LOLO CREEK PILOT BASIN STUDY
PART I: HYDROLOGY AND WATER USE 2016 – 2019 APPENDICES

MONTANA DEPARTMENT OF NATURAL RESOURCES AND CONSERVATION
WATER RESOURCES DIVISION
WATER MANAGEMENT BUREAU

This document contains additional information on methods and data analysis for the Lolo Creek Pilot Basin Study, Part I (Hydrologic Investigation Report HI220218-WMB)

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Helena, MT

CONTENTS:

APPENDIX A

EXTENDED METHODS FOR DATA ANALYSIS AND WATER BALANCE CALCULATIONS

A1.0 STREAMFLOW DATA AND METHODS

Streamflow was collected as instantaneous values (15-minute intervals for real-time stream gages and 30-minute for non-real-time). Mean daily flows were calculated from the instantaneous values and used for analyzing hydrographs at the gaging stations. For the water balance, monthly values were calculated from mean daily discharge. Daily discharge values for all stream gages used is included in the digital datasets released with the report.

All raw, instantaneous gage data is available for download via Montana Department of Natural Resources and Conservation's Stream and Gage Explorer (StAGE, https://gis.dnrc.mt.gov/apps/StAGE/).

DISCLAIMER:
Data retrieved from StAGE is raw, unprocessed daily or instantaneous streamflow data. Data is approved on a water year basis. All streamflow for this study is approved.

The streamflow data used in the Lolo Creek study was altered from the raw instantaneous values by correcting winter data that represented river ice and interpolating between various gages to extend records where there was no data. Records were extended using the Maintenance of Variance Extension Type 1 (MOVE.1) method (Hirsch 1982). MOVE.1 is a regression technique that relies on a linear model between two datasets. For this study, monthly records were extended using a relation between the gage with missing data and data from a nearby gage on the same stream to synthesize flows during the data gaps. This was only possible on the mainstem of Lolo Creek as tributaries typically only had one gage and may not be correlated with mainstem flows. For small gaps in daily discharge data (i.e. less than 7 days), values were interpolated between the discharge at the start of the missing data and the end of the missing data.

The final mean daily discharge, and mean monthly data, used in this study are available from Montana DNRC's Water Management Bureau website, under Lolo Creek Study (http://dnrc.mt.gov/divisions/water/management/programs-projects-and-studies/continuing-projects-and-studies-in-progress/lolo-watershed-study).

A2.0 GROUNDWATER DATA AND METHODS

A2.1 Well Data

Montana Bureau of Mines and Geology (MBMG) and DNRC operated 123 active sites during the Lolo Creek study to monitor groundwater elevations, surface water elevations, and associated inputs (precipitation). These sites are scattered between the Montana Department of Transportation (MDT) compound downstream of Lolo Hot Springs and the Bitterroot River, at the mouth of Lolo Creek. Of the total sites there were 79 monitoring wells, 32 surface water (stage) sites, 7 shallow piezometers, and 5 precipitation monitoring sites. Some of the surface water sites were those gage locations operated by DNRC, discussed previously, while others were operated solely by MBMG for use in a ground water model. Some MBMG surface water sites collected only river stage elevation data, no discharge values. All MBMG sites can be found through GWIC (http://mbmggwic.mtech.edu/sqlserver/v11/data/dataProject.asp?project=BWIPLO&datatype=well&). The following table summarizes groundwater monitoring sites used for interpolating groundwater elevation maps, and the groundwater balance.

Table A1: Groundwater Monitoring Site Information

GWIC ID	Site Name	Latitude	Longitude	Datum	Measuring Point Elevation and date of survey	Type	Aquifer	Total Depth (ft)	Static Water Level (ft)	Period of Record
65972	ETZEL, KELLY	46.7449	-114.0773	NAD83	3180.5310 (05/11/2016)	WELL	100UDFD	68	12	5/11/2016 - 12/13/2017
288385	HART SCOTT * HOUSE WELL	46.74448	-114.1414	NAD83	3285.3140 (05/25/2016)	WELL	100UDFD	60	24.92	5/25/2016 - 12/13/2017
289399	ENOCHSON, PATTI AND GAYLAN * PP6	46.74245	-114.1524	NAD83	3307.4030 (10/07/2016)	WELL	100UDFD	26		10/7/2016 - 1/23/2020
287017	ENOCHSON GAYLAND * OLD SHOP WELL	46.74293	-114.1516	NAD83	3304.2660 (05/22/2018)	WELL	111SNGR	8		4/22/2016 - 1/23/2020
287971	SAPPHIRE RANCH * CORRAL WELL	46.72984	-114.067	NAD83	3161.7820 (06/24/2016)	WELL	111SNGR	9	7.09	6/24/2016 - 3/29/2018
292003	LARSON NEVA * BARN WELL	46.75134	-114.0818	NAD83	3182.4350 (03/29/2017)	WELL	100UDFD	17		3/29/2017 - 12/12/2017
69019	LOLO WATER AND SEWER - TEST WELL 2 * TEST WELL 2	46.76565	-114.0769	NAD83	3173.4260 (06/24/2016)	WELL	400BELT	109	23.75	5/17/2016 - 1/23/2020
288386	GRUNOW, MATT AND KASEY	46.7496	-114.1441	NAD83	3311.8450 (05/25/2016)	WELL	100UDFD			5/25/2016 - 12/14/2017
287546	HOLT RANCH * WORKSHOP WELL	46.75343	-114.1313	NAD83	3276.9100 (06/10/2015)	WELL	100UDFD	80	25.43	6/10/2016 - 12/14/2017
177966	BARTLETTE, BARRY AND BOBBIE	46.74901	-114.1345	NAD83	3276.1520 (04/13/2016)	WELL	100UDFD	58	20	4/13/2016 - 12/14/2017
290664	DANCE HALL CAMPGROUND * DH20	46.7475	-114.1343	NAD83	3273.2970 (05/22/2018)	WELL	100UDFD	59.5		12/8/2016 - present
289720	HOLT, BRET AND RAMONA * HOLT GP08	46.75574	-114.1231	NAD83	3251.1590 (10/12/2016)	WELL	100UDFD	60		10/12/2016 – 01/23/2020
289718	HOLT, BRET AND RAMONA * HOLT GP09	46.75479	-114.1231	NAD83	3250.0390 (10/12/2016)	WELL	100UDFD	55	12.1	10/13/2016 – 01/23/2020
289449	HOLT, BRET AND RAMONA * HOLT GP10	46.75552	-114.1206	NAD83	3247.1180 (10/11/2016)	WELL	100UDFD	53		10/11/2016 – 01/23/2020
134194	ARLEO, ADRIAN	46.7491	-114.129	NAD83	3260.0620 (04/21/2016)	WELL	100UDFD	36	12	04/21/2016 – 12/14/2017

67427	NORGAARD, STANLEY & JAN	46.75392	-114.1137	NAD83	3282.3150 (05/18/2016)	WELL	400BELT	84	37	05/08/2016 – 12/13/2017
67454	HADNOT, DOUG AND SUE	46.75328	-114.094	NAD83	3205.1580 (07/26/1999)	WELL	100UDFD	50	18	07/26/1999 – 12/13/2017
287164	HART SHANE	46.75601	-114.0954	NAD83	3204.1030 (05/18/2016)	WELL	100UDFD	63	13.01	05/08/2016 – 12/13/2017
166000	NELSON JOHN * WELL 1	46.75044	-114.0975	NAD83	3208.4040 (04/23/2016)	WELL	100UDFD	70	16	04/23/2016 – 12/12/2017
290661	HOLT RANCH * HOLT19	46.75664	-114.0898	NAD83	3196.3800 (05/22/2018)	WELL	120SNGR	95		12/08/2016 - present
287018	STEIGER, DON	46.75009	-114.092	NAD83	3197.5140 (04/21/2016)	WELL	100UDFD	54	11.28	04/21/2016 – 12/12/2017
290558	LANDQUIST, MICHELE AND BRUCE * LQ 27	46.75505	-114.1082	NAD83	3227.6460 (04/02/2018)	WELL	110ALVM	18		12/08/2016 – 08/28/2020
193691	LANDQUIST, BRUCE AND MICHELE * A-FRAME WELL	46.75593	-114.1077	NAD83	3222.9680 (04/02/2018)	WELL	100UDFD	60	8	04/13/2016 – 08/28/2020
67442	HILLBERRY, STEVEN	46.75387	-114.1064	NAD83	3224.1040 (05/18/2016)	WELL	100UDFD	50	10	05/18/2016 – 12/12/2017
67441	LIEN TIM	46.74976	-114.1004	NAD83	3226.7450 (05/25/2016)	WELL	100UDFD	60.7	31	05/25/2016 – 12/13/2017
163042	TRAVELERS REST STATE PARK * IRRIGATION WELL	46.74918	-114.0883	NAD83	3203.5260 (04/14/2016)	WELL	100UDFD	99.5	19	04/21/2016 - present
131373	DONNA AND NICK GRAHAM	46.76036	-114.0691	NAD83	3173.0500 (07/20/2016)	WELL	100UDFD	74	30	07/20/2016 – 12/13/2017
167764	MILLER SUZANNE & STERLING	46.75547	-114.0662	NAD83	3170.2300 (05/22/2016)	WELL	100UDFD	100		05/22/2016 – 12/13/2017
67500	FOURNIER BONNIE/FRANK MILLER	46.75759	-114.0832	NAD83	3202.9130 (05/25/2016)	WELL	100UDFD	63	29	05/25/2016 – 01/23/2020
287328	TAKAS STORAGE LLC	46.75197	-114.0864	NAD83	3192.6730 (05/11/2016)	WELL	100UDFD			05/11/2016 – 12/13/2017
67523	LARSON, NEVA	46.75232	-114.0822	NAD83	3184.3540 (07/20/2016)	WELL	100UDFD	42	10	07/20/2016 – 04/10/2018
67527	LARSON, NEVA AND BILL	46.75092	-114.0823	NAD83	3185.7890 (04/21/2015)	WELL	100UDFD	67.4	10	04/21/2016 – 12/12/2017
290589	J.E., MCHATTON/MCHANE, SKIP * HWY93S13	46.74866	-114.0824	NAD83	3181.1750 (04/01/2018)	WELL	100UDFD	55	8.69	12/08/2016 – 07/01/2020
287563	DOYLE TANA	46.74944	-114.0772	NAD83	3173.3580 (05/22/2016)	WELL	110ALVM	14.5		05/22/2016 – 04/24/2018

290554	LARSON BILL * HWY93N26	46.74964	-114.082	NAD83	3181.0030 (04/01/2018)	WELL	110ALVM	14		08/19/2016 - present
67512	LARSON, NEVA AND BILL * IRRIGATION WELL	46.7507	-114.0797	NAD83	3178.4870 (06/08/2016)	WELL	100UDFD	60	6	04/22/2016 – 12/12/2017
210067	MALCOLM, MARK AND KIM	46.75222	-114.0678	NAD83	3162.3100 (05/17/2016)	WELL	100UDFD	80	15	05/17/2016 – 12/13/2017
151202	MWWQD W122035D * MICHEAL LANE	46.75362	-114.0713	NAD83	3164.6150 (07/05/1995)	WELL	100UDFD	24	9	07/05/1995 - present
287399	MORRIS NORA	46.75375	-114.075	NAD83	3169.5280 (04/04/2017)	WELL	100UDFD			05/25/2016 – 07/14/2018
290654	NOTTINGHAM, MARIE/HOWARD, DAVE * LC17	46.7479	-114.0755	NAD83	3172.4650 (05/21/2018)	WELL	100UDFD	66		12/08/2016 – 01/23/2020
67465	BOSCHMANN, JEFF AND MARIAM	46.74759	-114.0731	NAD83	3169.8620 (05/09/2016)	WELL	100UDFD	89	7	05/09/2016 – 12/13/2017
67538	LOLO TRAIL RANCH * WEST WELL	46.76415	-114.2829	NAD83	3569.7820 (05/12/2016)	WELL	400BELT	58	10	05/12/2016 – 12/11/2017
287121	LOLO TRAIL RANCH * EAST WELL	46.7562	-114.2442	NAD83	3494.5030 (05/12/2016)	WELL	400BELT			06/09/2016 – 01/23/2020
287122	LOLO TRAIL RANCH * POND WELL	46.75337	-114.2487	NAD83	3500.8650 (05/12/2016)	WELL	112SNGR			05/12/2016 – 12/11/2017
67613	AMIDNAMIN, MIKE	46.75788	-114.3172	NAD83	3625.5670 (07/08/2016)	WELL	112SNGR	41	10	07/08/2016 – 01/23/2020
67412	SQUARE DANCE CENTER AND CAMPGROUND - WELL 2	46.74779	-114.13406	NAD83	3261.2000 (04/22/2016)	WELL	100UDFD	61	14	4/22/2016 – 12/8/2016
67450	TRAVELERS REST STATE PARK * FARMHOUSE WELL	46.74907	-114.08718	NAD83	3200.3200 (04/21/2016)	WELL	100UDFD	63	20	1 Measurement 04/21/2016
67503	DON TRIPP TRUCKING	46.75815	-114.08072	NAD83	3186.2500 (05/09/2016)	WELL	100UDFD	68.7	31.75	1 Measurement 05/09/2016
67507	LOLO COMMUNITY CHURCH	46.75781	-114.07720	NAD83	3181.6000 (05/09/2016	WELL	100UDFD	74	25.5	05/09/2016 – 10/05/2016
149678	LOLO WATER AND SEWER DISTRICT-WELL #3 * WELL 3	46.75715	-114.08892	WGS84		WELL	100UDFD	115	17	1 Measurement 05/08/2017
292005	LARSON, NEVA * ORIGINAL HOUSE WELL	46.75091	-114.08233	NAD83	3181.0920 (03/29/2017)	WELL	100UDFD	17	0	03/29/2017 – 04/26/2018

A2.2 Groundwater Elevation Mapping Methods

The network of 79 groundwater monitoring wells shown in Table A9 was used to map groundwater levels for the extent of the Lolo Creek aquifer (downstream of the South Fork of Lolo Creek to the Bitterroot River). The aerial extent of alluvium mapped by Lewis (1998) was assumed to represent the extent of the aquifer because the Lolo Creek valley bottom is bounded by bedrock (Quartzite and Wallace Formation). All wells were measured on a monthly basis, but a subset of the 79 were measured hourly using an electronic pressure transducer. Data from the 79 wells were resampled to average monthly elevations to create a temporally consistent dataset. For wells that were measured only once a month, the measured elevation was considered the average. Wells with hourly data were resampled by averaging all measurements in a month. After resampling the data, the wells were screened by location, for erratic measurements, for clusters of wells that were duplicating measurements, and deeper wells that appeared to be measuring a different part of the aquifer. The total amount of wells after screening was reduced to 47.

The 47 remaining monitoring wells were used with the geostatistical method Kriging, to interpolate continuous, gridded maps of groundwater elevations (potentiometric surfaces). Kriging with External Drift (KED) is an accepted variation of Kriging that includes collateral information from a digital elevation model (DEM; Desbarats et al. 2002). This method was suitable for Lolo Creek because the well network was sparse in certain areas and dense in others, thus, including terrain information from a DEM constrains the interpolation to more realistic estimates by not allowing the interpolated groundwater elevation to exceed the ground surface.

The first step in implementing KED was to detrend the data. The algorithm used by KED assumes that there is a relation between water table elevation and the elevation of the ground surface, such that the water table is a subdued version of the ground surface. When tested, this assumption was not true for the valley bottom of Lolo Creek because there was a significant down-valley trend. This elevation trend creates a major source of uncertainty in the relation between ground surface and water table depth. A linear trend adequately described the down-valley slope of Lolo Creek, such that a linear model was fit using the ground surface elevations at the 47 monitoring wells (Fig. A1). The KED methods were applied to the residuals of this linear relationship, $e(x)$, referred to as the detrended elevations (i.e. the difference between the linear model and the ground surface elevation at each well). The DEM was also detrended to create a relative elevation model (REM; Fig. A2) for use in the KED algorithm.

The same KED model used by Desbarats et al. (2002) was used for Lolo Creek. Equation A1 is the basic framework of the KED model. Figure A3 shows that there is a positive correlation between detrended ground surface and detrended groundwater elevations, where the linear line is represented by Equation A1.

$$h(x) = Z(x) + d(x) \qquad \{Eq. A1\}$$

In Equation A1, $h(x)$ is the groundwater elevation, $Z(x)$ is the ground surface elevation, and $d(x)$ is depth to the water table. In this model, groundwater elevation and ground surface elevation are represented as detrended values, labeled as $h_0(x)$ and $Z_0(x)$ respectively. $h_0(x)$ and $Z_0(x)$ were transformed, after interpolation, back to real elevations (i.e. $h(x)$ and $Z(x)$). The entire process is as follows:

(1) Interpolate $d(x)$ using Kriging method,
(2) Add the interpolated $d(x)$ values to the detrended elevations $Z_0(x)$ to obtain $h_0(x)$, which is still normalized by the down valley trend,
(3) Transform $h_0(x)$ using the linear model in FigureA1 (add the trend back in) to get $h(x)$ in terms of normal elevations.

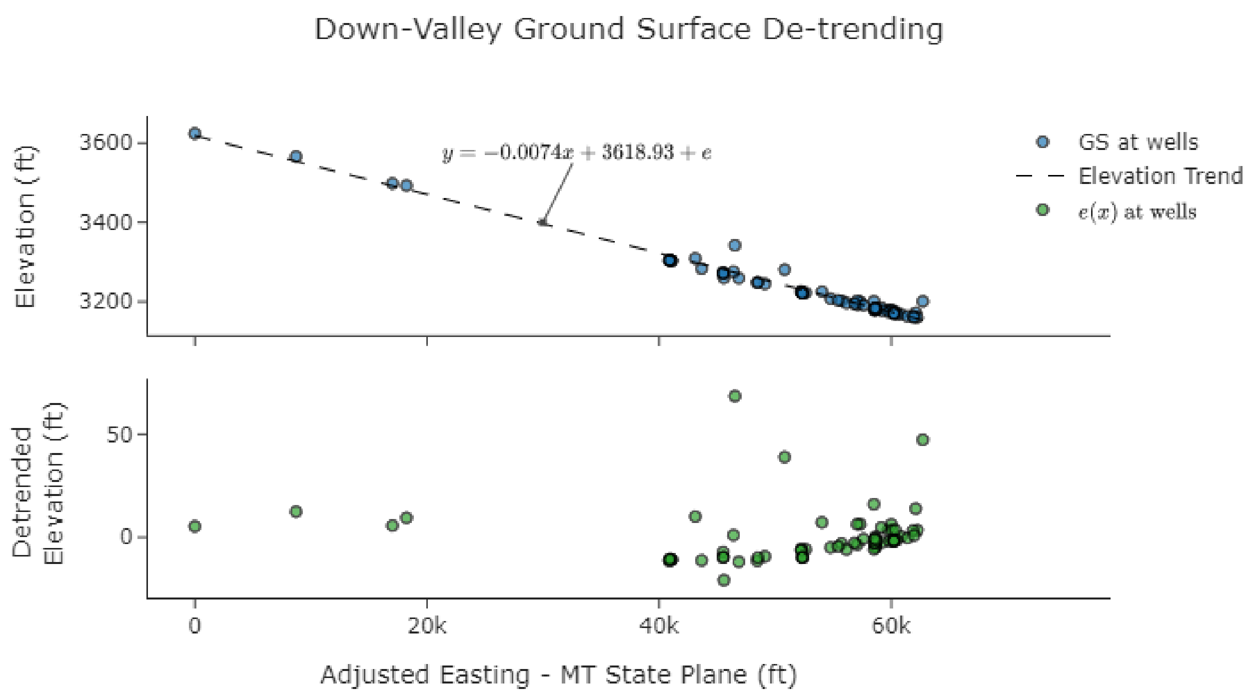

Figure A1. Graphs showing the linear relationship used to detrend monitoring well and DEM data. Top graph shows the real elevations with trend line of monitoring wells and the bottom graph shows the relative elevations after detrending. Easting was adjusted by subtracting the farthest west monitoring well Easting from the rest of the locations to make the x-axis a smaller number.

The actual interpolation of groundwater elevations using KED depends on the variogram. A variogram determines the relation between distance (from one location to another) and covariance (i.e. the similarity or difference in variance between two locations). In geostatistics, this variability between two points in space is sometimes referred to as the semivariance; although the nomenclature is a point of contention within the field. This study uses the term semivariance, despite ongoing debate regarding its correctness (Bachmaier and Backes, 2010). Semivariance, theoretically, represents the variability in water table depth at all possible distances from a monitoring well. It is not feasible to have pairs of monitoring wells spaced at all possible distances, so semivariance is estimated using bins of distances, referred to as "lags," instead of exact distances. For example, if semivariance was calculated for 6 lags with bin sizes of 100 feet, lag 1 would include pairs of wells from 0 to 100 feet apart, lag 2 would include pairs of wells from 101 to 200 feet apart, and so on to 600 feet. The number of lags to use, and the bin sizes, can vary depending on how many wells are in the monitoring network and the distribution of distances between wells. A variogram is an analytical formula that describes the relation between semivariance and distance; it is a mathematical representation of the concept that things close together are more similar than things farther away. There are several types of variograms typically used in Kriging algorithms, this study used a Gaussian model based on the best fit for the semivariances. There are three parameters used to decide the shape of the Gaussian variogram, the range, sill, and nugget. These parameters serve as coefficients to fit the variogram, or model, by determining the shape and fit of the analytic curve. The range represents the distance at which monitoring wells are no longer spatially correlated. The sill represents the maximum semivariance, which occurs at a distance equal to the range (the variogram becomes a flat line equal to the sill at this point). The nugget is the parameter that determines the minimum semivariance of the variogram. At a distance of zero feet from a given monitoring well, the semivariance theoretically equals zero because you are comparing a well to itself. In real datasets the minimum semivariance is typically a non-zero, positive number; this phenomenon is referred to as the nugget effect and can be caused by uncertainties in monitoring equipment or density of the monitoring network, among other things.

Figure A4 shows a histogram of distances between monitoring wells. This distribution describes the spatial variability in the monitoring well network and informs the variogram used in KED. For example, from Figure A4 there are some wells that are very far apart, but most of the wells are less than 3,000 ft from each other (as visualized by the mode of the distribution). This distribution was used to estimate initial variogram parameters that were optimized by visually fitting a curve and manually comparing the sum of the squared errors. An automated optimization procedure was attempted using ordinary least squares (OLS), but the smaller lag distances carried more weight and the OLS method applied equal weight to farther distances. While visually fitting variograms, lag distances less than ~5000 ft were given the most importance.

For this study, variograms were fit for periods in which the number of monitoring wells was relatively consistent. Figure A5 shows a time series of the number of wells with monthly data from 2016 to 2019. The first measurements began in February of 2016 with one well, increased to a maximum of 47 wells measured in March of 2017, and declined again after December of 2017. During the latter part of the study period, 2018 and 2019, the number of wells dropped by ~50% and fluctuated significantly, making it difficult to interpolate groundwater maps and compare them. Not only did the differing number of wells over time affect the results, but their location was also important for accurate groundwater maps. If two surfaces were interpolated using the same number of wells, but the wells were at different locations, the results created problems when differencing between months. To fix this problem, the data were split into time periods where the number and location of wells monitored was the most consistent. The six time periods are shown as colored bars in Figure A5.

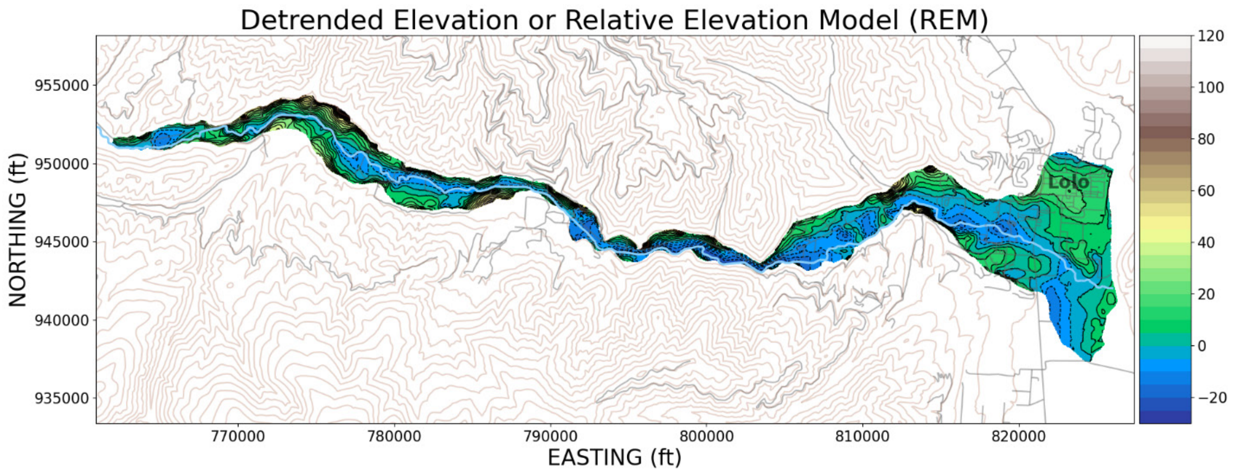

Figure A2. Map of the detrended, relative elevation model (REM) of the Lolo Creek valley bottom in MT State Plane coordinate system. Color bands represent detrended elevation (i.e. elevation from trendline in Figure A1). Contour interval is 5 ft, dotted contour lines are negative numbers. Light gray lines are roads, Lolo Creek is shown as a light blue line, and non-detrended topographic contours (at 200 ft intervals) are shown in light brown.

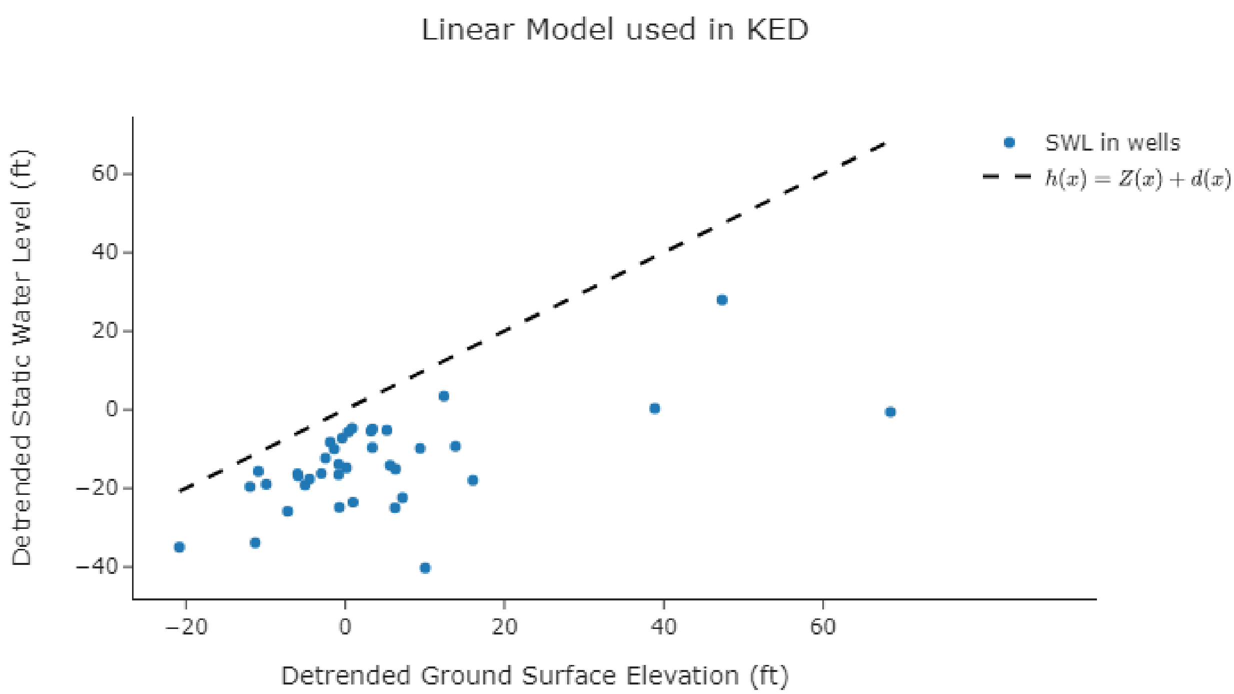

Figure A3. Relationship used in KED between groundwater elevation and ground surface elevation (there is an observable positive trend). Dashed line represents the 1:1 line or $h(x) = Z(x)$.

For each of the six time periods, the month with the least number of monitored wells was selected. This allowed for a consistent subset of wells, geographically (i.e. the same wells were used for the whole time period even though there are months within each time period when more monitoring wells are available). This drastically reduced the error when comparing between months for the groundwater balance, it also allowed for a single variogram to be fit for the entire time period (which is computationally more efficient that a new variogram for each individual months).Each time period overlaps at the start and end with the previous and latter model, respectively, so that no comparisons are done between variograms. For example, two different surfaces are interpolated for May 2016 using two different variogram models, one for differencing May 2016 and April 2016 and a separate one for differencing June 2016 and May 2016. The graphs of the six variograms for each time period are shown in Figures A6 – A11.

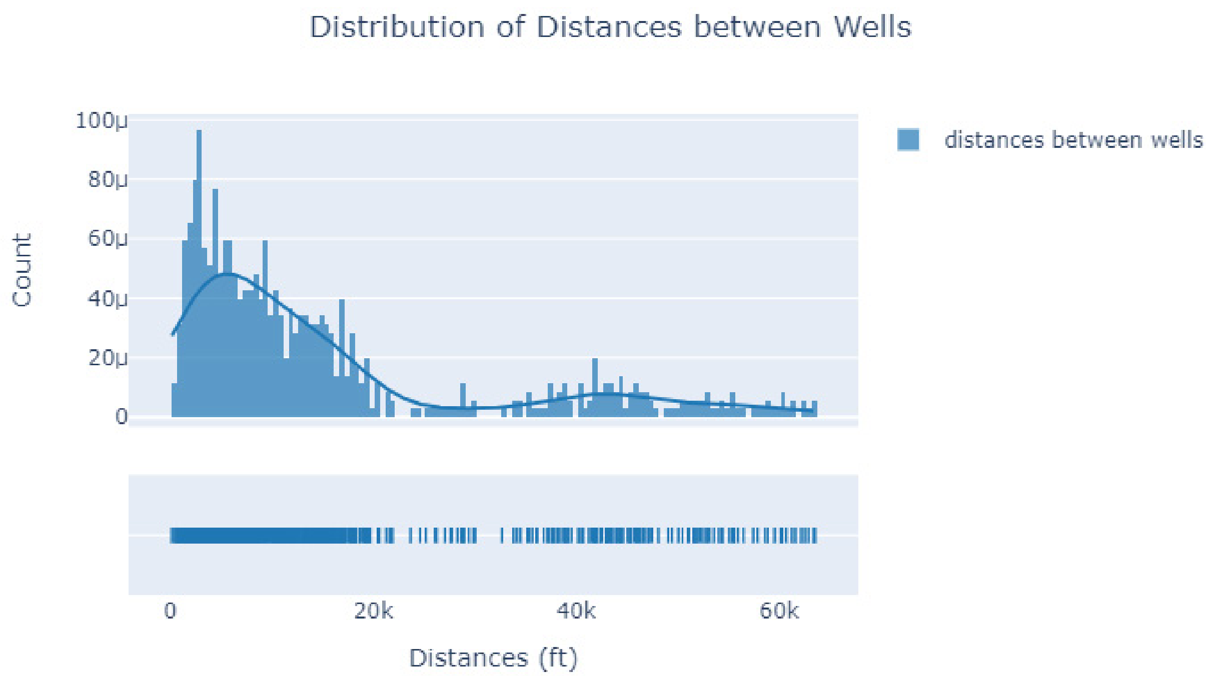

Figure A4. Distribution of distances between all monitoring wells in Lolo Basin.

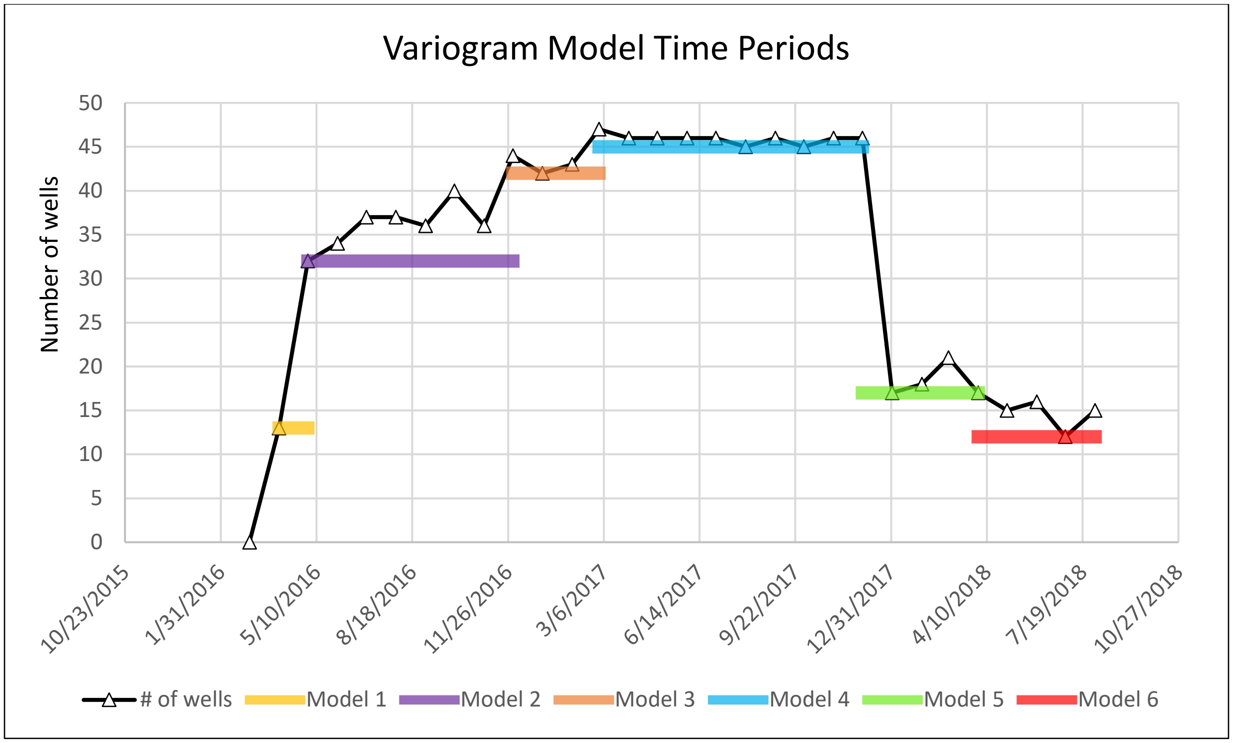

Figure A5. Number of monitoring wells per month with Kriging variogram model time periods overlain. Models were constructed for a constant subset of wells that is equal to the month of each time period with the least number of wells with data.

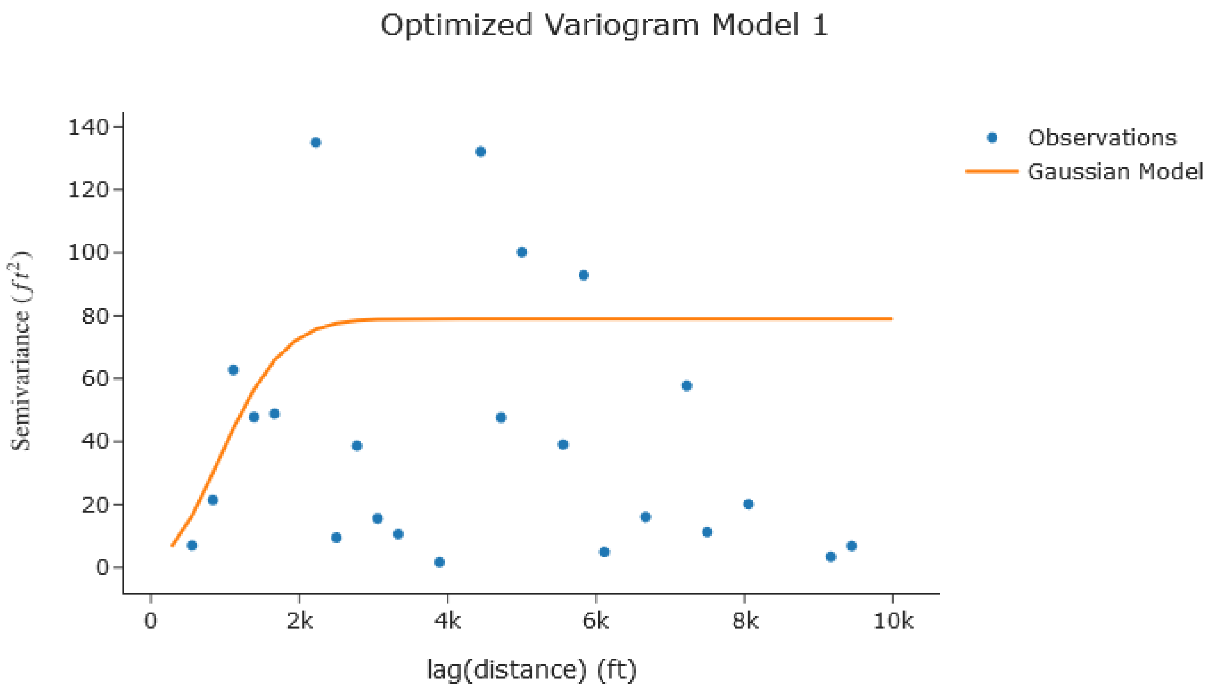

Figure A6. Variogram Model 1 for time period April – May 2016.

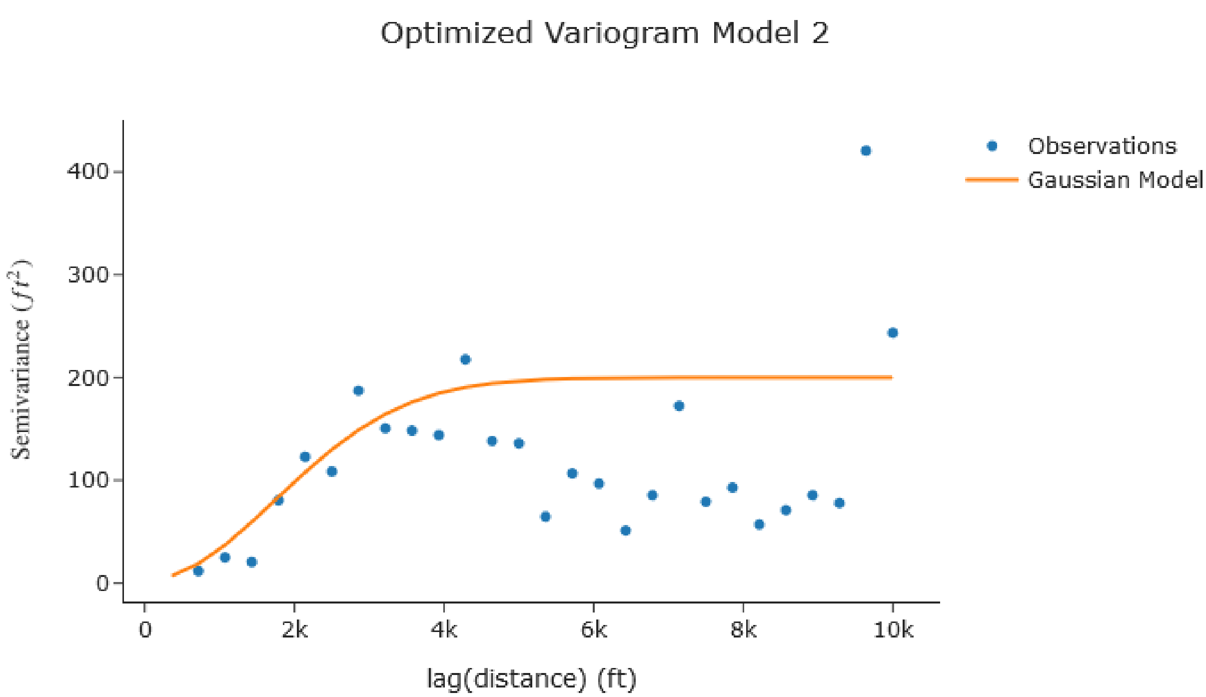

Figure A7. Variogram Model 2 for time period May – December 2016.

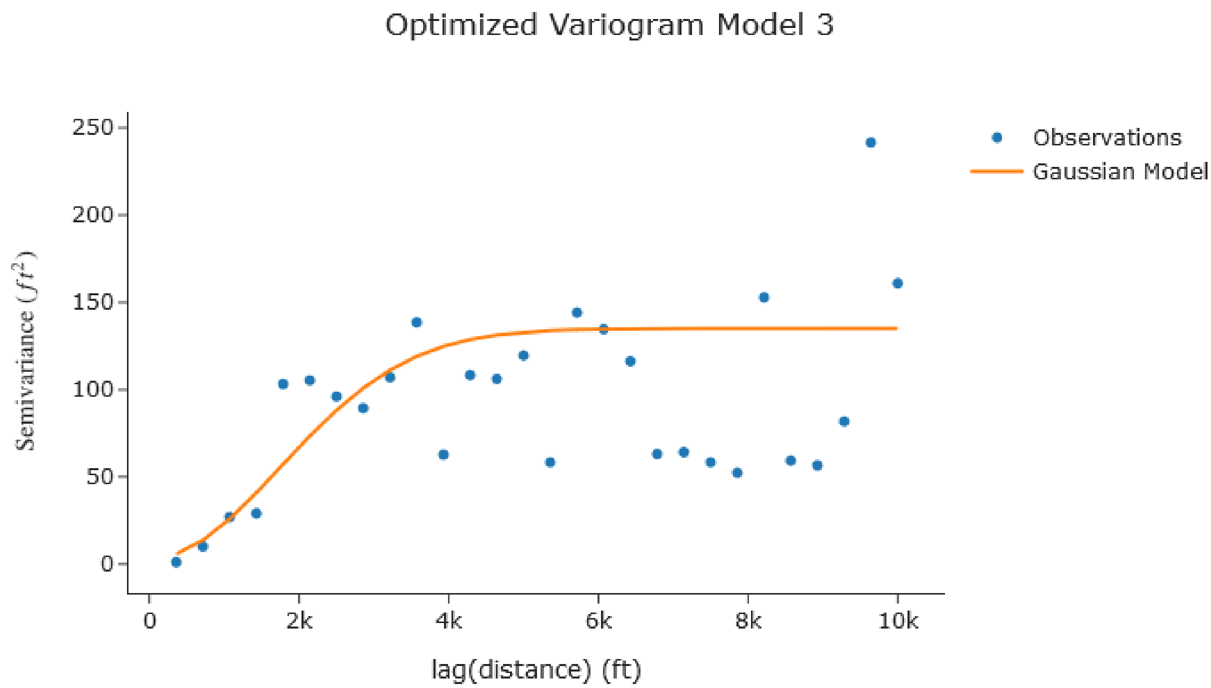

Figure A8. Variogram Model 3 for time period December 2016 – March 2017.

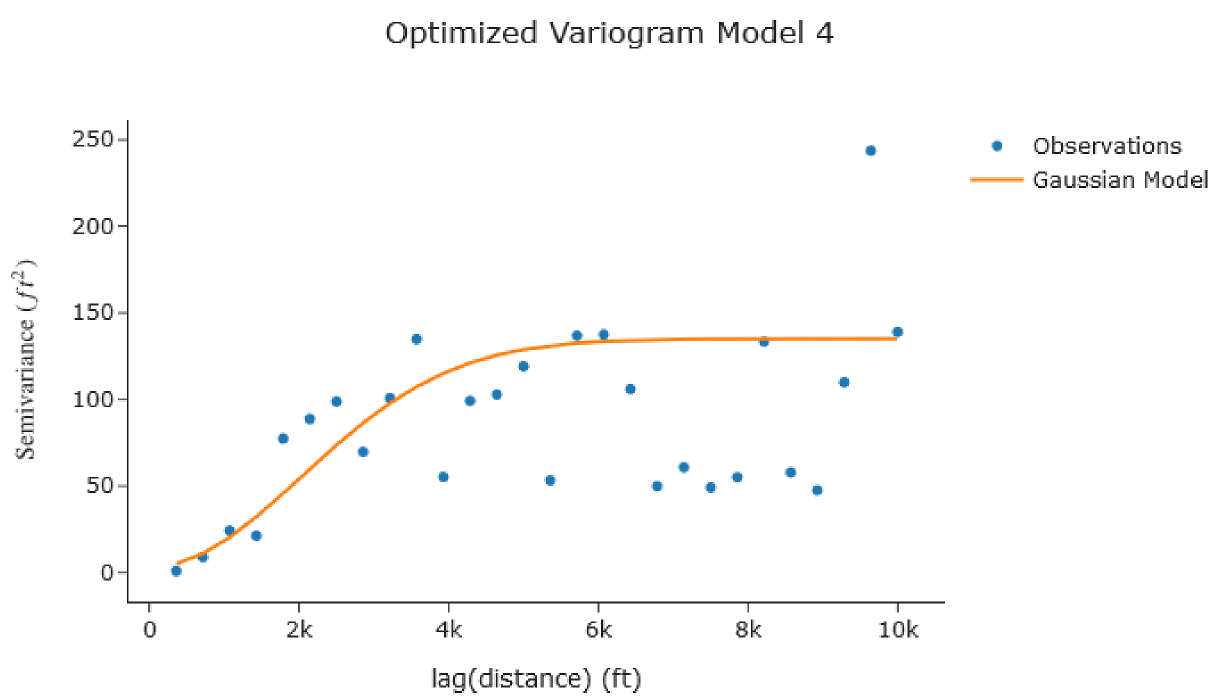

Figure A9. Variogram Model 4 for time period March – December 2017.

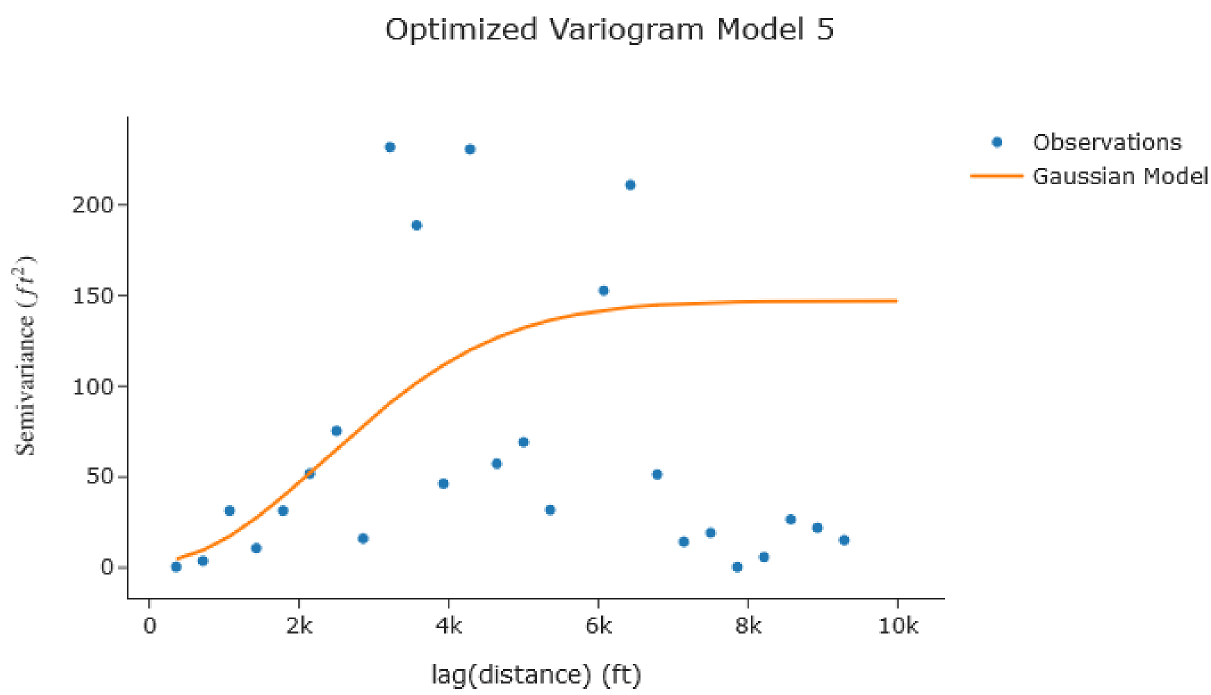

Figure A10. Variogram Model 5 for time period December 2017 – April 2018.

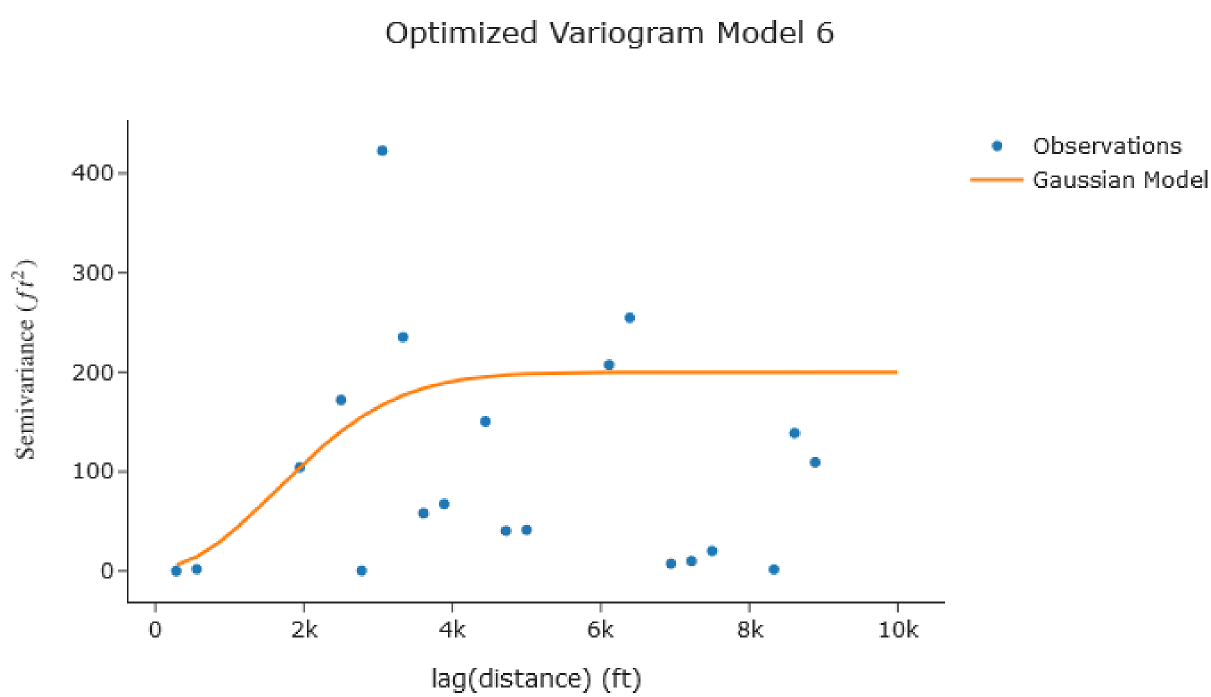

Figure A11. Variogram Model 6 for time period April – August 2018.

A2.3 Groundwater Balance Methods

The Groundwater Water Balance for Lolo Creek was calculated using the same Water Balance Regions as the surface water components. This was accomplished by clipping the interpolated groundwater elevation maps to the boundary of each Water Balance Region. Equation 7 from the main report was then used to calculate (ΔS) or change in storage. Unlike the surface water balance, the shallow unconfined aquifer of Lolo Creek was considered a "reservoir" and therefore has a storage term when using the governing water budget equation (Equation 6) in the main report. Thus, the procedure for the ground water budget was to calculate ΔS, then back calculate the inputs (I) and outputs (O) using Equation 6 from the main report. Equation 7 was used within a geographic information system (GIS) to subtract the raster cells of one groundwater elevation map from the previous month, multiply each cell by its dimensions (uniform grid of 30 ft x 30 ft cells), then sum all the resulting cell values for a given area (in this case, the boundary of a Water Balance Region). These calculations were not done for Water Balance Regions 1 and 2 because of the limited groundwater use and almost no valley bottom (i.e. limited aquifer area). Upstream of the South Fork of Lolo Creek, the groundwater balance is assumed to be influenced by the natural hydrologic processes of the Lolo Creek watershed. The groundwater balances for Water Balance Regions 3, 4, and 5 were estimated independently, with slight variations of Equation 6 (from the main report) and are described below by region.

Groundwater balances were calculated from the downstream most Water Balance Region, working upstream; however, only two of the Water Balance Regions were relevant for the overall water budget, Regions 3 and 4. A groundwater balance was calculated for Region 5 to explore inputs and outputs for the lower most portion of Lolo Creek and analyze any effects within the Lolo Development Area, but there is no equivalent surface water balance to couple with the groundwater.

Equation A2 (variation of Equation 6 in the main report) was used to estimate the outputs for Water Balance Region 4 first. Region 4 was easier to constrain given its hydrologic properties. This region consistently loses surface flow in Lolo Creek to the aquifer, that loss of flow does not return to Lolo Creek as surface flow within Region 4 and is therefore assumed to leave the region via groundwater outflow. Thus, all inflows to the aquifer in Region 4 were assumed to leave only as groundwater outflow, allowing all measured inputs, and some outputs, to equal groundwater outflow. Inflows were back calculated using values of (ΔS) determined from groundwater elevation maps. For Region 4, an aquifer storage coefficient (σ) of 0.1 was assumed (Lohman, 1972).

$$I = \Delta S\sigma + O \qquad \{Eq. A2\}$$

$$where$$
$$I = GW_I + (R\gamma) + (LG_r\gamma) + H_r + (Q_L\omega)$$
$$O = (R\gamma) + (LG_r\gamma) + H_r + (Q_L\omega) + U_O + LG + H$$

Outputs from Region 4 were considered the sum of withdrawals for lawn and garden irrigation, household use, and un-known outflows (U_O) (i.e. all other outflows not measured or estimated). In Equation A2, seepage recharge from irrigation (R), seepage recharge from lawn and garden irrigation (LG_r), household return flows (H_r), and streamflow loss (Q_L) are measured, or estimated, values; therefore, groundwater inflows

(GW_I) were calculated using the value of total inputs (I) and solving for (GW_I). The coefficients (γ) and (ω) determine the proportion of irrigation seepage and streamflow loss that contribute to changes in aquifer storage, respectively. For Water Balance Region 4 a value of one was used for both (γ) and (ω), such that 100% of seepage and streamflow loss contribute to changes in aquifer storage. A value of 1 was assumed because no additional information was available to inform these coefficients. Equation A3 describes how (U_O) was calculated as the surplus outflow when the decrease in storage is greater than the measured outflows.

$$U_O = \begin{cases} (-\Delta S) - (LG + H) & if \quad \Delta S < 0 \\ 0 & if \quad \Delta S > 0 \end{cases} \qquad \{Eq. A3\}$$

From Equation A2, the groundwater outflow (GW_O) from Water Balance Region 4 is equal to $O - (LG + H)$. This outflow volume becomes potential inflow for Water Balance Region 5. (GW_I) for Region 4 becomes potential outflow (GW_O) from Region 3.

The groundwater balance for Water Balance Region 3 was calculated as the inverse of Region 4, where inputs were assumed based on measured volumes and outputs were back calculated using Equation A4 (another variation of Equation 6 from the main report).

$$O = I - \Delta S \sigma \qquad \{Eq. A4\}$$

$$where$$
$$I = GW_I + c_I + (R\gamma) + (LG_r\gamma) + H_r + (Q_L\omega)$$
$$O = GW_O + Q_G + LG + H$$

Region 3 is different from Region 4 because there is more irrigation, less domestic use, and more interaction between streamflow and groundwater. Region 3 is a gaining segment of Lolo Creek, based on measured streamflow gains from synoptic surveys. This leads to a few different water balance variables than in Equation A2, including constant inflow (c_I) and streamflow gains from groundwater (Q_G). In Region 3, (GW_I) was defined as the volume of water that remains in the aquifer and does not interact with surface water. Total groundwater inflow is the sum of (GW_I) and a constant inflow term (c_I) that was used to balance (ΔS). The first assumption for Region 3 was that some constant inflow must occur to maintain streamflow in Lolo Creek. Based on synoptic measurements (Figure 4 in the main report), August streamflow gains were 8.2 cfs, November streamflow gains were 9.08 cfs, and March streamflow gains were 6 cfs. These values align with the conceptual model of recharge to the aquifer and groundwater outflow to Lolo Creek. August has the highest streamflow gains during the peak of irrigation season and following spring runoff, gains are still higher at the end of the irrigation season in November but less than the peak, and gains are the lowest before spring runoff in March when only natural sources of recharge have occurred through the winter. These synoptic runs show that Lolo Creek gains streamflow year-round, but that fluctuations occur around various sources of inflow. The March streamflow gain of 6 cfs was considered the lowest baseflow maintained by groundwater. (ΔS) is approximately zero throughout the winter in Region 3 meaning that inflows equal outflows. This means that some inflow must occur year-round to maintain baseflow in Lolo Creek because it is not derived from water stored in the aquifer. A (c_I) of 363 acre-ft per month was used (~6 cfs for 30.5 days, the average length of a month) because it constrained groundwater outflows to the measured baseflow. This leads to the second assumption for Region 3, that $GW_O^{R3} = GW_I^{R4} = GW_I^{R3}$, where superscripts designate Water Balance Region. Therefore, groundwater inflow to Region 4 is equal to groundwater outflow from Region 3 and groundwater inflow and outflow (that do not interact with surface water) are equivalent. (Q_G) represents the portion of total groundwater outflow that becomes streamflow, this is an important variable to estimate because it ties the groundwater balance to the surface water balance. The amount of streamflow contributing to recharge (ω) is equal to zero for Region 3 because there is not measured streamflow loss from Lolo Creek. The coefficients for aquifer storage and seepage recharge were not assumed, instead, these coefficients were used to calibrate Equation A4 in the form $Q_G = I - \Delta S\sigma - GW_O - LG - H$, where I is dependent on aquifer storage and seepage recharge. The resulting monthly values of (Q_G) were compared with calibration timestamps of synoptic streamflow gains. The calibration timestamps were the month and year of a synoptic survey or synoptic gains calculated using stream gage data for late summer months when there are little to no un-gaged surface water inflows (e.g. ephemeral tributaries). Five total timestamps were chosen for the calibration procedure, these dates were 8/2016, 8/2017, 9/2017, 10/2017, and 8/2018. The sum of the squared errors between (Q_G) and the observed streamflow gains for each calibration timestamp were calculated for a range of (σ) and (γ) values in which the minimum sum of the squared errors was selected. Figure A12 illustrates the results of this minimization procedure as a 2D heatmap and calibration curves. The aquifer storage coefficient and seepage recharge coefficient that resulted in the lowest sum of the squared errors was $\sigma = 0.07$ and $\gamma = 0.51$, respectively. (Q_G) was used as an input for the Water Balance Region 3 surface water budget.

Although not included in the surface water balance, the Water Balance Region 5 groundwater balance was calculated using Equation A4, like Region 3. (GW_O^{R4}) was used as (GW_I) for Region 5. Outflows were not split between surface and groundwater because there was no additional information to estimate those values. The Region 5 groundwater budget was estimated for subsequent analyses about Lolo population growth and increasing groundwater use within the Lolo Development Area.

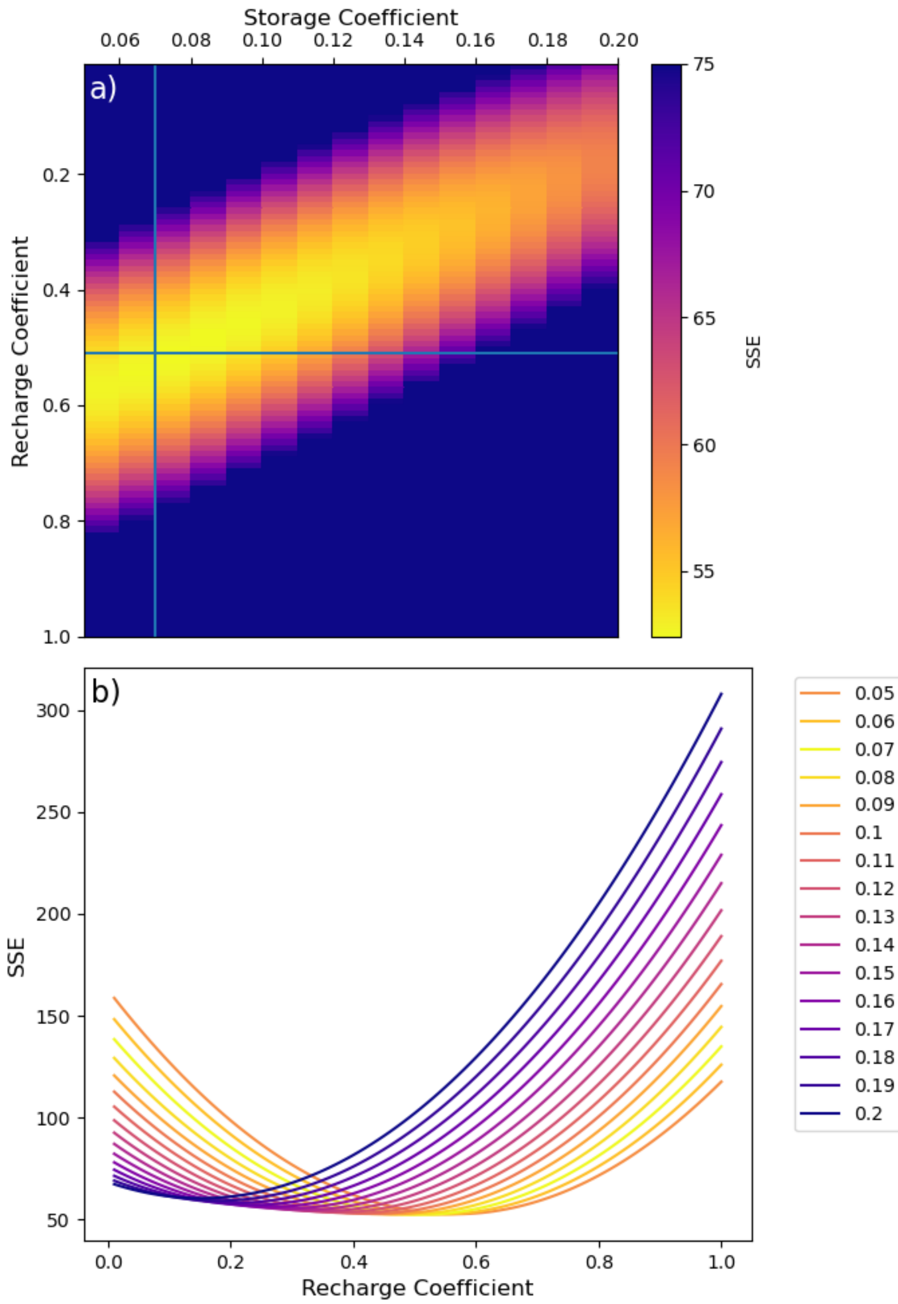

Figure A12. Graphs showing the optimization results for minimizing the sum of the squared errors (SSE) between the groundwater balance variable Q_G and observed streamflow gains measured during synoptic surveys as a 2-dimensional heatmap a), and as a series of calibration curves b). The heatmap in plot a) shows the SSE for each combination of coefficients, seepage recharge (y-coordinate) and aquifer storage (x-coordinate), that determine Q_G. The color ramp shows yellow as lowest SSE and dark blue as highest SSE, the crosshairs highlight the combination of seepage recharge and aquifer storage with the lowest SSE. Plot b) shows the results on normal cartesian axes where the dependent variable (y-axis) is SSE, independent variable (x-axis) is seepage recharge coefficient, and each successive curve represents this relation for various aquifer storage coefficients (shown in the legend). The color scheme is the same as plot a) and each curve's color is determined by its lowest SSE value.

A2.4 Estimating Natural Groundwater Outflows

To estimate a natural flow dataset for Lolo Creek, from 2016 to 2019, the surface and groundwater balances were combined to remove consumptive losses from irrigation and domestic uses. This included adjusting groundwater-surface water interactions that result specifically because of these water uses. The change in storage for the Lolo Creek aquifer includes these uses and therefore, the existing outflow from the aquifer to streamflow in Lolo Creek is considered not natural. To remove the influence of irrigation and domestic return flow via seepage, the calculated inputs from Section A2.3 were adjusted by removing measured irrigation and domestic inflows. Depending on the Water Balance Region, inputs or outputs were dependent on the change in storage, thus storage was also adjusted based on the irrigation season. During the irrigation season, May through October, the natural change in storage was assumed to be zero (absent any additional information about aquifer storage without irrigation seepage). A new outflow time series was calculated using Equation A4. Natural groundwater outflows were only estimated for Water Balance Region 3 because it was the only region that had measurable streamflow gains from the aquifer. Using this method, the outflow from the aquifer that becomes streamflow is constrained by the constant inflow (c_I) term described previously. Such that during the irrigation season, when change in storage is equal to zero, outflow to Lolo Creek is equal to (c_I), which is equivalent to a constant 6 cfs.

A3.0 DOMESTIC AND MUNICIPAL WATER USE

A3.1 Estimating Indoor Domestic Water Withdrawal and Consumption

Indoor water use was estimated for domestic sources of water using Lolo Water and Sewer District data. The main methodology is adequately described in the main report, under the methods for domestic and municipal water use. This section of Appendix A provides clarification on some assumptions made while estimating indoor use.

Data provided by LWSD was in the form of monthly volumes (in gallons) delivered to the public water supply (PWS) system from 1990 to 2018. The data was separated into indoor/outdoor monthly volumes by assuming that indoor water use from April to September was equal to the average water delivery from November to March (these months have negligible or nonexistent outdoor water use). Although indoor use likely was not static for 6 months of the year, this is the best estimate given the available data because even if indoor use fluctuates slightly from month to month, these fluctuations are a small percentage of the total indoor use.

LWSD data also included the number of connections to the PWS system each year. The estimated monthly indoor use for the LWSD was used with the number of annual connections to the system to calculate daily household indoor use. This calculation was equal to the monthly indoor use divided by the number of annual connections for that year. Thus, even if more connections were added within a year, that additional indoor use was not included in the per household estimates until the next year. This is a reasonable approach because the number of connections added per year in a population center the size of Lolo is small and would not drastically affect the per household value. Use per household was calculated for every month, each year, from 1990 to 2018; however, indoor use for domestic sources (PWS outside the LWSD and individual wells) was estimated using the average of all monthly values during the study period (in this case

2016 – 2018). This per household average of 232 gallons/household/day was used to estimate indoor use for the whole watershed based on the number of households in specific water budget regions (discussed later in A3.4). Additionally, the per capita indoor use was estimated by dividing 232 by 2.31 (average persons per household from 2010 Missoula County Census data). The per capita indoor use is helpful for comparing with other estimates of indoor use in Montana and provides an additional metric to calculate indoor water use based on population where there is limited information on coverage areas for PWS outside of the LWSD.

Based on the estimated per household indoor use, the per capita use is very similar to USGS estimated indoor water use for the state of Montana. This study estimates 100.4 gallons per person per day for the Lolo watershed, USGS estimated 106 gallons per day per person for the whole state of Montana (Dieter et al. 2018). The USGS estimates that PWS use is 118 gallons/person/day and self-supplied (domestic well) use is 78 gallons/person/day. Therefore, using PWS data to estimate domestic well use could potentially overestimate water use from this source. USGS estimates are based on the whole state and there are likely regional differences in use. This study uses the per capita rate of 100.4 gallons per day, estimated from local use data, rather than adopting the USGS statewide estimate, despite the potential for overestimation. While overestimation could meaningfully affect the overall water balance in a basin with a higher population, domestic use in the Lolo Creek watershed is a small percentage of the annual yield and any additional uncertainty resulting from previously mentioned assumptions is, therefore, considered acceptable. Additionally, when exploring scenarios that could affect water supply in the future (i.e. population growth), it is best to overestimate domestic use so that the "worst case" scenario is represented.

A3.2 Estimating Irrigated Lawn Acreage and Domestic Source

Data from LWSD was separated into indoor and outdoor use, however, much of the LWSD service area is outside the Lolo Watershed boundary. There are two sources of domestic water in the watershed, other PWS and individual wells (self-supplied). The LWSD data was not used to estimate outdoor household use (i.e. irrigated lawn and garden) nor extrapolate that data to the rest of the watershed because lawn size may differ between municipal and domestic water users.

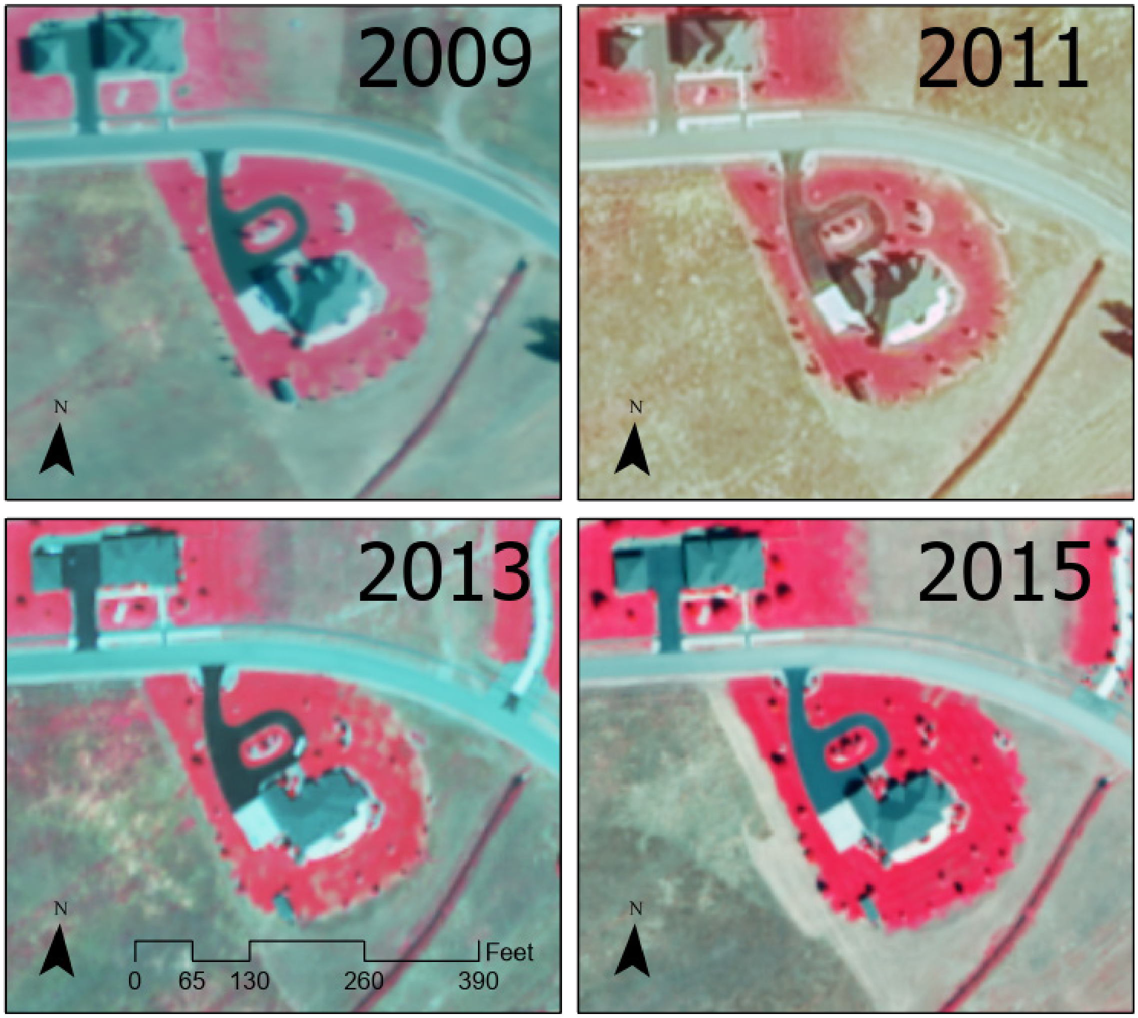

Figure A13. Example images showing multiple years of National Agricultural Imagery Program (NAIP) Color Infrared (CIR) aerial images at a scale of 1:2000. CIR displays green, growing vegetation as red pixels making it easy to identify watered areas. The extent of the red pixels within land parcels was used to estimate the area, in acres, of irrigated lawns in the Lolo Watershed. Notice the reoccurrence of red pixels over time from 2009 to 2015 suggesting that this area is indeed irrigated and has been in the past.

The size of irrigated lawns was used to estimate outdoor use across all household sources within the watershed boundary and outside as well. This was done by determining the average size, in acreage, of lawns for each municipal and domestic source. Lawns were delineated by hand using ESRI ArcGIS and multiple years (2009, 2011, 2013, 2015) of NAIP color infrared (CIR) imagery. CIR imagery displays green, growing vegetation as red pixels allowing easy identification of watered areas. NAIP imagery is collected in the fall when irrigated land is green and the rest of the landscape is typically not. As described in the main report, county parcel data was used to first constrain parcels in the Lolo watershed that were likely domestic residences rather than forest or agricultural lands. Thus, using NAIP CIR images, the area of irrigated lawn was estimated by mapping the extent of the red pixels for individual parcels (Fig. A13). This process was not done for every parcel in the watershed. Which parcels, and how many parcels, this method was applied to is adequately described in the main report methods section on determining random parcels from a finite population. Here we clarify that using a statistical approach, rather than mapping every lawn in the watershed, introduces certain biases in determining outdoor water use. Using average lawn size does not acknowledge slight differences, and outliers, in lawn acreage. Thus, when calculating water withdrawal and consumption for outdoor use, the values could be an overestimate or underestimate depending on the distribution of actual lawn sizes. The only way to negate these biases would be to determine the total acreage of irrigated lawn in the watershed (by mapping all irrigated acreage in every residential parcel of land). This exhaustive approach was beyond the scope of work for this study but could be an area of improvement for future water budgets if an automated workflow was developed. Additionally, there was no spatial weighting applied to the parcels when randomly selecting a sample, meaning that the areas with denser populations (community of Lolo) could be over-represented in the averaging, resulting in more lawns being mapped for LWSD municipal source than the other two domestic sources.

After irrigated lawn acreage was determined for all parcels (within the subset of parcels randomly selected from the total), each lawn was categorized by source before averaging. This categorization was done using various spatial datasets. For the LWSD, all mapped lawns within the service area boundary were considered irrigated from that source. Determining lawns associated with PWS outside of the LWSD was not as straightforward. DEQ's Database on Drinking Water Sources is the most reliable source for PWS wells and shows seven PWS wells outside LWSD. Using DEQ, GWIC, and DNRC water rights databases, lawns were categorized as other PWS if they were near a PWS well and did not have an individual well or water right (in GWIC and DNRC database). This approach obviously has some uncertainty and may not capture all parcels serviced by one of the seven PWS wells, especially in the case where a residence receives water from PWS but also has a well for outdoor irrigation. This was, however, the best categorization given available information that was within the scope of this study. Lawns not categorized as LWSD or other PWS were thus assumed to be serviced by an individual well and were assigned to that category.

A3.3 Estimating Lawn and Garden Withdrawals and Consumption

For this study, lawn and garden withdrawals (from the aquifer) and consumption (evapotranspiration from grass) were estimated using an irrigation efficiency approach. As discussed earlier, LWSD data was separated into indoor and outdoor monthly volumes. However, as outlined in the main report text, this data only describes one source of household water in the watershed. To use the available data to estimate lawn and garden use from any household source, it was related to a common metric that does not fluctuate greatly over a region the size of the Lolo Creek watershed, if a few assumptions are met. This metric is a net irrigation requirement (NIR), or depth of water required to grow a crop (in this case grass in residential lawns) on a per acre basis. This section of Appendix A outlines the assumptions that must be made to allow Equations 3 and 4 in the main report to be used for estimating lawn and garden use; as well as validating the estimates by using the same method to predict LWSD data, which is known.

There are several efficiency coefficients used in studying and evaluating irrigation and irrigation systems. For this study, the relevant coefficients are conveyance efficiency (CE), irrigation efficiency (IE), overall irrigation efficiency (OIE), irrigation consumptive use coefficient (ICUC), and application efficiency (AE). These terms are defined as follows, using definitions from Sandoval-Solis et al. (2013) and others:

$$CE: \qquad e_C = \frac{V_a}{V_t} \qquad \{Eq. A5\}$$

Conveyance efficiency (e_C) is a coefficient that describes the irrecoverable loss of water through the distribution infrastructure (i.e. from point of diversion to the place of use). (V_a) is the volume of water applied at a place of use, in this case lawns, and (V_t) is the total volume of water diverted or withdrawn from the source.

$$IE: \qquad e_I = \frac{V_b}{V_a} \qquad \{Eq. A6\}$$

Irrigation efficiency (e_I) is the measure of the proportion of a volume of irrigation water applied to an area that goes towards "beneficial uses." Here, beneficial uses are not the same as the legal definition used in western water law for water rights but refer to losses determined to be beneficial for an irrigation operation (i.e. crop evapotranspiration, percolation for salinity control, infiltration due to field preparation, etc.). Considering a single field, if all the irrigation water applied is used by a beneficial use, 100% irrigation efficiency is achieved. (V_b) is the volume of water applied/lost to beneficial uses. It is worth noting that beneficial uses do not have to be consumptive, such that some uses may return water to the aquifer or to a stream via surface runoff.

$$OIE: \qquad e_O = e_C \times e_I \qquad \{Eq. A7\}$$

The overall irrigation efficiency (e_O) is the combined efficiency of conveying water to a place of use and how efficiently it is used for beneficial uses at the place of use.

$$ICUC: \qquad e_{CU} = \frac{V_C}{V_a} \qquad \{Eq. A8\}$$

The irrigation consumptive use coefficient (e_{CU}) is a measure nearly identical to the irrigation efficiency coefficient except for the variable (V_C), which is the volume of water consumed (i.e. irrecoverable loss from the system). Consumptive losses are not always beneficial, so it is a different measure of efficiency based solely on consumption.

$$AE: \qquad e_a = \frac{d_{NIR}}{d_a} \qquad \{Eq. A9\}$$

The application efficiency (e_a) is a measure of how well a given irrigation system, or practice, distributes water to a field based on a target depth of water per unit area (d_{NIR}) and average depth of water applied per unit area (d_a). In this study, the target depth of water is considered the NIR for lawns. AE is often measured or estimated for many types of irrigation systems.

From the definitions and equations, CE, IE, OIE, and ICUC, are all closely related aside from the specific definitions of the variables. All these terms define the efficiency of a whole system from diversion to application to consumption. Irrigation efficiency is therefore specific to irrigation systems and their operation, is scalable from a single field to a whole region and is applicable over some specified period (e.g. the irrigation season). However, AE is slightly different and, as described by Burt et al. (1997), has a specific purpose for evaluating irrigation system performance over the span of a single irrigation event. It requires a lot of data to estimate IE or OIE but estimates of AE for various irrigation systems are readily available (Sandoval-Solis et al., 2013 and others). AE and

IE are different measures of efficiency for different purposes, but given the following assumptions, the two coefficients are related.

(1) The main assumption when using AE to calculate water withdrawals for lawn and garden irrigation is that the estimated volume of water consumed for outdoor uses is equal to the required amount of water for lawns and gardens, or NIR.

$$\frac{V_C}{\bar{A}} = d_{NIR}$$

(2) Because water is delivered to each household via a closed system (i.e. either pumped from a well or via public water supply infrastructure), CE is assumed to be 100%.

$$V_t = V_a$$

(3) Because the only "beneficial" use for lawn irrigation is growth of the grass, the volume of water used for beneficial uses is equal to the volume of water consumed in the irrigation process.

$$V_b = V_C$$

(4) Following assumptions (1) and (3), based on Burt et al. (1997), AE can be considered a reasonable approximation of IE:

$$e_a \approx e_I$$

Two important conclusions result from assumptions (1 – 4). The first conclusion is that $e_I = e_O = e_{CU}$, based on assumptions (1) and (2), such that $e_I = \frac{V_C}{V_t}$. The second conclusion is that IE and AE are interchangeable, such that AE can be re-written as $e_a = \frac{V_C}{V_t}$. This is important because we do not know IE for lawn irrigation, but we can reasonable estimate AE based on known values of sprinkler systems. Using AE and IE in this context is also the same concept as "on-farm efficiency," which is a synonymous term used by some agencies including Montana DNRC, where AE, IE, and on-farm efficiency are all equal to the percentage of water delivered to the field/lawn used by the crop. It is important to note that in more in-depth irrigation system water budgets, these assumptions may not be justified. For the scope of this study, assumptions (1 - 4) allow Equations 3 and 4 in the main report to be derived from Equations A6 and A9. When these assumptions are not met, IE is calculated based on volumes of water where AE is calculated as a depth independent of the size of the irrigated area. This is another reason AE was favorable for this study, because lawn irrigation needed to be scalable based on acres of lawn irrigated and a NIR for lawns that is spatially consistent across the watershed (reasonable given its small geographic area).

To validate this method of estimating lawn and garden irrigation, Equations 3 and 4 in the main report were used, with the total number of households estimated for the LWSD service area (discussed later in *Section A3.4*), to calculate the volume of water withdrawn and consumed. This estimated dataset was compared with the observed LWSD data to determine how well the irrigation efficiency approach preformed (Fig. A14 and Fig. A15). Goodness of fit tests were not preformed but a visual inspection of the comparison confirms the results were adequate for the scope of this study. Based on Figure A15, the method is expected to reproduce lawn and garden water use volumes adequately well for smaller volumes but slightly underestimate for larger volumes. This is likely due to the actual number of connections, or households, in the LWSD service area increasing over time while the irrigation efficiency method assumes a static number of households for the study period.

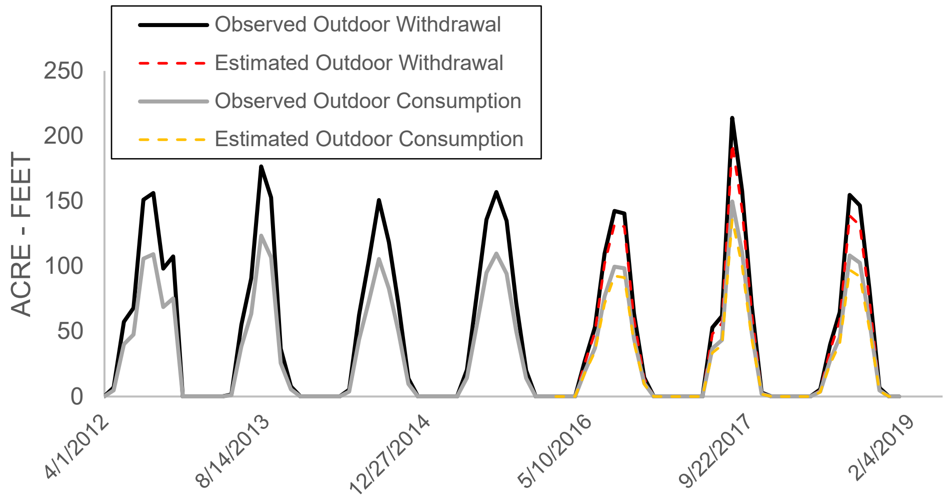

Figure A14. Graph showing the observed, monthly volumes of water delivered to the LWSD service area (black solid line) for outdoor uses; amount of that delivered water consumed by sprinkler irrigation (solid gray line); estimated, monthly volumes of water delivered to the LWSD service area for outdoor uses using lawn acreage and irrigation efficiency method (dashed red line), and amount of the estimated water consumed by sprinkler irrigation (dashed yellow line). Observed volumes were the outdoor portion of LWSD use data, which were isolated based on methods described in the main report and Section *A3.1*. Consumption for both observed and estimated data is based on 70% application efficiency (i.e. consumption is 70% of withdrawn volume).

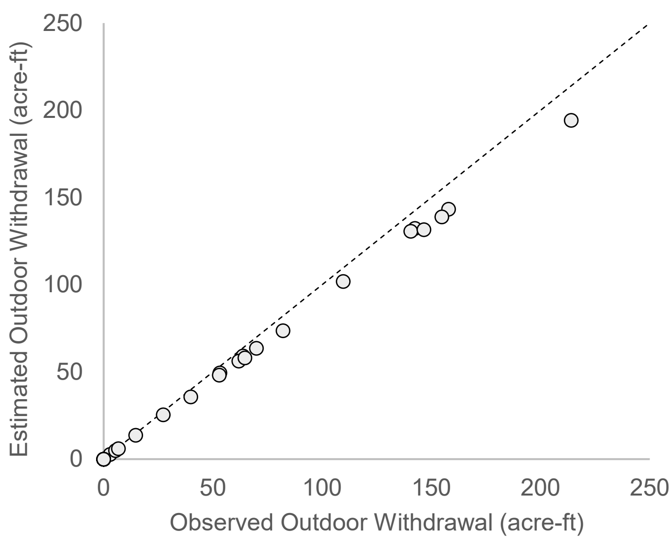

Figure A15. Comparison plot of observed (x-axis) vs. estimated (y-axis) monthly volume of water delivered to LWSD. Dashed line represents the 1:1 line (i.e. if the irrigation efficiency method estimated outdoor water use with 100% accuracy, all points would fall on the dashed line). Points above the line represent overestimated volumes, while points below the line are underestimates.

A3.4 Calculating Domestic Uses within Water Balance Regions

The water balance model for this study was applied to water balance regions, as described in the main report under water balance methods. The main report identifies five water balance regions in the Lolo Creek watershed with Region 1 being the most upstream and Region 5 being the most downstream. This approach provided a better spatial picture of the water budget for Lolo Creek, rather than considering just the entire watershed. However, it also required inputs and outputs to be assigned to spatial categories (in this case, the water balance regions).

Structures were categorized in ArcGIS by applying spatial filters to the NRIS structures dataset, based on the Region in which they exist. Households serviced by PWS, other than LWSD, were first associated with a PWS well, which were identified from the MBMG GWIC database. This process also used DNRC water rights information for wells, Missoula County parcel data, and DEQ data on service population for PWS wells. All structures associated with a PWS well were assigned to the water balance Region in which the community well was located. The process of assigning structures was as follows:

1) Locate a PWS well, outside of the LWSD service area boundary.
2) Count the number of structures near, or around the PWS well (this was sometimes easy given that homes serviced by a community well were in identifiable developments, but that was not always the case).
3) Cross reference the selected structures near the well with GWIC wells, DNRC water rights, and parcel data, to determine if the parcel that the structure was on also had a water right or documented domestic well.
4) Remove any structures on parcels with documented domestic wells from the count.
5) Finally, where available, cross reference DEQ service population with estimated number of households serviced by the PWS well using 2.31 persons per household to convert DEQ service population to number of households.

The final step involved professional judgement on deciding whether to use the DEQ population derived number of households, or the spatial count of households serviced by a PWS well (if they differed drastically). If counting structures spatially was difficult and imprecise, the population data was favored. Any structures that overlapped with a water balance Region and the LWSD service boundary were excluded from domestic use estimation. As discussed in the main report, LWSD has three wells (Well #1, Well #2, and Well #3) that feed a gravity storage system (Fig. A16). LWSD data included pumping volumes for these three wells, but that means the location of the pumping was not related to the location of households serviced by the public water supply system. This is complicated by the fact that Wells #1 and #2 are not within the Lolo Creek Watershed boundary, but that Well #3 is within Region 4 (Fig. A16). The available data, and topography around the city of Lolo, suggest that Wells #1 and #2 are hydrologically connected to the Bitterroot River, not Lolo Creek. The way that the public water system is operated did not allow for water from Well #3 pumping volumes to be associated with a given number of households, nor their spatial locations; which is why all structures in the LWSD were excluded. Instead, pumping volumes from Well #3 were considered the only relevant withdrawal from the Lolo Creek watershed for municipal use by the LWSD.

After LWSD structures and other PWS structures were assigned to a water balance Region, the remaining number of structures were considered self-supplied residences with domestic wells as a source. The results of this analysis are shown in Table A2.

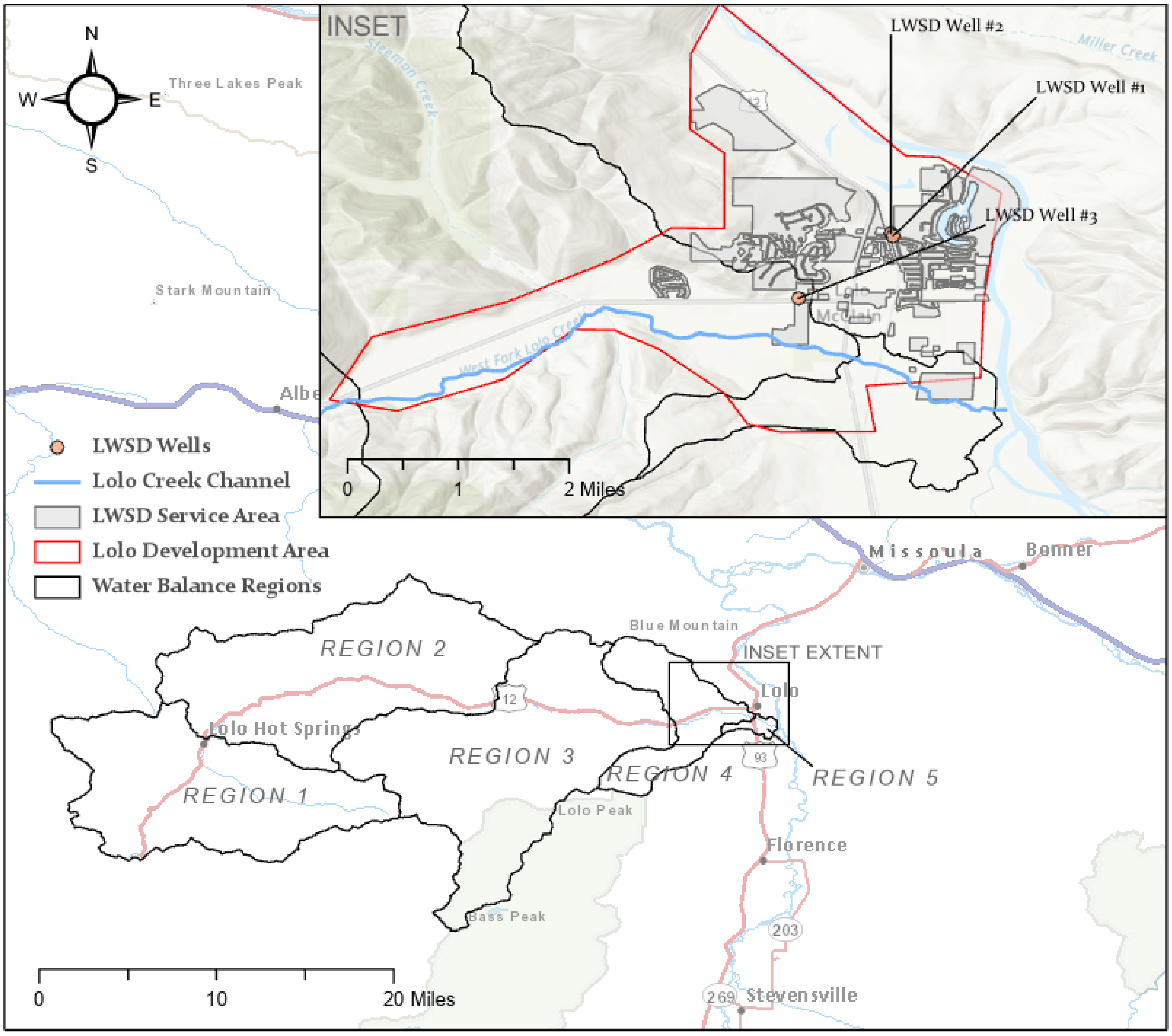

Figure A16. Map showing the Water Balance Regions delineated for this study based on stream gage locations. The inset also shows the area around the city of Lolo to highlight that the majority of Lolo is outside the topographic boundary of the Lolo Creek Watershed, including the LWSD service area. The red polygon shows the area of recent and potential future, development around Lolo.

Table A2. Results of the spatial analysis for determining number of households serviced by each domestic water source.

Domestic Source	Well Location	Number of Households	Irrigated Lawn/Garden Acreage	Estimated Population Serviced
Water Balance Region 1[0]				
Domestic Source	Well Location	Number of Households	Irrigated Lawn/Garden Acreage	Estimated Population Serviced
-	-	-	-	-
Totals		-	-	-
Water Balance Region 2				
Domestic Source	Well Location	Number of Households	Irrigated Lawn/Garden Acreage	Estimated Population Serviced[1]
Self-Supplied	Region 2	36	17.64	83
Totals		*36*	*17.64*	*83*
Water Balance Region 3				
Domestic Source	Well Location	Number of Households	Irrigated Lawn/Garden Acreage	Estimated Population Serviced[1]
Self-Supplied	Region 3	189	92.61	437
Totals		*189*	*92.61*	*437*
Water Balance Region 4				
Domestic Source	Well Location	Number of Households	Irrigated Lawn/Garden Acreage	Estimated Population Serviced[1]
LWSD[2]	NA	121	22.99	280
Other PWS	Region 4	149	68.54	344
Self-Supplied	Region 4	278	136.22	642
Totals		*548*	*227.75*	*1266*
Water Balance Region 5[3]				
Domestic Source	Well Location	Number of Households	Irrigated Lawn/Garden Acreage	Estimated Population Serviced[1]
LWSD[2]	NA	2	0.38	5
Other PWS	Region 5	60	27.6	139
Self-Supplied	Region 5	10	4.9	23
Totals		*72*	*32.88*	*167*
Lolo Development Area				
Domestic Source	Well Location	Number of Households	Irrigated Lawn/Garden Acreage	Estimated Population Serviced[1]
LWSD[2]	NA	1087	206.53	2511
Other PWS	Outside watershed	134	61.64	310
Self-Supplied	Outside watershed	-	-	-
Totals		*1221*	*268.17*	*2821*

[0]No spatial analysis done on this Water Balance Region.
[1]Based on an average of 2.31 persons per household.
[2]Households/population within the LWSD service area and within the watershed were not counted when estimating domestic use, they are shown here for consistency, but actual data from LWSD were used for that source in the water balance.
[3]This water balance region was not used for a surface water budget because there was no outflow data. Use data is included because it was used for a groundwater budget for Region 5 and to analyze trends around the Lolo Development Area.

A4.0 IRRIGATION CONSUMPTIVE USE

A4.1 Diversion and Seepage Measurements

The methods used to measure irrigation diversions were identical to streamflow measurement methods described in the main report, except where measuring devices were found. In the case that a ditch contained a flume, the discharge was derived from the specific equation for the flume and verified with occasional in-channel measurements. Ditch seepage was measured identically to the synoptic runs on Lolo Creek except for individual ditches.

Four seepage runs (same as synoptic runs for groundwater but specific to an irrigation ditch) were done for the two main irrigation ditches on the OZ Lolo Trail Ranch; OZ South Fork Ditch and OZ Lolo Ditch. The results of those seepage runs are shown in Tables A11 – A14. Each ditch had two seepage runs done in September of 2018 and November of 2019. The average seepage loss for the OZ South Fork Ditch (based on values from Tables A11 and A13) is 39.6%. The average seepage loss for the OZ Lolo Ditch is 79.1%.

Table A3. September 11, 2018 Seepage run on OZ South Fork Ditch

Time	Location	Discharge (cfs)	Discharge Error (%)	Loss/Gain (cfs)	Loss/Gain (%)	Latitude	Longitude
11:00	Ditch at Gage	2.15	5			46.376053	-114.273618
11:55	Below Culvert	1.46	5	-0.69	-32.09	46.760529	-114.273621
12:00	Trib #1	0					
12:35	Above Pump Pit #1	1.76	10	+0.30	+20.55	46.754984	-114.260083
13:00	Below Pump Pit #1	0.41	5	-1.35	-76.70	46.754885	-114.259627
14:24	Above Trib #2	0.42	7	+0.01[2]	+2.44	46.753346	-114.25617
	Trevis Cr	0.5[1]	10				
13:30	Above Pump Pit #2	0.9	5	-0.02[2]	-2.17	46.753659	-114.25128
	Waste gate leakage	0.1[1]	10				
15:00	Above Confluence with Lolo	1.03	5	+0.03[2]	+3.00	46.754195	-114.247713
Total Loss				-2.04	-94.88		
Seepage Loss				-0.69	-32.09		
Consumptive/Return to Lolo				-1.35	-62.79		

[1]Discharge was estimated.
[2]Loss/Gain calculated is less than the combined discharge measurement errors and is considered indeterminant (i.e. not included in the total losses/seepage).

Table A4. September 12, 2018 Seepage run on OZ Lolo Ditch

Time	Location	Discharge (cfs)	Discharge Error (%)	Loss/Gain (cfs)	Loss/Gain (%)	Latitude	Longitude
9:30	Lolo Ditch 10' above Headgate	3.35	5			46.761758	-114.29338
	Waste Gage	0.1[1]	10				
11:00	Flume	2.56	5	-0.69	-20.60	46.761758	-114.291023
10:30	Below Culvert, Slaughter Pasture	1.68	5	-0.88	-34.38	46.759953	-114.294533
12:00	End of Ditch 3' abv Pump Pit	0.64	7.5	-1.04	-61.90	46.766745	-114.269547
Total Loss				-2.61	-80.31		
Seepage Loss				-2.61	-80.31		

[1]Discharge was estimated.

Table A5. November 4, 2019 Seepage run on OZ South Fork Ditch

Time	Location	Discharge (cfs)	Discharge Error (%)	Loss/Gain (cfs)	Loss/Gain (%)	Latitude	Longitude
10:00	Ditch at Gage	0.497	5			46.376053	-114.273618
10:30	Below Culvert	0.3	5	-0.20	-39.64	46.760529	-114.273621
11:00	Above Trib #1	0.45	10	+0.15	+50.00	46.754984	-114.260083
Total Loss				-0.05	-10.06		
Seepage Loss				-0.20	-39.64		

Table A6. November 4, 2019 Seepage run on OZ Lolo Ditch

Time	Location	Discharge (cfs)	Discharge Error (%)	Loss/Gain (cfs)	Loss/Gain (%)	Latitude	Longitude
13:00	Flume	4.63	5			46.761758	-114.291023
13:30	End of Ditch 3' abv Pump Pit	1.03	7.5	-3.60	-77.75	46.766745	-114.269547
Total Loss				-3.60	-77.75		
Seepage Loss				-3.60	-77.75		

The other two gaged diversions were downstream of the Lolo Cr abv Sleeman Cr stream gage and were not measured for seepage. A comparative, ratio approach was used to estimate seepage, as a percent of flow, for these lower diversions, the Holt Ditch and the McClay Ditch. The first step was determining the dominant soil type that each of the four ditches flows across. Soils data for the Lolo Creek area were downloaded from USDA Web Soil Survey. The path of the ditch was overlaid on the soil data in ArcGIS and each soil type that the ditch crossed was noted. As part of the USDA soils data, there are estimates of soil storage capacity and hydraulic conductivity in inches per hour. Boer (2002) estimated a hydraulic conductivity of 4 ft/day for the McClay ditch, using an in-channel piezometer to calculate a head gradient. Table A15 summarizes all the available information used in the comparative analysis. Hydraulic conductivity and storage capacity values are the average values of all soil types that the ditch crosses. Boer's (2002) estimate of hydraulic conductivity is 0.04 ft/day different than the high estimate for average hydraulic conductivity of soils that the McClay ditch flows over; therefore, the USDA value of 3.96 ft/day was considered the best estimate. Equation A10 is the proportionality equation used to relate two ditches that have similar soil properties, but where one ditch has seepage information and the other does not, by treating the two ditches as ratios.

$$Q_{Div}\,\phi \propto KL \qquad \{Eq. A10\}$$

$$From\ Darcy's\ Law\quad Q_s = -KA\left(\frac{dh}{dx}\right) = -KbL\left(\frac{dh}{dx}\right)$$
$$with\ the\ assumption\ Q_s = Q_{Div}\,\phi$$

Equation A10 is derived from Darcy's Law and assumes that, in this case, Darcy's Law is being used to calculate a downward flow rate through the bottom of the irrigation ditch. Thus, (Q_{Div}) is the discharge of the diverted water in the ditch, (Q_s) is the downward seepage discharge, (ϕ) is the ditch loss coefficient or seepage proportion, (K) is the hydraulic conductivity, (L) is the length of ditch, (b) is the average width of the ditch, (A) is the wetted area of the bottom of the ditch, and ($\frac{dh}{dx}$) is the hydraulic gradient.

Table A7. Information used for comparative seepage analysis

Ditch Name	Seepage (%)	Dominant Soil Types[1]	Avg Diversion Rate (cfs)	K low[1] (ft/day)	K high[1] (ft/day)	Storage[1] Capacity (in)	Length of reach (ft)
OZ S. Fork	36.9	Moiese Gravelly Loam, Granstdale Loam	2.15	1.14	3.96	4.5	3722
OZ Lolo	79.1	Bigarm Gravelly Loam	3.25	1.14	3.96	7	9090
McClay	-	Bigarm Gravelly Loam, Repp very gravelly loam, Whitecow-Azaar Rentsac Complex, Burnt-fork Subwell Complex	22	1.14	3.96	7	17300
Holt	-	Moiese Gravelly Loam, Granstdale Loam	3.8	1.14	3.96	4.5	8565

[1]Data from USDA Web Soil Survey.

Equation A11, is the ratio created by dividing Equation A10 for one ditch (subscript 1) by Equation A10 for another ditch (subscript 2), in which the unknown variable is solved for.

$$\frac{Q_1\phi_1}{Q_2\phi_2} = \frac{K_1L_1}{K_2L_2} \qquad \{Eq. A11\}$$

From Table A7, it was clear that the OZ Lolo Ditch flowed across soils very similar to the McClay Ditch (mostly Bigarm Gravelly Loam), whereas the OZ South Fork Ditch and the Holt ditch were more similar in terms of soils (Moiese Gravelly Loam). Notice that the two soil types have identical hydraulic conductivity values in the USDA database, but different storage capacities. Although USDA soils data provides high and low estimates of hydraulic conductivity, they are course estimates and using the measured value from Boer (2002) provides better regional accuracy. To do this, the same value of 4 ft/day measured by Boer (2002) in the McClay Ditch was adopted for the OZ Lolo Ditch given the similarity of soil types. The associated hydraulic conductivity for the OZ South Fork Ditch was estimated using Equation A11, where subscript 1 represents OZ Lolo Ditch and subscript 2 represents the OZ South Fork Ditch. Values of $Q, \phi,$ and L were derived from Table A7 and the equation was rearranged to solve for a value of $K_2 = 2.92\ ft/day$, which is within the high/low estimates provided in the USDA database. The same ratio calculation was used for the McClay/OZ Lolo Ditches to solve for $\phi = 0.22$ (or seepage of 22% diversion volume) for the McClay Ditch; and again using the Holt/OZ South Fork Ditches to solve for a $\phi = 0.47$ (or seepage of 47% diversion volume) for the Holt Ditch.

Representing seepage as a static percentage has its drawbacks because it assumes there are no seasonal fluctuations (which there likely are); however, this method was adequate to meet objectives of the water balance. Additionally, estimating seepage (rather than measuring directly) carries a much larger uncertainty that must be acknowledged regarding the use of the ditch loss coefficient (e.g. subsequent analysis on conveyance efficiency or recharge from ditch losses).

A4.2 Irrigated Lands Evapotranspiration

This section provides additional details about applying the METRIC method for estimating evapotranspiration (ET). As described in the main report, the first step is acquiring the satellite thermal imagery central to the METRIC algorithm. Because this relies on optical data from satellites, there are many atmospheric occurrences that render images unusable (e.g. cloud cover, smoke from wildfire). This process is done manually by reviewing all images to determine viability. The resulting, usable images per month from 2014 to 2019 are shown in Table A8. The return frequency of the satellites makes several ET estimates possible over the growing season and provides ‘anchor’ points in time between which ET is interpolated.

Various GridMET data products were used in the implementation of the METRIC method, and in determining the water used by plants from irrigation rather than received via rainfall. One of the key data products from GridMET is spatially gridded reference ET (ET_r). ET_r is simply the rate of ET from a reference alfalfa crop at 0.5 m height, healthy and actively growing, given local meteorological conditions. This metric is used to scale the actual ET values in non-reference crops using daily local meteorology data in a calculation standardized by the American Society of Civil Engineers (Equation A12; NRCS 1997).

$$ET_r = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad \{Eq. A12\}$$

Where R_n is calculated net radiation at crop surface in MJ m^2 d^{-1}, G is ground heat flux density at the soil surface in MJ m^2 d^{-1}, T is mean daily air temperature at 1.5 to 2.5 m height in °C, u_2 is mean daily wind speed at 2 m height in m s^{-1}, e_s and e_a are mean saturated and mean actual vapor pressure at 1.5 to 2.5 m height in kPa, Δ is the slope of the saturation vapor pressure-temperature curve in kPa °C^{-1}, γ is the psychrometric constant in kPa °C^{-1}, and C_n and C_d are constants that change with reference crop type and calculation time step (Walter et al., 2005). As described in the main report, GridMET ET_r values are typically biased high and thus were adjusted using the Lolo Mesonet data. Figure A17 shows the difference between GridMET ET_r estimated at the site of the Mesonet station compared with ET_r calculated using the Mesonet station's accurate data at that location.

Table A8. The count of Landsat image captures that are sufficiently free of clouds, snow, and smoke to be used in METRIC analysis.

Path, Row	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total Images
p041r 027	2014	0	0	0	1	0	1	4	1	3	1	0	0	
p041r 028	2014	0	0	0	1	0	0	4	1	3	0	0	0	20
p041r 027	2015	0	1	1	2	1	2	2	2	1	1	0	0	
p041r 028	2015	0	1	1	2	1	2	3	2	2	1	0	0	28
p041r 027	2016	0	0	0	4	1	3	1	3	2	2	1	0	
p041r 028	2016	0	2	1	3	1	3	1	3	2	1	0	0	34
p041r 027	2017	0	0	0	0	2	1	2	3	3	1	0	0	
p041r 028	2017	0	0	0	0	0	1	2	3	3	1	0	0	22
p041 r027	2018	0	0	0	0	2	1	3	3	1	1	1	0	
p041 r028	2018	0	0	0	0	1	1	3	3	1	1	0	0	22
p041 r027	2019	0	0	0	0	2	1	3	3	1	0	0	0	
p041 r028	2019	0	0	0	0	0	1	3	1	1	1	0	0	17

The METRIC algorithm was used to find the ET reference fraction (ET_{rf}), which is the ratio of actual ET to ET_r, for each valid image. To fill in the data gaps, ET_{rf} was linearly interpolated between valid images. To find daily ET, the interpolated daily ET_{rf} values are multiplied by ET_{rf} (Equation A12) from GridMET available daily over the conterminous United States.

$$ET = ET_r \times ET_{rf} \qquad \{Eq. A12\}$$

During the processing of the METRIC algorithm, calibration of the model is required using a Geographic Information System to place point features marking important calibration locations in each image. This calibration consists of choosing both a 'hot' and 'cold' pixel location. These pixels are found within the target agricultural area, and should consist of an actively growing, well-watered 'cold' location, and a recently harvested, dry, or fallowed 'hot' location. The selection of these locations is somewhat subjective and requires an expert user. The pixel locations are then used in the METRIC calibration step as the low and high reference ET points, between which the remaining pixels in the image are interpolated, based on surface temperature.

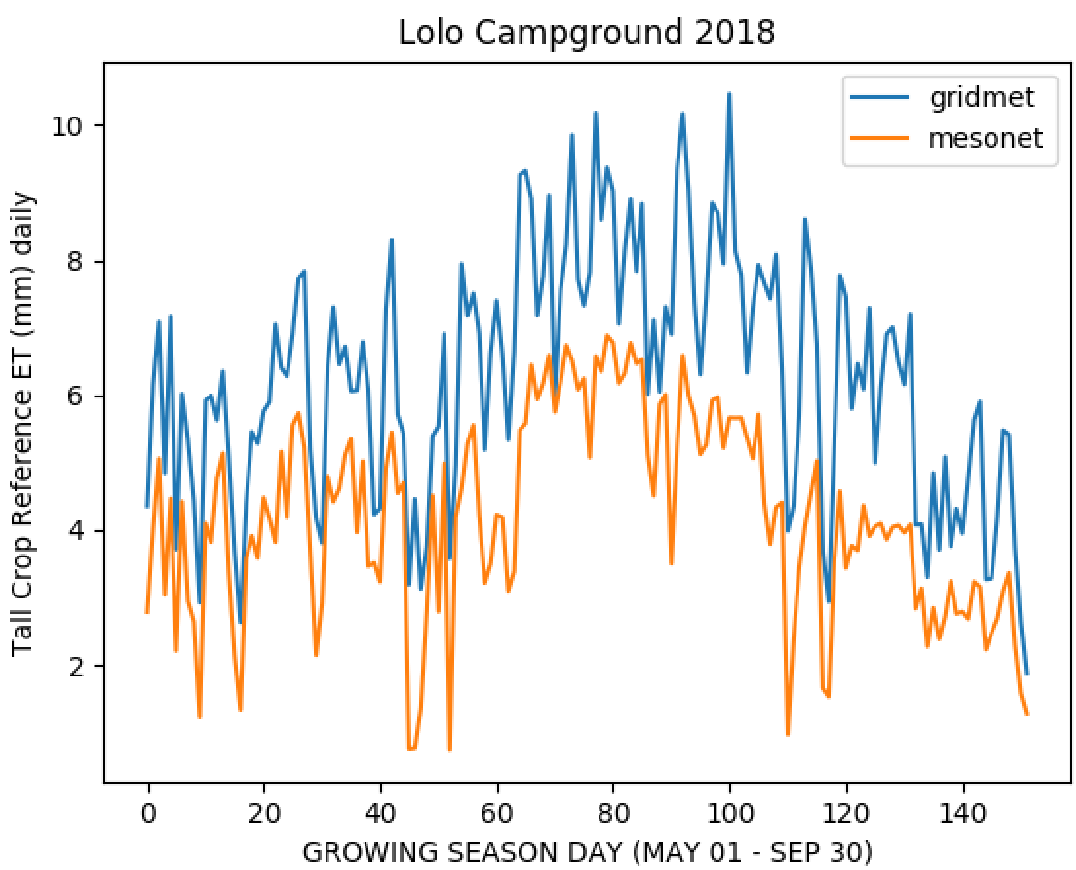

Figure A17. Graph visualizing the bias between GridMET and local meterological observations from Mesonet station.

In this study, crop consumption is defined as the water lost by evapotranspiration from a crop that was sourced from irrigation. To find crop consumption, first effective precipitation (i.e., the portion of crop consumption that can be attributed to precipitation rather than irrigation) must be estimated using an empirically derived equation from the National Engineering Handbook (Equation A14; NRCS 1997). This equation is used to calculate monthly effective precipitation and requires monthly ET inputs.

$$P_e = SF(0.70917\, P_t^{0.82416} - 0.11556)(10^{0.02426 ET_C}) \qquad \{Eq. A14\}$$

In Equation A14, P_e is the effective precipitation, SF is the soil water storage factor (calculated via Equation A15), P_t is the mean monthly precipitation, ET_C is the average monthly total evapotranspiration.

$$SF = (0.531747 + 0.295164\, D - 0.057697\, D^2 + 0.003804\, D^3 \qquad \{Eq. A15\}$$

The soil water storage factor (Equation A15) depends on one variable, the usable soil water storage (D). D was derived from USDA Web Soil Survey data. Each irrigated parcel where ET was estimated was correlated with a dominate soil type. As discussed previously, in Section A4.1, Web Soil Survey data includes D in inches for each soil type. The associated D for the dominant soil type of an individual field was chosen for that field when calculating P_e. The crop consumption of water sourced from irrigation is then determined via Equation 5 in the main report, by subtracting P_e from the total ET.

A4.3 Analysis of Ditch Systems

Three of the four irrigation ditches measured during this study were analyzed for OIE (i.e. Overall Irrigation Efficiency defined in Section A3.3). There were no actively irrigated lands sourced from the Holt ditch, thus, it was not analyzed for OIE. OIE provides a measure of how efficient the existing irrigation practices/systems are, but, was also used in this study to estimate other variables for the overall water balance. Referring to Section A3.3 definitions and equations, OIE was calculated using Equation A7 (alternatively written as $e_O = V_b/V_t$) where V_b, for the purposes of this study, is water consumed by crops via evapotranspiration. ET calculated using the METRIC method for all irrigated fields in the basin was used in this analysis. To use ET data, fields were first grouped by source and again by irrigation type. The total monthly ET for all fields irrigated by one of the measured ditches was divided by the total monthly diversion volume. Monthly OIEs were calculated for the irrigation season from 2016 to 2019. Monthly values were summarized as a single average for each month. The results highlight the variable nature of OIE both monthly and inter-annually. Figure A18 shows the summary graphs of monthly OIE for each of the irrigation ditches and the average values for each Water Balance Region.

One value not measured directly was the amount of diverted water that returns to Lolo Creek directly as surface return flow. This accounts for excess diverted water that is not lost as seepage via conveyance, consumed by ET, nor lost during application to crops. To estimate the excess diversion amount, the IE and CE must also be known. CE was measured directly during synoptic ditch seepage surveys (see Section A4.1), but the resulting conveyance efficiencies reflect only the points in time when the surveys were conducted. It is important to note that the actual seepage likely varies throughout the growing season based on changing soil moisture conditions and water table levels. IE was unknown because the volume of water delivered to individual fields was not measured (only the volume at the point of diversion). The same set of assumptions used in Section A3.3 for domestic lawn irrigation were used here to approximate IE based on known values of AE (or on-farm efficiency) for various irrigation types. Table A9 shows the application efficiencies for irrigation standards adopted by the Administrative Rule of Montana (ARM 36.12.115; and other sources) that were used to estimate the volume of water delivered to fields. V_a (volume of water delivered to the field) was estimated using the monthly ET divided by the AE for the type of irrigation used on that field (from Table A9) and is represented by solving Equation A6 for V_a and substituting so that Equation A16 is written in terms of V_t and V_b. Monthly surface return flow (Q_{SR}) was then calculated using Equation A16.

$$Q_{SR} = V_t - \left(\frac{V_b}{e_I}\right) - (V_t e_C) \qquad \{Eq. A16\}$$

Where (as described in Section A3.3) V_t is total volume diverted, V_b is volume consumed by crop ET, e_C is the conveyance efficiency measured for that ditch, and e_I is the irrigation efficiency which, given past assumptions, is equivalent to application efficiency or on-farm efficiency. Negative values of Q_{SR} are assumed to be zero surface return flow.

Table A9. Application efficiencies (or "on-farm efficiencies") by irrigation type – adapted from ARM 36.12.115 with additional information added

Irrigation Method	**Application Efficiency**
Sprinkler	
Center Pivot*	80%
Other Sprinkler**	70%
Surface	
Level Border	60%
Graded Border (*slope = 0.1 – 0.4%*)	70%
Graded Border (*slope = 0.75 – 1.5%*)	65%
Graded Border (slope = 3%)	60%
Furrow (*slope = 0.1 – 0.4%*)	70%
Furrow (*slope = 0.75 – 1.5%*)	65%
Furrow (*slope = 3%*)	60%
Contour Ditch (*slope = 0.75%*)	60%
Contour Ditch (*slope = 1.5 – 3%*)	55%
Contour Ditch (*slope = 6%*)	45%
Wild Flood*	25%

*Not specifically mentioned in ARM 36.12.115, were added from published sources (Sandoval-Solis et al., 2013; Neibling, 1997; Utah State, 2008).
**ARM 36.12.115 lists all sprinklers at 70%, which is consistent with most published sprinkler application efficiencies aside from center pivot. Thus, all sprinkler types are not differentiated here.

It is worth noting that using Equation A7 to calculate OIE from Table A9 values as IE and CE measured by synoptic surveys (as opposed to Equation A7 of the form $e_O =$

V_b/V_t using measured diversions and METRIC derived ET) produces different values of OIE. This difference may appear as an inconsistency but is a result of including or excluding excess diversions. As an example, fields irrigated by the OZ South Fork Lolo Ditch are all irrigated by sprinklers, thus IE = 70% from Table A9 and the synoptically measured CE is 60.4%. Using Equation A7, this equates to an OIE of 42% which is much higher than any of the monthly efficiencies in Figure A18a. This is because the excess diversions are included in Figure A18a but not in the OIE derived from Table A9 and the measured CE. These excess diversions can be conceptualized a few ways, either as a beneficial use under V_b or as part of the CE representing less efficient conveyance. These conceptualizations do not necessarily matter if the volumes are all represented in the water budget. Using IE from Table A9, and measured CE, is adequate to determine what proportions of diverted water were allocated to direct surface return flows and seepage in the overall water balance. However, it is more accurate to refer to the OIE values in Figure A18 when considering overall system efficiency because they are derived from measured (not assumed) daily or monthly values.

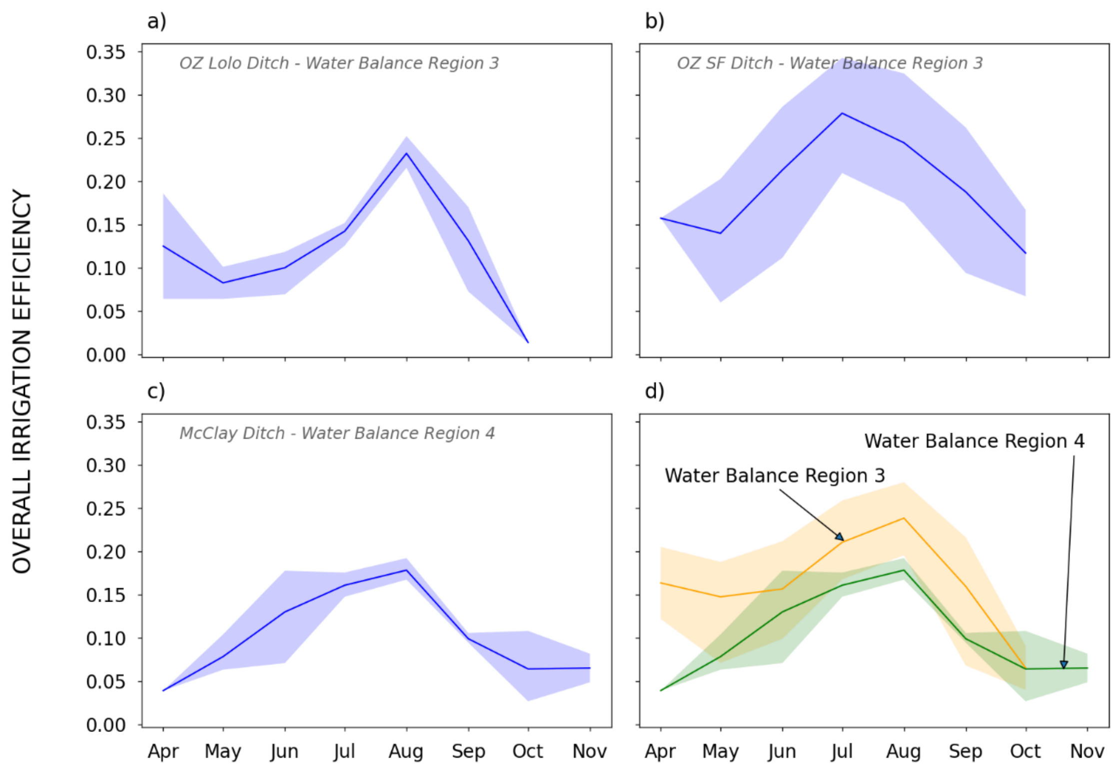

Figure A18. Graphs showing average monthly Overall Irrigation Efficiency for the a) OZ Lolo Ditch, b) OZ South Fork Lolo Ditch, and c) McClay Ditch for years 2016 to 2019. The shaded regions represent the Interquartile Range (IQR) of efficiencies for each month (median and mean were nearly identical). d) shows the average monthly efficiencies (and IQR) by Water Balance Region. Water Balance Region 4 is identical to the McClay ditch because it was the only ditch analyzed in Region 4. Water Balance Region 3 is the average of the efficiencies in a) and b) because both ditches are within Region 3.

A4.4 Estimating Unmeasured Diversions

Detailed analyses of irrigation efficiencies were done for ditches/canals where diversion rates were directly measured, however, there are more irrigated lands in the Lolo Creek watershed than just those associated with one of the measured ditches. Although the measured ditches represent the largest diversions in the watershed, it was still important for the overall water balance to incorporate some estimate of unmeasured diversions. The best method to do this was to use efficiency estimates to back-calculate diversion rates, as was done previously for lawn and garden irrigation. However, agricultural irrigation is more complex than lawn and garden and requires a better understanding of the irrigation system overall (which is not always in a closed system and can service multiple uses). The most accurate method, given the available data, was using the average monthly OIE values (Section A4.3) for each Water Balance Region and ET from fields irrigated by an unidentified or unmeasured source. This process consisted of grouping irrigated lands by Water Balance Region, removing all irrigated lands associated with a measured source, and then calculating the total ET from the remaining fields. The total ET was then divided by the average, monthly OIE values for that Water Balance Region. To evaluate the performance of this method, monthly diversion volumes were estimated for fields serviced by the measured sources OZ Lolo Ditch, OZ S.F. Lolo Ditch, and McClay Ditch (Figure A19). Another approach to estimate unmeasured diversions is to use AE values from Table A9 and an estimated or measured CE (as discussed previously in Section A4.3). This method produces a constant OIE rather than a monthly fluctuating value, thus, fluctuations in ET are the only source of monthly variability. This method was also used with the measured CEs for each ditch and shown for comparison in Figure A19. The performance of these methods in estimating unmeasured diversions is also tabulated as differences between measured and estimated annual irrigation season diversion volumes in Table A10. Estimating diversions (rather than directly measuring) always incorporates a lot of uncertainty, but the monthly fluctuating OIE method provides an adequate estimate and, for the purposes of this study, are acceptable for the overall water balance. Notice that the fluctuating monthly OIE method produces more accurate diversion volumes than the constant OIE method (which tends to greatly underestimate the actual diverted volume).

As discussed in Section A4.3, the OIE values account for seepage loss and direct surface return flows. It is worth noting that some of the fields irrigated by an unmeasured source could have less direct surface return flow or less seepage loss than the measured ditches, creating overestimation of the diverted volume. Because actual consumption is known from METRIC derived ET, any overestimation of the diverted volume is routed to Lolo Creek via return flows. Given a lack of additional information on unmeasured diversions, surface and seepage return flows were not separated like the measured ditches in Section A4.3. Instead, AE values from Table A9 were used to estimate the proportion of the diverted volume applied to the fields and the remainder of the diverted volume was classified as return flow. The proportion classified as return flow was used in calibrating the groundwater balance, which in turn determined the proportion of that return flow that contributes to aquifer storage or was returned to Lolo Creek via interflow or surface flow.

The main assumption with this method is that the ditches from which OIE were calculated are representative of the entire Water Balance Region. Although this is not always true, the results in Figure A19 and Table A10 show that the method does a better job of replicating diverted volumes for measured ditches. The constant OIE method used in this comparison is a common technique of using published efficiency coefficients to estimate the diverted volume based on crop consumption. For this comparison, the constant OIE (see Table A18 for values) was computed using the application efficiencies in Table A17 multiplied by the 62% regional conveyance efficiency empirically determined for Missoula County (USDA 1976). The more detailed monthly OIE values determined using measured diversions and remotely sensed *ET* produce noticeably better estimates. The constant OIE method tends to underestimate diverted volume for all ditches while the mean monthly OIE method overestimates some of the time but also underestimates some of the time, and by a much smaller margin than the constant OIE.

Figure A19. Graphs of diversion estimation results (orange dashed and green dotted lines) compared with measured diversions (blue solid line) for a) OZ Lolo Ditch, b) OZ South Fork Ditch, and c) McClay Ditch.

Table A10. Differences between estimated (using two methods) and measured diversions

Year	Error using mean monthly OIE (acre-ft)	Error using OIE = 0.43* (acre-ft)	Error using mean monthly OIE (cfs**)	Error using OIE = 0.43* (cfs**)
OZ Lolo Ditch				
2016***	-651	-1162	-1.53	-2.74
2017	-720	-1589	-1.70	-3.74
2018	-303	-940	-0.71	-2.21
2019	-1128	-1995	-2.66	-4.70
OZ South Fork Ditch				
Year	**Error using mean monthly OIE (acre-ft)**	**Error using OIE = 0.43* (acre-ft)**	**Error using mean monthly OIE (cfs**)**	**Error using OIE = 0.43* (cfs**)**
2016***	107	-376	0.25	-0.88
2017	391	-390	0.92	-0.92
2018	-324	-880	-0.76	-2.07
2019	86	-911	0.20	-2.15
McClay Ditch				
Year	**Error using mean monthly OIE (acre-ft)**	**Error using OIE = 0.42* (acre-ft)**	**Error using mean monthly OIE (cfs**)**	**Error using OIE = 0.42* (cfs**)**
2016***	-226	-3948	-0.53	-9.30
2017	106	-5541	0.25	-13.05
2018	-628	-5326	-1.48	-12.55
2019	761	-5810	1.79	-13.69

*This value is calculated via Application Efficiency for irrigation type (Table A9) multiplied by 62% to get a constant, Overall Irrigation Efficiency. Where multiple irrigation types existed, a weighted average Application Efficiency (based on the percent of acreage irrigated by each type) was used.
**Cubic feet per second constant discharge over 214 days of the irrigation season (April – October).
***2016 did not have a complete period of record, so the comparison for this year was done only for June through November.