi River lc-excess, as is seen at the Lemhi near Cheney Well site. Moving downstream from there, the lc-excess then increased again at the Lemhi at L-1 location.

There are a few possible reasons why the Upper Lemhi River had lower lc-excess values than the Lower Lemhi River. First, the portion of Lemhi River streamflow that is sourced from the Beaverhead range is larger towards the headwaters than it is further downstream. Eighteenmile Creek, Hawley Creek, and Canyon Creek contribute significant flows to the Lemhi River. Even Texas Creek, which sources much of its flow from valley bottom springs and seeps, had a lower lc-excess value than other tributaries draining the Lemhi Range. Moving downstream from the Lemhi above L-63 site, the tributaries draining the Lemhi Range contribute significantly more runoff than those draining the Beaverhead range, namely Big Timber Creek, Big Eightmile Creek, Lee Creek, and finally, Hayden Creek, and as mentioned previously, these flow contributions likely have higher lc-excess values than tributaries draining the Beaverhead Range. As a result, waters from these tributaries mixing in with the Lemhi River would increase lc-excess values as the river flows down valley.

When comparing the sampled wells, the diversion, and the Lemhi River, it is important to note that both the wells and the diversion are located near Salmon, at the downstream end of the basin. There is not a notable difference between the isotopic signatures at the wells, the diversion, and the Lemhi at L-1 gage. Again, this likely indicates a great deal of mixing between surface water and groundwater by the time water reached these sampling sites.

Another aspect of the stable isotope dataset that warranted exploration was temporal trends. However, despite employing all of the methods used in McCutcheon et. al. (2017), IDWR was unable to find any significant temporal trends in the data. There are short-term trends (e.g. increasing lc-excess throughout 2017), but it is unknown whether these were mere coincidence, or the result of something unique happening in the basin. Due to lack of findings, seasonality of the stable isotope data is not characterized in this report.

Task 8 – Lemhi Basin Water Quality Analysis

This section summarizes the findings of previous Lemhi Basin water quality studies and discusses some of the impacts of water quality on salmonid habitat. Information from previous studies is being used to develop future water quality monitoring programs that target sensitive areas and provide the information most beneficial to salmonid recovery efforts.

Idaho Department of Environmental Quality Studies (1999 – 2020)

IDEQ has completed several reports on water quality within the Lemhi Basin. In 1999 they developed TMDLs including fecal coliform bacteria for the Lemhi River, temperature for Kirtley Creek, and sediment for Bohannon Creek, Eighteenmile Creek, Geertson Creek, McDevitt Creek, Sandy Creek, and Wimpey Creek (IDEQ, 1999). Salmonid spawning, cold water aquatic life, and primary and secondary contact recreation were all identified as beneficial uses that were affected by these impaired waters. Additional water quality data were collected for the 2010 Integrated Report, leading to several additional TMDLs being implemented in 2012 (IDEQ, 2012). The Lemhi River was listed for temperature, Canyon Creek was listed for E.Coli, and Eighteenmile Creek, Sandy Creek, and Bohannon Creek were listed for temperature. Lastly, IDEQ published a report on an agricultural implementation plan, which details steps that can be taken for listed sections of the Lemhi River and its tributaries to meet the TMDLs (IDEQ, 2020). The report lists the water quality samples collected and analyzed by the IDEQ Beneficial Use Reconnaissance Protocol. This information is very valuable, but there are many years between samples at some locations, which suggests the need for a more consistent long-term water quality monitoring program that IDWR continues to develop.

Appendix A of IDEQ (2020) provides additional information on the percent shade adjustment needed to mitigate sub-optimal high water temperatures in the Lemhi River and select tributaries, which may be useful to habitat improvement project managers. Also of note, Appendix B (IDEQ, 2020) documents the steps being taken by the USDA Natural Resource Conservation Service to develop and implement best management practices in the Lemhi Basin. This information can be helpful in preventing future duplication of work efforts.

Integrated Status and Effectiveness Monitoring Program and Columbia Habitat Monitoring Program (2011-2017)

The Integrated Status and Effectiveness Monitoring Program and Columbia Habitat Monitoring Program (CHaMP) was a series of data collection and research projects that occurred between 2011 and 2017 (CHaMP, 2015; CHaMP, 2016a; CHaMP, 2016a; CHaMP, 2016b; CHaMP, 2017a; CHaMP, 2017b). Data from the entire Columbia River Basin (including the Lemhi Basin) was collected and analyzed to characterize trends in salmonid habitat quality. The studies have been used extensively by USBWP Tech Team members to develop and evaluate habitat improvement strategies. CHaMP data on habitat quantity and quality was used by Rio Applied Science and Engineering to inform quantile regression forest models that estimated the number of redds and juveniles that the Lemhi River can support during summer (parr) and winter (presmolt) rearing (USBWP, 2019).

CHaMP studies collected a wide variety of biological, geomorphic, hydrologic, and water quality datasets at 121 sites in the Lemhi Basin. Water quality datasets include streamwater temperature, alkalinity, and conductivity. Additional datasets that can be used to learn about water quality include pool tail fines and streambed substrate composition, both of which provide indirect information on sediment transport. Solar access (solar radiation available at the center of the wetted channel) is another dataset that provides water quality related information, as it informs the causality of streamwater temperature fluctuations. Drift biomass and drift invertebrates data provide a compliment to turbidity data, as these datasets inform on the constituents causing turbidity. The main CHaMP field program was discontinued in 2017; however, all of the collected data is still accessible to the public (StreamNet).

Idaho Department of Water Resources Studies (2022)

As part of a study on the feasibility of Lemhi Basin aquifer recharge (IDWR, 2022a), IDWR collected 57 water quality sample sets, with each set tested for 29 unique analytes at Idaho Bureau of Laboratories. Overall, the results were considered typical for higher elevation drainages in agricultural areas. Water geochemistry was similar for most Lemhi River and return flow samples, further suggesting that a substantial amount of water source mixing occurs in the Lemhi Basin (see "Lemhi Basin Stable Isotope Analysis"). All nitrogen and ammonia samples were well below levels considered harmful to salmon during spawning. Total phosphorous levels from four of the inflows were higher than recommended by EPA (0.075 mg/L) for rivers and streams, though zero samples from the Lemhi River exceeded the EPA threshold. Interestingly, the study also found that return flows had more stable water temperatures than the Lemhi River, and that river water temperatures were more heavily influenced by air temperature than return flows.

IDWR (2022b) used a multiparameter water quality sonde to measure water quality field parameters in all salmonid-bearing waters of the Lemhi Basin approximately eight times (varied per site) in 2020 and 2021. The sonde recorded temperature, pH, dissolved oxygen, and turbidity. Temperature, dissolved oxygen, and turbidity readings were often outside of ideal ranges for salmonid habitat. Temperature was above optimal for Steelhead especially in June and July, mostly as a result of Steelhead incubation and emergence life stages occurring at this time. July and August dissolved oxygen levels were sometimes low enough to cause oxygen distress for eggs. Turbidity levels that impair the ability of salmonids to feed occurred throughout the year in parts of the Lemhi River and its tributaries, though the measured levels were not acutely harmful.

In summary, little water quality work has been conducted in the Lemhi Basin to date. All studies outside of this project have either been discontinued or infrequently assess water quality at salmonid-bearing sites (once every few years or less). IDWR plans to implement a long-term water quality monitoring program in salmonid-bearing waters moving forward. This should result in a better understanding of salmonid habitat quality, as well as an improved ability to evaluate habitat improvement projects and other efforts to improve water quality in the basin.

Task 9 – Develop a plan for an intensely monitored study site near the confluence of the Mainstem Lemhi and Lower Hayden Creek

At the request of the PCSRF Board, IDWR developed a plan to monitor and analyze the hydrogeology near the confluence of the Lemhi River and Hayden Creek (Figure 2). This site was chosen because several habitat improvement projects have already broken ground or are likely to break ground (on both the Lemhi River and Hayden Creek) over the next few years. The purpose of establishing this site is to characterize the local hydrogeology, sediment transport, and water quality before, during, and after the implementation of these projects. Some data has already been collected, including streamflow data at the three gages listed below, eight spot measurements of water quality parameters at four sites (includes the stream gage sites), and continuous groundwater level data at four nearby wells. However, a more robust streamflow and water quality data collection campaign is set to begin in the summer of 2023. Slight adjustments may be made to improve the water quality study, as is detailed under "Task 4 – Surface Water Quality Measurements". However, the current plan for monitoring and research is as follows:

- Ensure continued collection of streamflow data at three stream gages
    - Hayden Creek (Aqua Info)
    - Lemhi River near McFarland (5.7 miles upstream of the confluence). Formerly managed by IDWR, but managed by the USGS from 2022 onward (NWIS)
    - Lemhi River nr Lemhi (5 miles downstream of the confluence). Operated by the USGS (NWIS)
- Conduct two additional streamflow measurements every six weeks (weather permitting) – used to calibrate the LRBM and calculate daily differences in flow between the above stream gages and the locations of the manual measurements
    - Just above proposed habitat improvement work on the Lemhi River
    - Just below habitat improvement work on the Lemhi River
- Four Instrumented Monitoring Wells – Continue to collect groundwater levels and temperature data within two miles of the confluence (Groundwater Data Portal).
    - 18N 24E 33ACB1
    - 18N 24E 31ACD1
    - 18N 24E 20ADD1
    - 18N 24E 21BCD1
- Three Water Quality Monitoring Sites - Continuous monitoring of temperature, pH, DO, and turbidity using water quality sondes. Grab samples collected three times per year and tested for ammonium as N, nitrogen nitrite-nitrate, total phosphorous, total coliforms, E.coli, and suspended solids.
    - Just above proposed habitat improvement work on the Lemhi River
    - Just below proposed habitat improvement work on the Lemhi River
    - At the mouth of Hayden Creek
- Continued data collection for a minimum of five years after completion of habitat improvement projects.
- Descriptive statistics and trend analyses will be performed on all collected hydrogeologic data, as well as salmonid monitoring and habitat data collected by other agencies.
- The cumulative impact of the habitat improvement projects on salmonid populations and health will be characterized in a final report.

REFERENCES

Anderson, A. L. 1961. Geology and mineral resources of the Lemhi quadrangle, Lemhi County. Idaho Bureau of Mines and Geology Pamphlet 124. Moscow, ID.

Biomark Applied Biological Services, Rio Applied Science and Engineering, U.S. Department of the Interior Bureau of Reclamation, Idaho Governor's Office of Species Conservation, Trout Unlimited, The Nature Conservancy (USBWP). 2019. Upper Salmon Subbasin Habitat Integrated Rehabilitation Assessment.

Borden, J.C. 2014. Flexible Framework for Assessing Water Resource Sustainability in River Basins. Doctoral dissertation, University of Idaho, Civil Engineering Department, January 2014. 243 p.

CH2M HILL. 2014. Upper Salmon Basin Ground Water – Surface Water Interactions Study, Phase 2 Support Final Report. Prepared for Idaho Office of Species Conservation.

DHI 2003. Evaluation of Diversion Operations Plans to Meet Negotiated Flow Targets for Salmon and Steelhead in the Lemhi River Basin Using the MIKE BASIN Model. Report for U.S. Bureau of Reclamation and Idaho Department of Water Resources.

Colt, J., S. Mitchell, G. Tchobanoglous, and A. Knight. 1979. The use and potential for aquatic species for wastewater treatment: Appendix B, the environmental requirements of fish. Publication No. 65, California State Water Resources Control Board, Sacramento, CA.

Davis, J.C. 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. Journal of the Fisheries Research Board of Canada. 32:2295-2332.

DHI, Inc. 2006. The Lemhi River MIKE BASIN Model: A Tool for Evaluating Stream Flows, Diversion Operations and Surface Water – Ground Water Relationships in the Lemhi River Basin, Idaho. Report for U.S. Bureau of Reclamation, Idaho Governor's Office of Species Conservation, and Idaho Department of Water Resources. Boise, ID.

Donato, M. M. 1998. Surface-Water/Ground-Water Relations in the Lemhi River Basin, East-Central Idaho. U.S. Geological Survey, Water Resources Investigations Report 98-4185. Boise, ID

Dorratcaque, D. E. 1986. Lemhi River Habitat Improvement Study. OTT Water Engineers, Inc. Report for the Bonneville Power Administration. Portland, OR.

EPA. (2012, March). Channel Processes: Bedload Transport. In Water: Science & Technology. Retrieved from http://water.epa.gov/scitech/datait/tools/warsss/bedload.cfm

EPA. (2023, June 1). My Waterway – Community. https://mywaterway.epa.gov/community/170602040503/overview

Huntington, Justin & Hegewisch, Katherine & Daudert, Britta & Morton, Charles & Abatzoglou, John & McEvoy, Daniel & Erickson, Tyler. (2017). Climate Engine: Cloud Computing and Visualization of Climate and Remote Sensing Data for Advanced Natural Resource Monitoring and Process Understanding. Bulletin of the American Meteorological Society. 98. 2397-2409. 10.1175/BAMS-D-15-00324.1.

Idaho Department of Environmental Quality (IDEQ), 1999. Streams and Pollutants for Which TMDLs Were Developed.

Idaho Department of Environmental Quality (IDEQ), 2012. Addendum to 1999 report: Streams and Pollutants for Which TMDLs Were Developed.

Idaho Department of Environmental Quality (IDEQ), 2020. Lemhi River Subbasin Assessment And Total Maximum Daily Load Implementation Plan for Agriculture For the 2012 Addendum and Five-Year Review.

Idaho Soil Conservation Commission (ISCC). 1995. Model Watershed Plan: Lemhi, Pahsimeroi, and East Fork of the Salmon River. Report funded by the Bonneville Power Administration. Portland, OR.

IDEQ – see Idaho Department of Environmental Quality

IDWR – see Idaho Department of Water Resources

IDWR, 2012. Hydrologic Analysis and Monitoring Phase IV Final Project Report

IDWR, 2019. Upper Salmon Basin Groundwater – Surface Water Interactions Study, Phase 3 Final Project Report.

IDWR, 2022a. Upper Lemhi River Managed Aquifer Recharge Feasibility Study

IDWR, 2022b. Upper Salmon Basin Groundwater – Surface Water Interactions Study, Phase 5 Final Project Report.

ISCC – see Idaho Soil Conservation Commission

ISEMP and CHaMP (Integrated Status and Effectiveness Monitoring Program and Columbia Habitat Monitoring Program). 2015. Combined annual report for the Integrated Status and Effectiveness Monitoring Program and Columbia Habitat Monitoring Program: 2014. Prepared by ISEMP and CHaMP for the Bonneville Power Administration.

ISEMP and CHaMP (Integrated Status and Effectiveness Monitoring Program and Columbia Habitat Monitoring Program). 2016a. Annual combined technical report, January 2015-December 2015. BPA Projects 2003-017-00 and 2011-006-00, 39 pages.

ISEMP and CHaMP (Integrated Status and Effectiveness Monitoring Program and Columbia Habitat Monitoring Program). 2016b. RPA rollup reports for BPA Projects 2003-017-00 and 2011-006-00. Prepared by ISEMP and CHaMP for the Bonneville Power Administration.

ISEMP and CHaMP (Integrated Status and Effectiveness Monitoring Program and Columbia Habitat Monitoring Program). 2017a. Product summary. BPA Projects 2003-011-00 and 2011-006-00, 88 pages.

ISEMP and CHaMP (Integrated Status and Effectiveness Monitoring Program and Columbia Habitat Monitoring Program). 2017b. Annual combined technical report, January-December 2016. BPA Projects 2003-017-00 and 2011-006-00, 90 pages.

Landwehr, J., & Coplen, T. (2006). In Isotopes in Environmental Studies 132–135 (IAEA-CN-118/56, International Atomic Energy Agency).

McCutcheon, RJ, McNamara, JP, Kohn, MJ, Evans, SL. An evaluation of the ecohydrological separation hypothesis in a semiarid catchment. Hydrological Processes. 2017; 31: 783– 799. doi: 10.1002/hyp.11052.

MDEQ. (n.d.). Total Suspended Solids. In Michigan Department of Environmental Quality. Retrieved from http://www.michigan.gov/documents/deq/wb-npdes-TotalSuspendedSolids_247238_7.pdf

Muan, C. Moulton, P. 2011. Optimal Water Quality Values for Aquatic Ecosystems Pierce County Public Works and Utilities, WA

National Oceanic and Atmospheric Administration (NOAA): National Integrated Drought Information System. (2023, June 1). https://www.drought.gov/historical-information?state=idaho&dataset=0&selectedDateUSDM=20210914

National Weather Service. (2023, June 15). Advanced Hydrologic Prediction Service. https://water.weather.gov/ahps2/

Spinazola, J. 1998. A Spreadsheet Notebook Method to Calculate Rate and Volume of Stream Depletion by Wells in the Lemhi River Valley Upstream from Lemhi, Idaho. U.S. Bureau of Reclamation report. Boise, ID.

Upper Salmon Basin Watershed Program (USBWP). 2020. https://modelwatershed.idaho.gov/the-program/.

U.S. Bureau of Reclamation, 2004. Instream Flow Assessment Big Timber Creek, Idaho

U.S. Department of Agriculture Natural Resource Conservation Service (USDA NRCS). (2023, May 15). Water Year to Date Precipitation.

Scheff, J. and Frierson, D. 2014. Scaling Potential Evapotranspiration with Greenhouse Warming. Journal of Climate. DOI: https://doi.org/10.1175/JCLI-D-13-00233.1

Washington State Department of Ecology (WDOE). 2002. Evaluating Criteria for the Protection of Freshwater Aquatic Life in Washington's Surface Water Quality Standards: Dissolved Oxygen. Draft Discussion Paper and Literature Summary. Publication Number 00-10-071. 90pp.

Zhang, C., Yang, Z., Zhao, H., Sun, Z., Di, L., Bindlish, R., Liu, P.W., Colliander, A., Mueller, R., Crow, W. and Reichle, R.H., 2022. Crop-CASMA: A web geoprocessing and map service based architecture and implementation for serving soil moisture and crop vegetation condition data over US Cropland. International Journal of Applied Earth Observation and Geoinformation, 112, 102902. doi: 10.1016/j.jag.2022.102902