Water Conservation Project Impacts on Streamflow in the Kremmling Area

lōtic hydrological

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1 Introduction

Water conservation projects on irrigated lands have the potential to alter the magnitude and timing of streamflows in waterways that are either sources of irrigation water or recipients of surface or groundwater return flows. Such is the case in the area around Kremmling, Colorado where Trout Unlimited and its partners initiated a project to assess the impacts of water conservation on consumptive water use quantities on local and regional streamflows. This project, titled 'Evaluating Conserved Consumptive Use in the Upper Colorado' (ECCU), applied irrigation reduction treatments to 1142.6 acres of irrigated pasture in 2020. Conservation actions were expected to impact both surface flows and groundwater flows. This report discusses data collection and analysis approaches employed in an effort to detect and quantify the impacts of the ECCU project on streamflows. This work described here is companion to a parallel investigation focused on quantifying the impact of conservation on consumptive water uses. The results presented here are, therefore, best considered within the context of the full body of work.

Evaluation of potential hydrological changes produced by water conservation activities requires understanding the quantity and timing of streamflow in the stream under 'normal' operations and changes along the reach due to a specific water conservation treatment. Split season or full-season fallowing of irrigated fields reduces surface water diversions and consumptive water use in across some or all of the irrigation season. The reduction in water application on irrigated fields is also expected to limit accrual of irrigation water to groundwater, attenuating or eliminating lagged groundwater return flows to down-gradient streams or rivers. Field-based channel water balance studies provide a potentially valuable approach to assessing such changes. However, this approach is challenged by the quality and resolution of data available for completing a water balance and by the signal noise created by inter-annual and inter-seasonal variability in climate, the actions of adjacent water users not participating in conservation projects, anisotropy in the physical characteristics of the soil column and aquifer underlying each irrigated parcel, and the unique arrangement of geographical (e.g., ditches or reservoirs) and geological features (e.g., springs or bedrock outcrops) on the landscape surrounding each treatment and control field.

The primary goal of the work described here was to demonstrate the opportunities and challenges associated with empirical and simulation approaches for evaluating local and regional impacts of water conservation projects on streamflows. This effort involved the following activities:

- Measurement of longitudinal streamflow patterns along reaches impacted by the ECCU project during a typical irrigation year and a year when conservation took place;
- Characterization of the uncertainty of field-based streamflow measurements at project sites and evaluating the impact of this uncertainty on the interpretation of the longitudinal patterns in streamflow discussed above; and
- Application of simulation tools and analytical methods for approximating the effects of the ECCU project on streamflows and lagged groundwater return flows.

2 Site Selection

Two study reaches, one on the Colorado River and one on Pass Creek, were selected for evaluation under this investigation. These reaches were selected due to their proximity to one or more irrigated parcels participating in the ECCU project. No monitoring was conducted on stream segments on Bull Run or Reeder Creek—alternate locations likely impacted by conservation actions under the ECCU project. The Colorado River and Pass Creek reaches represent useful bookends for the gradient of site characteristics that may be encountered at water conservation projects sites across the region. The Colorado River reach exhibits large flows relative to the quantity of water utilized for irrigation on adjacent fields, a large alluvial aquifer, and a comingling of fields participating and not participating in conservation actions. These attributes present significant challenges for any effort endeavoring to directly measure the impacts of water conservation on streamflow. Pass Creek, on the other hand, is small relative to the size of water diversions used for irrigation, the alluvial aquifer is likely limited in extent and depth, and the geographic arrangement of ECCU participating fields and the stream makes observation of irrigation/conservation practice impacts on streamflows/lagged groundwater return flows are much more likely.

Flow measurements were collected on the two reaches monthly from August to November in both 2020 and 2021 to maximize the likelihood of detecting the impacts of water conservation on lagged irrigation groundwater return flows. Individual streamflow measurement locations were selected in response to the conceptual model where lagged groundwater return flows drive an increase in streamflow downstream from irrigated fields. This difference between the downstream and upstream data collection points is defined here as net streamflow (Figure 1). The absence of surface water and groundwater returns to the stream should result in reduced or no increase in net streamflow during the late summer following water conservation.

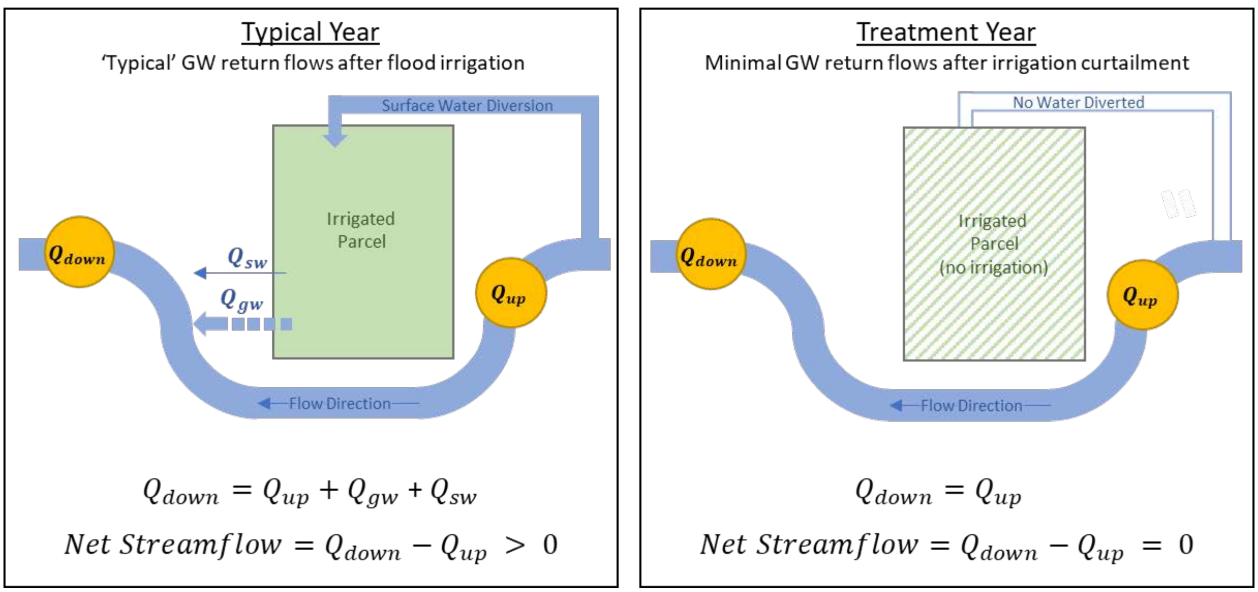

Figure 1. Expected impacts of water conservation on net streamflow during late summer and fall where Q_{up} indicates streamflow monitoiring location upstream from the participating field, Q_{down} indicates streamflow monitoring location downstream from the participating field, Q_{sw} indicates surface water return flows and Q_{gw} indicates groundwater return flows.

2.1 Colorado River Reach

The selected Colorado River reach extends six-miles above the confluence with the Blue River (Figure 1). The river along this segment flows through an unconfined valley. Irrigated fields fall on either side of the river. Two parcels along the reach participated in the ECCU project. The upper parcel (SBR-T1), a 70.3-acre hay field, underwent full season curtailment in 2020. The lower parcel (RSR-T1), a 123.3-acre hay field, underwent split-season curtailment—no water was applied to the field after June 15th, 2020. Other agricultural parcels situated along the reach did not participate in the ECCU project. Five discharge measurement sites were established along the Colorado River reach. Measurement sites extended from upstream of SBR-T1 to below RSR-T1 (Figure 1). The general arrangement of measurement sites intended to bracket the ECCU participating fields. The specific locations where streamflow measurements were collected reflects this intention to bracket and isolate impacts associated with the ECCU project and the availability of public access to the Colorado River throughout the reach.

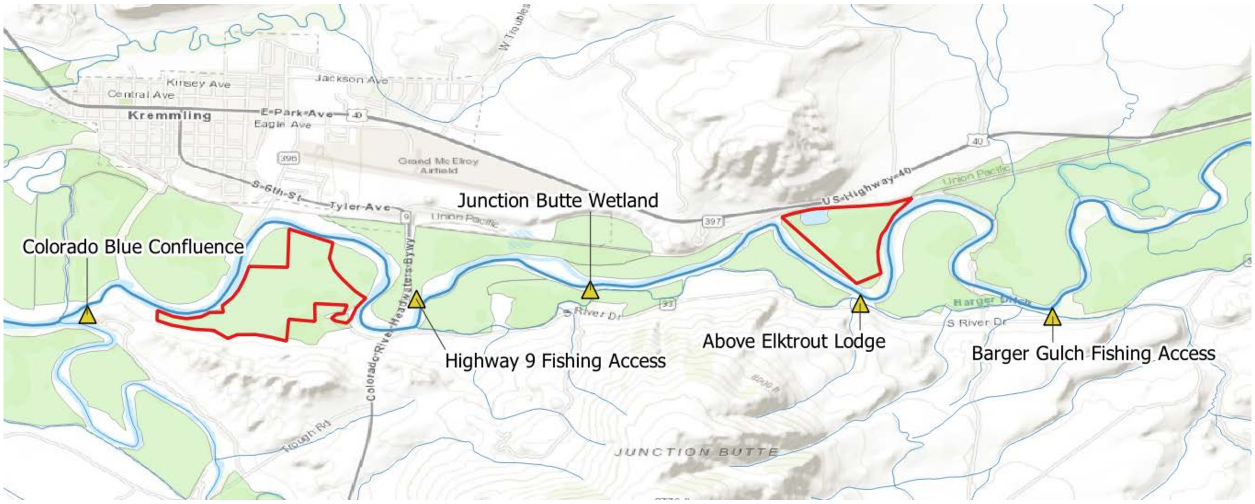

Figure 2: Map of discharge monitoring locations (yellow triangles) on the Colorado River. Red boundaries indicated treatment fields with irrigation curtailment in 2020. Green polygons are irrigated parcels in 2015 obtained from CDSS. Blue lines are flowlines including streams and ditches included in the National Hydrography Dataset. The Colorado River is indicated by a thicker line.

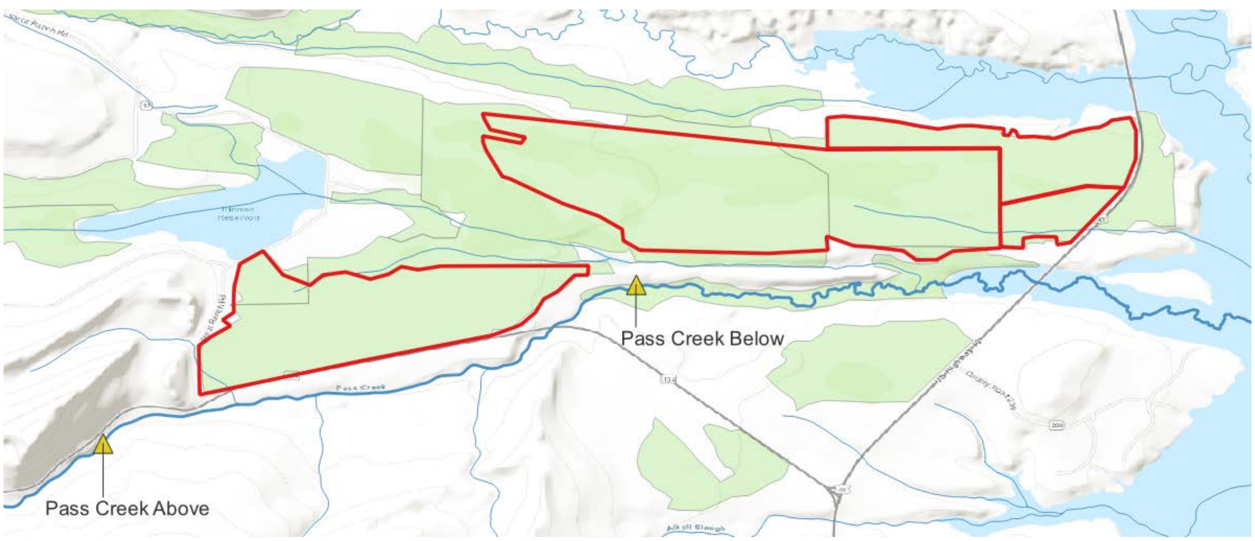

Figure 3: Map of discharge monitoring locations (yellow triangles) on the Pass Creek. Red boundaries indicated treatment fields with irrigation curtailment in 2020. Green polygons are 2015 CDSS irrigated parcels in 2015. Blue lines are flowlines including streams and ditches included in the National Hydrography Dataset. Pass Creek is indicated by a thicker blue line.

2.2 Pass Creek Reach

The selected Pass Creek reach is a two-mile segment flowing from McElroy Reservoir to a point below the Highway 134 road crossing. Pass Creek flows into Wolford Reservoir below the study reach (Figure 2). The reach is impacted by diversions and ditches that transport water across several drainage divides and supply water to neighboring irrigated parcels. Four ECCU project fields (GPR-T1, GPR-T2, BJM-T1, JLM-T1), situated to the north of the creek and totaling 595.9 acres, receive Pass Creek water. Irrigation water for treatment parcels is typically released from Hinman Reservoir, which collects water from Pass Creek Ditch and ditches on Red Dirt Creek. We understand that some irrigation of GPR-T1 is also source directly from Pass Creek Ditch, before it feeds the reservoir. Site reconnaissance suggests that surface return flows from the fields accrue to Red Dirt Creek or directly feed into Wolford Reservoir (Figure 4). Return flows from three of the participating fields are expected to accrue directly to Wolford Reservoir. Return flows from only one field (GPR-T1) are expected to accrue back to Pass Creek above the reservoir. Groundwater flow gradients were approximated from overlying surface topography. The slope and aspect of GPR-T1 suggest that a majority of groundwater flow may accrue back to Pass Creek near a swale downstream of the Highway 134 road crossing. Two discharge monitoring sites were established to bracket GPR-T1. The upper site was situated immediately below the Pass Creek Ditch diversion point. The lower site was established at the point of presumed groundwater return flow. GPR-T1 underwent full irrigation curtailment in 2020 and was returned to normal irrigation in 2021.

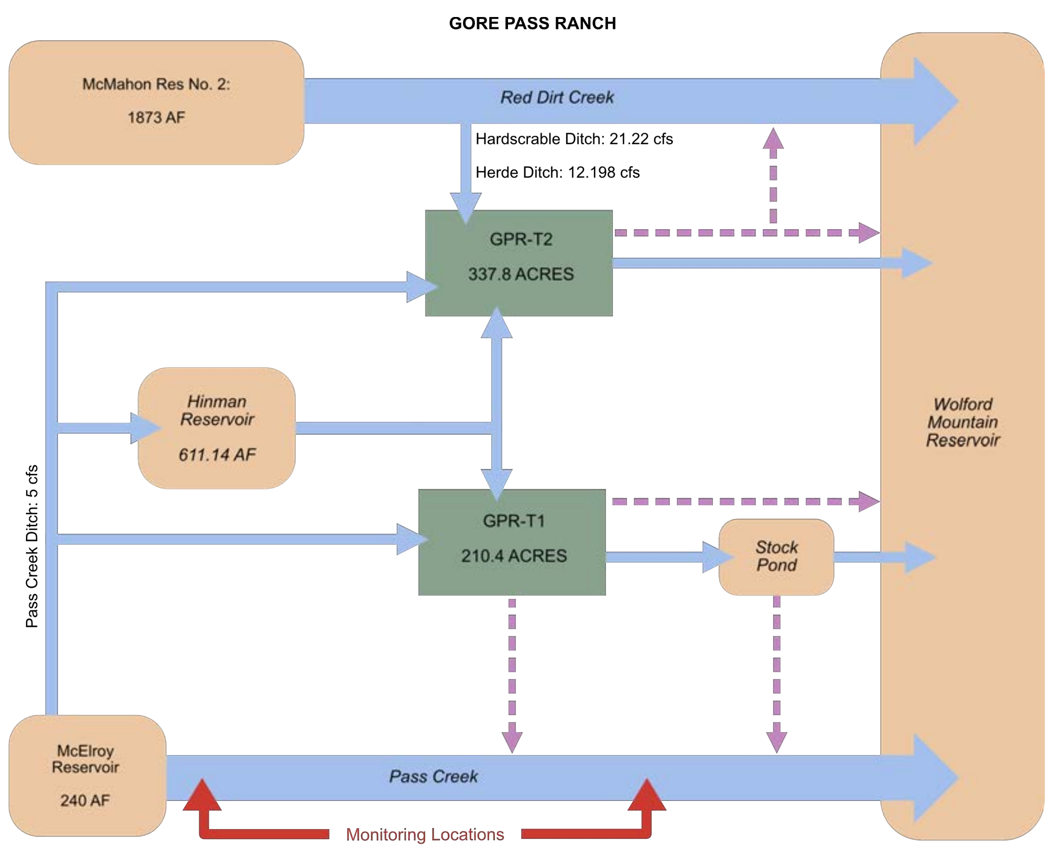

Figure 4. Schematic representation of water sources for GPR T-1 and GPR-T2. Fields participating in the ECCU project are symbolized in green rectangles; streams and ditches are indicated in blue lines, reservoirs as tan polygons; presumed location of return flows symbolized as purple dashed lines; the relative locations of streamflow monitoring stations are marked in red.

3 Methods of Investigation

Characterization of the impacts of ECCU conservation actions on streamflows in the Kremmling area required characterization of irrigation water application during the treatment year (2020) and a year of normal irrigation operations (2021), periodic streamflow measurements during the irrigation season on stream segments proximate to participating ECCU parcels, and use of simulation modeling tools to estimate soil water balances and groundwater return flow characteristics. Each method is described in detail in the sections below.

3.1 Longitudinal Streamflow Patterns

Discharge was measured monthly from August to November on the Colorado River and on Pass Creek in both 2020 and 2021. Discharge was measured in a quasi-synoptic fashion—all sites were visited on the same day during each field campaign. Measurement dates were targeted to maximize the likelihood of detecting the impacts of water conservation on lagged irrigation groundwater return flows in Pass Creek and the Colorado River.

Discharge measurements at Colorado River sites were obtained using a Teledyne StreamPro Acoustic Doppler Current Profiler (ADCP). The ADCP measures 2-dimensional cross-sectional profiles of streamflow velocities and cross-sectional area, enabling faster and more accurate streamflow measurements when compared to traditional measurement approaches. Between 5 and 15 cross-sectional measurements were collected at each measurement site on each sampling date. Measurements occurred in both the right-to-left and left-to-right direction. Streamflow measurements affected by obvious errors, such as those not representing full cross-sectional widths, were removed. Remaining measurements were processed with USGS's QREV software[1] to produce discharge estimates for each site visit. A median discharge was calculated for each site and date. ADCP streamflow measurement uncertainty was characterized using the QREV software. QREV produces an 'estimated 95 percent uncertainty' for a given site/day measurement that accounts for: the coefficient of variation across the multiple measurements; error associated with estimated unmeasured areas including edges and the top/bottom of the cross-section; and systematic uncertainty such as measurement device biases. USGS guidelines suggest that discharge measurements be rated using the 'estimated 95 percent uncertainty' on the following quality ranking:

- *Excellent*: <3% uncertainty
- *Good*: 3-5% uncertainty
- *Fair:* 5-9% uncertainty
- *Poor:* >8% uncertainty

Each estimate was assigned a measurement quality rating based on the USGS guidelines. ADCP streamflow measurement error was also assessed using statistical tests that consider the full distribution of discharge measurements collected at a single site on a single sampling day.

Longitudinal changes in streamflow along the Colorado River were assessed using a two-step process. Initially, statistically meaningful differences between measurements collected across the reach on a single sampling date were evaluated using a pairwise Wilcoxon rank sum test–a non-parametric test of differences. Where differences were detected on a given date, the magnitude of

[1] https://hydroacoustics.usgs.gov/software/QRev_Users.pdf

streamflow change between two sampling locations was assessed by comparing the median streamflow values produced for each location. Characteristic differences in longitudinal streamflow patterns between the treatment year (2020) and the reference year (2021) were assessed visually by plotting the percent change in the median streamflow values observed in a given month, moving from upstream to downstream. This approach makes the fundamental assumption that all differences observed in longitudinal streamflow within the reach in any given year are driven by regular irrigation activities on adjacent fields and not by antecedent soil moisture conditions, non-linear behavior in streamflow-groundwater interactions driven by changing river stage, inter-annual variability in watershed-scale environmental conditions, and/or upstream water operations. Furthermore, it is assumed that the irrigation patterns on non-ECCU fields adjacent to the assessment reach did not vary between 2020 and 2021.

Discharge measurements on Pass Creek were obtained using a Marsh-McBirney handheld flow meter. The stream was deemed too small to accommodate the ADCP. The velocimeter measurements were more time consuming and therefore only a single measurement was possible at a given site on each sampling date. As a result, no direct assessment of streamflow uncertainty was possible. Individual streamflow measurements are generally expected to have 5-20% error[2]. We choose to use here a static value of 20% uncertainty both to be conservative and because extremely shallow flow during the late summer months on Pass Creek made it difficult to completely submerge the velocimeter. A graphical comparison of discharge patterns on Pass Creek was used to assess upstream-downstream differences in flow between treatment year and the reference year. No statistical comparison of measurement results was possible due to the limited number of individual discharge measurements collected at each sampling location on a given date.

3.2 Observable Reservoir Impacts

Water conservation projects on irrigated lands have the potential to impact downstream reservoir operations through reducing consumptive use and changing the timing and magnitude of reservoir inflows. Observing impacts of these projects on reservoirs depends both on project outcomes and on exogenous factors such as watershed conditions and variability in interannual reservoir operations. An analysis was conducted to assess what, if any, discernable impacts 2020 irrigation curtailments had on operations at Wolford Reservoir.

Wolford Reservoir is located along Muddy Creek, 5 miles north of Kremmling. Wolford is operated by the Colorado River Water Conservation District (CRWCD) and stores up to a maximum of 66,000 acre-feet. Water in the reservoir is used to offset Front Range diversion impacts with water typically released later in the season to augment streamflow in Muddy Creek and the Colorado River for West Slope agricultural and municipal withdrawals and environmental flows.

Four project treatment fields including two at Gore Pass Ranch (GPR-1, GPR-2), Hill Ranch (HR), and Brian Mahon Ranch (BMR) site adjacent to Pass Creek and Red Dirt Creek, which both flow directly into Wolford Reservoir. The four project fields, totaling 665.8 acres, underwent full curtailment during the 2020 irrigation season (Table 1).

[2] Pelletier, P. M. (1988). Uncertainties in the single determination of river discharge: a literature review. Canadian Journal of Civil Engineering, 15(5), 834-850.

Table 1. Project treatment fields in the watershed draining to Wolford Reservoir.

Creek	Watershed Area (sq mi)	Percentage of Wolford Reservoir Drainage Area	Percentage of Wolford Tributary Drainage Area	Treatment Fields (acres)	Associated Water Rights[a]
Red Dirt Creek	36.6	13.6%	29.0%	HR (85.6) BMR (31.4) GPR T2 (345.7)	Herde Ditch* Hardscrable Ditch McMahon Res. No. 2 Sarvis Ditch
Pass Creek	25	9.3%	19.8%	GPR T1 (203.1) GPR T2 (345.7)	Pass Creek Ditch* McElroy Reservoir Hinman Reservoir Clark Ditch No.1* Oil Ditch*

*** indicates water right comments in CO-DSS indicated participation in 2020 irrigation curtailment**

Red Dirt Creek and Pass Creek are both ungauged and contain numerous diversion structures, ditches, small reservoirs and stock ponds. Watershed area and stream statistics for each creek were computed using USGS StreamStats[3]. Water right diversion records were obtained from the State of Colorado Decision Support System (CO-DSS)[4]. Only water right records associated with project fields were included in the analysis. Evapotranspiration (ET) records were obtained from gridded OpenET[5] datasets using monthly model ensemble ET estimates. Mean monthly ET (inches per month) was calculated for each project field. ET records used in this analysis are reported in the Evaluating Conserved Consumptive Use in the Upper Colorado 2020 Report[6]. Following the approach in the 2020 report, conserved consumptive use (CCU) was calculated for each month at each project field as the difference between ET in 2020 and the mean ET between 2016-2019. Total monthly and seasonal CCU yields were estimated as the product between monthly CCU and project field acreage.

CCU yields provide information about the expected total changes in water yield to Wolford from Red Dirt and Pass Creeks during the conservation period. However, CCU yields don't necessarily reflect the timing of water yield changes to Wolford due to several considerations. Streamflow used for irrigation is often diverted and stored in small reservoirs prior to field application and subsequent consumptive loss as ET. Irrigated water can also be stored as soil moisture prior to being lost as ET. Applied irrigation water not lost to ET may be rapidly shunted off the field as surface flow or may experience a lagged return to nearby waterbodies as groundwater. Under irrigation curtailment, the 'conserved' water is assumed to bypass diversions and rapidly reach the reservoir as streamflow. As a result, there is imperfect alignment between the timing of observed differences in ET signals and expected impacts on water yields to downstream reservoirs.

Water right diversion records were analyzed to identify the changes in diverted flows under 2020 irrigation curtailment. Monthly conserved diversion flows (CDF) values were calculated in a similar manner to CCU. CDF was computed as the difference between 2020 diversion flows and the mean of diversion flows in 2016 to 2019. Diversion flow records were examined for all known water rights associated with project fields. Reservoir release records for small reservoirs on Pass Creek and Red Dirt Creek did not align with the mass balance computed on downstream water diversions. This

[3] https://streamstats.usgs.gov/ss/
[4] https://dwr.state.co.us/Tools/Structures
[5] https://openetdata.org/
[6] Cabot, P.E., et al., 'Evaluating Conserved Consumptive Use in the Upper Colorado 2020 Report'. November 18, 2021. Accessed at https://www.waterinfo.org/wp-content/uploads/2021/12/Evaluating-Conserved-Consumptive-Use-in-the-Upper-Colorado-Basin_2020-Project-Report-00484067xC13E4.pdf

was likely due to a combination of unaccounted-for irrigation return flows, groundwater-surface water interactions, imperfect and infrequent measurements at reservoirs and other factors. As a result, we restricted the analysis to consider only ditches that removed water directly from the two creeks and that included comments in the CO-DSS record indicating participation in the water conservation project. Records at two ditches, including Clark No 1 and Oil Ditch, indicated 2020 irrigated curtailment but had no associated flow data for years between 2016-2020 and were excluded from the analysis.

CDF provides a qualitative metric reflecting the amount of water not diverted for irrigation that instead may have reached Wolford within a one-month window. The metric can only approximate changes in timing of flows to Wolford because it doesn't account for return flows under normal irrigation conditions. It does not account for the portion of diverted water that would still reach Wolford in the same month as surface return flows and/or rapid groundwater flow. Nor does it account for changes to lagged return of groundwater that may not occur under irrigation curtailment. The metric likely overestimates change in watershed yields during active irrigation periods. Conversely, the metric may also underestimate watershed yields during periods without active irrigation if lagged groundwater return flows are significant.

Neither CCU and CDF can account directly for the possibility of downstream water users making use of conserved water prior to water reaching Wolford. There are only a limited number of downstream users in both Pass and Red Dirt watersheds who did not participate in the irrigation curtailment. For this analysis, we assume that any conserved water was not diverted by these users.

Wolford reservoir operation records were obtained from CRWCD to qualitatively assess the impacts of the irrigation curtailments. Records include reservoir inflows, outflow, elevations and storage amounts. Outflows on Muddy Creek are measured at the USGS streamflow gage Muddy Creek below Wolford (#09041400) and reservoir elevation are measured at a USGS gage on the reservoir (#09041395). Reseroivr storage was calculated based on an existing elevation- storage capacity curve. A streamflow gauge above Wolford Reservoir is located on Muddy Creek above Antelope Creek (USGS # 09041090). Several ungauged tributaries join Muddy Creek below the gauge prior to the reservoir inflow and/or feed directly into Wolford. Inflows are therefore calculated by CRWCD through a mass balance approach using changes in storage capacity, outflow discharge and modeled reservoir evaporation.

Inflows are likely influenced by watershed conditions such as the magnitude and timing of snowmelt, summer precipitation and resulting streamflow. Therefore, it is helpful to assess Wolford operations in the context of how the 2020 hydrologic year compared to other years. Because the Inflow record at Wolford in 2020 may be impacted by the water conservation project, we compared the 2020 hydrologic year to other years using the unaffected Muddy Creek Above Antelope Creek stream gauge. Tributary flows were also calculated as the difference between Inflows at Wolford and measured streamflow at the Muddy Creek gauge. Tributary flows affected by the project were explored to identify what, if any, influence the project had on reservoir inflow.

Monthly flows in Red Dirt Creek and Pass Creek were also estimated by calculating the tributary inflows to the reservoir and then adjusting them using the proportion of drainage area of each watershed relative to the drainage area of all tributaries to Wolford (Eq. 1).

$$Q_{creek} = (Q_w - Q_m) * \frac{DA_c}{DA_w - DA_m} \quad (Eq.\ 1)$$

Where Q_w is the monthly inflow at Wolford, Q_m is the monthly flow at Muddy Creek above Antelope Creek, DA_c is the drainage area of the creek, DA_w is the drainage area at the Wolford outflow and DA_m is the drainage area above the Muddy Creek above Antelope Creek stream gauge. This calculation assumes that all tributary watersheds have equal contributions to streamflow (acre-feet exported per square mile are equal) and doesn't account for any differences in watershed characteristics like precipitation and runoff efficiency or any impacts of diversions and irrigation practices. Results at Pass Creek were compared to spot discharge measurements. Spot measurements were assumed to reflect monthly mean flow during the observed.

3.3 Soil Water Budget and Analytical Return Flow Modeling

Simulation tools and analytical methods were developed to better approximate the effects of the ECCU conservation actions on streamflows and lagged groundwater (GW) return flows (hereafter referred to as GW return flows) (Figure 5). The approach selected involved coupling a one-dimensional soil water balance model with an analytical solution for computing lagged groundwater accretions to nearby stream channels. The modeling system was parameterized with the best-available site level data and reasonable value ranges established in academic literature. Water conservation impacts on GW return flows were assessed by simulating a year of normal operations and comparing results to simulations mimicking curtailments under treatments. The modeling framework is described in detail in the sections below.

3.3.1 Soil Water Balance Model

Soil water balance modeling helped bound expectations for conservation's impacts on infiltration of irrigation water that otherwise would remain in the stream and deep percolation of water through the soil column that ultimately returned to rivers as GW return flows. A one-dimensional soil water balance model was constructed as a series of ordinary differential equations that simulated infiltration, percolation, and deep percolation to the groundwater based on input rates of irrigation and precipitation and consumptive loss rates based on total evapotranspiration.

The model simulates soil water fluxes through four soil profile layers within the rooting zone and a fifth vadose zone layer located below the rooting zone but above the groundwater level (Figure 6). The model partitions inputs as either infiltration into the top soil layer or as surface runoff. The rate of infiltration is dependent on the soil infiltration rate and available void space in the upper soil layer. Infiltrated water percolates through the soil layers when soil layer conditions are above field capacity (FC). Rates of percolation between layers are controlled by soil water content, physical soil conditions and saturated hydraulic conductivity (K_{sat}). When soil water is above FC, the following function models percolation for a given layer:

$$Percolation = SW_{excess} * \left(1 - \exp\left[\frac{-\Delta t}{TT}\right]\right) \quad (Eq. 2)$$

Where SW_{excess} is the drainable height of water, t is the length of the simulation timestep, TT is the travel time for percolation. The travel time for percolation is defined as:

$$TT = \frac{SAT - FC}{K_{sat}} \quad (Eq. 3)$$

Where SAT is the water height required to saturate the soil layer and FC is the water height at field capacity. The function results in the highest percolation rates when a soil layer is saturated. Percolation rates decline as the soil water content declines toward field capacity. Percolation rates are constrained by soil porosity (φ) and available void space in the next lowest layer.

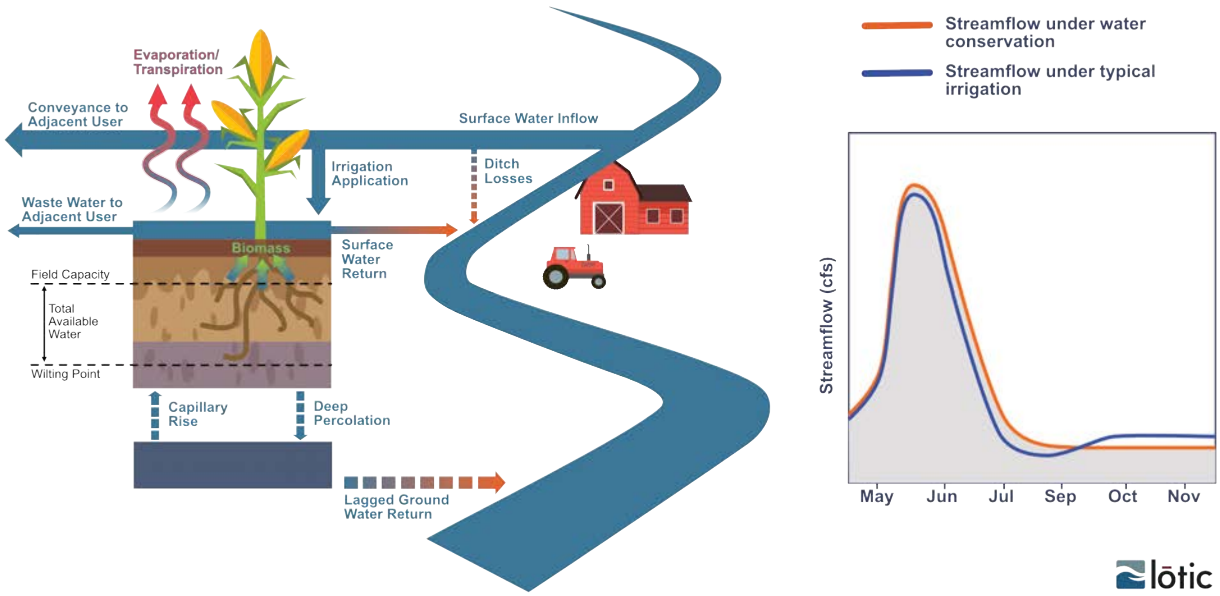

Figure 5: Conceptual diagram of the water balance and expected water conservation impacts to streamflow on project parcels.

Water losses to ET are partitioned through the soil column based on assigned rooting zone distributions between the four soil layers in the rooting zone. The model assumes that root densities are highest near the top of the soil profile and decline to the maximum rooting depth. Water losses to ET in each soil layer only occur when soil moisture in the layer is above the permanent wilting point (PWP). Water that percolates from the vadose zone is treated as deep percolation. Volumetric contributions to GW for a given timestep (t) are calculated as the deep percolation rate multiplied by the acreage of a project site.

Streamflow abstractions due to irrigation for t are also calculated to represent the magnitude of reduced streamflow along a reach due to irrigation. Daily streamflow abstractions are calculated as difference between daily infiltration and daily precipitation, multiplied by the acreage of a project site. This approach assumes no lag time between the time of diversion and the time of infiltration and that surface water return flows return instantaneously to the river.

The model requires several key simplifying assumptions: no lateral water fluxes within the soil column, the groundwater table is below the modeling boundary at all times, and capillary rise from the GW table does not contribute meaningfully to soil moisture in the water column. The model also makes use of daily timeseries of input fluxes including precipitation, irrigation, and evapotranspiration records. These fluxes are supplied to the model as daily averages and, therefore, do not reflect any sub-daily variability.

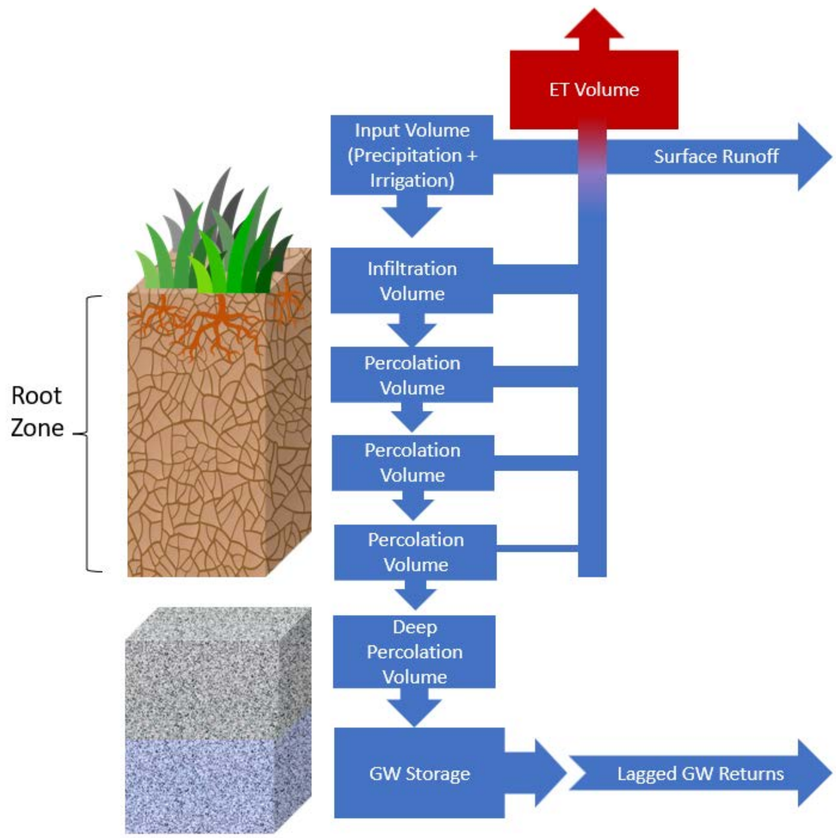

Figure 6: Coupled Soil Water Balance and Lagged Ground Water Model Compartments and Fluxes.

Model simulations run at an hourly timestep using the 4th order Runge-Kutta solver found in the *deSolve* R package. The solver is implemented with an event function that enforces that model state variables do not fall below zero. Simulated groundwater inflows were aggregated to weekly values for use by the analytical GW return flow solution.

3.3.2 Lagged Groundwater Return Flow

Volumetric GW contributions simulated by the soil water balance model were lagged back to a proximate water body using the analytical solution developed by Glover and Balmer (1954) and subsequently modified by Knight et al. (2005). The solution used to calculate GW return flows to a stream is based on reversing the sign of the formulation of the model commonly utilized by CDWR to estimate stream depletions due to well pumping. The model is also commonly used to approximate accretions to streams sourced from infiltration galleries or off-channel ponds. The solution adapted for this project deviates slightly from the original formulation proposed by Glover and Balmer (1954). Our solution utilizes an infinite series of paired image wells to approximate the effect of an impermeable alluvial valley boundary as follows:

$$RF(t) = \left\{ erfc\left(\frac{a}{2(Dt)^{1/2}}\right) + \sum_{n=1}^{\infty} (-1)^{n+1} \left[erfc\left(\frac{2nc - a}{2(Dt)^{1/2}}\right) - erfc\left(\frac{2nc + a}{2(Dt)^{1/2}}\right) \right] \right\} \quad (Eq. 4)$$

Where *RF* is the fractional return flow at time *t*, *a* is the distance from the recharge point source (generally the centroid of the irrigated area) and the river, *c* is the distance from the stream to the valley boundary and *D* is the hydraulic diffusivity of the aquifer. The hydraulic diffusivity is calculated as (K*aquifer thickness) / Sy where *K* is the aquifer saturated hydraulic conductivity and *Sy* is the aquifer specific yield. The first 20 well images are used with additional terms dropped as their contributions are assumed insignificant. The solution used here makes a number of key assumptions:

- The rate of horizontal flow is much greater than the rate of vertical flow (i.e. Dupuit assumptions hold);
- The aquifer is homogeneous and isotropic;
- Aquifer is either confined or, if unconfined, the change in head between the structure and the stream is small relative to the overall aquifer thickness;
- The stream is straight, infinitely long, and remains in hydraulic connection to aquifer;
- Stream stage is constant;
- Return flows are unaffected by well pumping;
- There is no storage of water in the streambank;
- Recharge rates are constant across any given time step;
- The aquifer extends to valley margins;
- The stream fully penetrates through aquifer; and
- There is no streambed resistance to flow.

The analytical solution detailed in *Eq. 4* computes a fractional return flow at time step *t* for a constant groundwater recharge rate of infinite duration. Calculation of total accretion volume at time t_n is a simple matter of multiplying the fractional return (*RF*) at time t_n by the groundwater recharge rate (*GW*). Groundwater contributions from irrigation are not constant through time. Application of the *Eq. 4* solution to the time-varying groundwater contributions supplied by the soil water balance model required an approach capable of accommodating periods of intermittent flow and changing groundwater recharge rates. A unit response function approach was used to estimate fractional accretion across an extended series for a groundwater recharge impulse of 1.0 that occurred across the interval [t_0, t_7]. The function that models the impulse response (*IR*) to at time *t* is structured as follows:

$$IR(t)dt = \begin{cases} RF(t)dt & for\ 0 < t \leq 7 \\ RF(t)dt - RF(t-7)dt & for\ 7 < t < \infty \end{cases} \qquad (Eq.\ 5)$$

Where RF is the solution generated from *Eq. 3* at time *t.* Outputs from *Eq. 5* were summed on a weekly time step and normalized such that the cumulative total of the infinite IR series equaled 1.0. The result was a weekly unit response function (*WUR*) that was used to estimate the streamflow accretion response (*SAR*) of an intermittent weekly groundwater recharge signal as follows:

$$\begin{bmatrix} GW_{t_1} \\ GW_{t_2} \\ GW_{t_3} \\ \vdots \\ GW_{t_n} \end{bmatrix} * \begin{bmatrix} WUR_{t_n} & WUR_{t_{n+1}} & \cdots & WUR_{t_{n+\infty}} \end{bmatrix} = \begin{bmatrix} SAR_{t_1} & SAR_{t_1+1} & \cdots & SAR_{t_1+\infty} \\ SAR_{t_2} & SAR_{t_2+1} & \cdots & SAR_{t_2+\infty} \\ SAR_{t_3} & SAR_{t_3+1} & \cdots & SAR_{t_3+\infty} \\ \vdots & \vdots & \cdots & \vdots \\ SAR_{t_n} & SAR_{t_n+1} & \cdots & SAR_{t_n+\infty} \end{bmatrix} \qquad (Eq.\ 6)$$

Summing along the columns of the matrix produced by *Eq. 6* yields a time series of volumetric streamflow accretions. The complete model was coded in the R statistical computing language[7], an approach that facilitated parameter sensitivity and uncertainty analyses and the generation of graphics that convey model results in an intuitive visual form.

3.3.3 Model Inputs

Parameterization and implementation of the coupled modeling approach required estimation of parameters for both the soil water balance model and the analytical groundwater model. The soil water balance models were parameterized based on available geospatial, field, and remotely sensed datasets at each treatment parcel and from publicly available related GIS datasets and academic literature.

Initial estimates for physical and hydraulic characteristics of the soils present at each site were initially obtained from the NRCS Web Soil Survey[8]. Physical soil properties including infiltration rate, saturated hydraulic conductivity in the soil (K_{sat}), soil porosity (φ), field capacity (FC), and permanent wilting point (PWP) were estimated from NRCS Web Soil Survey and NRCS soil group classifications and then refined using observation of field data. Daily precipitation records were obtained from the Kremmling Airport weather station[9]. Daily evapotranspiration totals were identified for each parcel using zonal average ET rates estimated by OpenET using the eeMetric model[10].

Irrigation water application on RSR-T1 and SBR-T1 during 2020 and 2021 was approximated using a combination of qualitative and quantitative data sources. Local water users indicated that parcels along the Colorado River typically utilize flood irrigation techniques whereby fields are ponded with water upwards of 2ft deep during a 10-day to two-week period in the early summer. Diversion records from the Colorado Division of Water Resources (CDWR) do not appear to adequately capture the timing and duration of water application where this technique is used. Instead, we verified verbal descriptions of water application provided by landowners with groundwater well and soil moisture probe measurements provided by other ECCU team members.

It is important to note that irrigation application characteristics on fields located between RSR-T1 and SBR-T1 were not evaluated as part of this effort. We expect that these fields received typical irrigation during the 2020 and 2021 seasons. Many of these fields likely utilize similar irrigation water application techniques to the ECCU participating parcels. However, the Barger Ditch may also provide a more consistent irrigation water supply to one or more field across the irrigation season. The ditch runs parallel to the river, beginning above the Barger Gulch Fishing Access and flowing along the southern boundary of the fields to the south of the river, terminating just below the Highway 9 Fishing Access.

Patterns of water application on GPR-T1 were also difficult to characterize using CDWR diversion records. Discussions with project coordinators and a former water commissioner indicate that water is supplied to the field from a mix of sources. Some water is sourced directly from Pass Creek via the Pass Creek Ditch. Some water conveyed through Pass Creek Ditch is also stored in Hinman Reservoir. Ditches on Red Dirt Creek also supply water to Hinman Reservoir. Water from the

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[7] https://www.r-project.org
[8] https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm
[9] https://mesonet.agron.iastate.edu/sites/site.php?station=20V&network=CO_ASOS
[10] https://openetdata.org/

reservoir is released to provide irrigation water for GPR-T1 and other nearby fields. No records of the timing and quantity of these reservoir releases were recovered by this project. Instead, we relied on soil moisture probes installed at a single location on GPR T-1 to approximate irrigation application timing and duration.

Most treatment parcels had records of volumetric soil water content (VWC, %) collected from soil moisture probes installed at a single location at depths of 6, 18, 30, and 42 cm (Table 2). In-situ soil moisture records, where present, were used to identify the timing and duration of irrigation. Irrigation duration was assumed to match periods when VWC plateaued for multiple days at a high value in the upper most soil layer (6 cm). Ponding of up to 2 ft in depth was assumed to occur on sites along on the Colorado River, including RSR-T1 and SBR-T1, during irrigation periods[11]. Irrigation application depths for GPR-T1, GPR-T2, and SPR-T1 was set at 0.176 ft/day, following a verbal description of irrigation application techniques at GPR-T1 by the ranch manager. The irrigation period and application rates for RCR-T1were estimates based on conversations with the landowner[12]. No soil moisture records exist at RCR-T1, JLM-T1, HSR-T1, or BJM-T1. At these locations, irrigation periods and rates were set equal to nearby parcels where soil moisture data was collected.

The modeling approach assumed that the entire field was irrigated during the identified inundation phase[13]. Water infiltrated into the soil column moved through the underlying soil horizons. Water content in excess of the PWP could be abstracted by ET and deep percolation. Partitioning of ET through the soil horizons was based on fractional root densities in each horizon. Rooting zones were assumed to be 3ft deep at all parcels. The fractional density of roots in each horizon was treated as a tuning parameter in the model since no observed data characterizing rooting depths or densities was available.

No observed data characterizing aquifer transmissivity exists for any of the study sites. Aquifer transmissivity was estimated as the product of saturated hydraulic conductivity in the aquifer (K_{sat}) and aquifer thickness. Values for K_{sat} were set to range between 1-1000 m/day. Low-end values reflect movement of water through fine sand, while rates at the high-end reflect water movement through clean gravel. Aquifer thickness was estimated for each site to range between 10 – 30m. The specific yield (Sy) of the aquifer at each site was allowed to vary between 0.2 and 0.3.

The distance between the point of recharge and the stream was approximated by measuring the perpendicular distance between the centroid of the field and the adjacent streambank of the most proximate water body where groundwater was likely to flow. Groundwater return flows on HSR T1 and JLM T1 were set to accrue directly to Wolford Reservoir. The width of the alluvial aquifer was estimated by measuring the distance between the proximate water feature and visually identifiable valley-margin geomorphological features. All measurements were carried out in a GIS.

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[11] 1ft/day irrigation rate was selected to ensure that the infiltration is not limited by water availability in the model space during irrigation periods. This rate may substantially overestimate the total cumulative volume of applied water since water is ponded by plugging the return flow ditches which helps maintain ponding by reducing surface return flows.

[12] Personal communication with Paul Bruchez: RCR T2 is irrigated under normal operations with an estimated 2 cfs of flow with irrigation durations of 3-4 days followed by a dry period of 8-10 days. Four cycles of irrigation occur from mid-May through late June and two cycles occur from early August through mid-September.

[13] Several parcels including GPR T1 and GPR T2 are irrigated in sets based on discussions with ranch managers, however the soil moisture data indicates a single prolonged inundation period. Due to uncertainty in actual irrigation rates, unknown spatial patterns of irrigation and limitations of the model, these sites were modeled as having a prolonged inundation period rather than periodic irrigation cycles. The irrigation rate was calculated based on a presumed 18 cfs application to the entire GPR T1 parcel.

Table 2: Irrigation, Soil and Aquifer Physical Parameters at Treatment Parcels

Parcel	Treatment Type	Parcel Size (ac)	Soil Moisture Data	Pattern Site	Irrigation Rate (ft/day)	Irrigation Type	Proximate Water Body	Downstream Water Body	Infiltration Rate (ft/day)	Soil Column K_{sat} (ft/day)	Soil Series (Soil Group)	Centroid Distance to Water Body	Stream distance to valley margin
BJM T1	Full	32.1	No	GPR T2	0.176	Flood	Wolford Reservoir	Wolford Reservoir	0.3	0.2	Harsha Loam (Group B)	320 ± 25%	800 ± 25%
GPR T1	Full	202.6	Yes	-	0.176	Flood	Pass Creek	Wolford Reservoir	0.3	0.2	Harsha Loam (Group B), Binco Clay (Group C)	500 ± 25%	800 ± 25%
GPR T2	Full	345.9	Yes	-	0.176	Flood	Unnamed tributary to Pass Creek	Wolford Reservoir	0.3	0.2	Harsha Loam (Group B), Binco Clay (Group C)	675 ± 25%	1000 ± 25%
HSR T1	Full	86.5	No	GPR T2	0.176	Flood	Wolford Reservoir	Wolford Reservoir	0.3	0.2	Harsha Loam (Group B)	250 ± 25%	800 ± 25%
RCR T2	Split Season	7	No	-	0.56	Flood	Colorado River	Colorado River	2	10	Tina Cobbly Sandy Loam (Group A)	250 ± 25%	1100 ± 25%
RSR T1	Split Season	125.5	Yes	-	1	Flood (with ponding)	Colorado River	Colorado River	0.15	0.1	Cumulic Cryaquolls (Group A/D)	300 ± 25%	900 ± 25%
SBR T1	Full	69.2	Yes	-	1	Flood (with ponding)	Colorado River	Colorado River	0.17	0.23	Cumulic Cryaquolls (Group A/D)	350 ± 25%	500 ± 25%
SPR T1	Full	220	Yes	-	0.176	Flood	Bull Run	Williams Fork Reservoir	0.3	2	Anvik Loam (Group B)	200 ± 25%	500 ± 25%

3.3.4 Model Calibration

The model calibration procedure for each field involved manual adjustment of numerous model parameters until a visual best fit between simulated and observed VWC was achieved at differing profile depths (Figure 7). Comparisons at all sites could only be made for the top two modeled soil layers as soil moisture probes did not extend deeper into the soil profile.

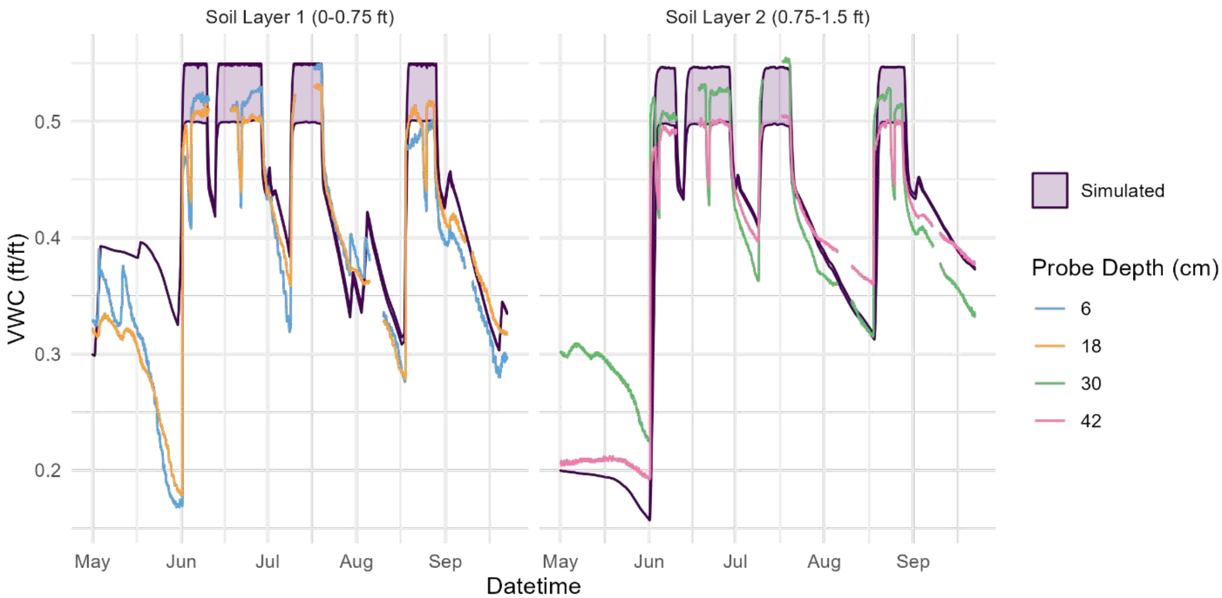

Figure 7: Observed vs simulated volumetric soil water content at SBR T1 for the top two soil layers in the soil water balance model. Probe depth was not deep enough for comparison with deeper soil layers in the model. Simulation envelopes (purple shaded area) reflect uncertainty in physical soil parameters including infiltration and saturated hydraulic conductivity.

Porosity, FC and PWP were parameterized individually for each soil layer in the model while a single K_{sat} was used for all soil layers. Soil column K_{sat} values were refined by comparing simulation outputs to the slopes of VWC declines during the free draining periods after the cessation of irrigation. Porosity was identified from the value at which VWC plateaued during periods of inundation when soils were likely fully saturated. Field capacity was identified visually during the falling period after irrigation cessation as the VWC where nighttime declines in VWC neared zero. PWP was estimated visually as the VWC where the overall slope in VWC declined to near zero. Several treatment sites lacked corresponding field soil moisture records. These sites were parameterized based on parameter sets developed for the most similar treatment parcel with observed soil moisture, from available geospatial datasets, and from literature values. Simulation outputs from the soil water balance model were generated using a Monte Carlo simulation that utilized an estimated set of parameters but then allowed K_{sat} and infiltration rate to vary by ±25%.

Limited information exists about the properties of the alluvial aquifer at the treatment sites. Critical parameters such as aquifer transmissivity can range multiple orders of magnitude and no field data was obtained that helped constrain or validate aquifer parameters. The analytical groundwater model therefore also employed a Monte Carlo simulation approach that allowed values of aquifer properties to range across the ranges described in the previous section and in Table 2. No effort was made to generate a single 'best' parameter set for any given field. Rather, lagged groundwater return flow envelopes were evaluated as the product of equally likely parameter sets.

3.3.5 Simulation Configurations

Soil water balance and GW return flow simulations were carried out sequentially for each treatment parcel. Multiple simulations (n=50) were performed using a Monte Carlo sampling approach to generate a time series of volumetric streamwater abstractions and groundwater contributions. During each simulation, soil column K_{sat} and infiltration rate were randomly sampled from uniform distributions that spanned their respective ranges. The ensemble of simulated groundwater contributions was then used as input to the GW return flow model. Multiple simulations (n=1000) were subsequently performed with the GW return flow model using a similar Monte Carlo sampling approach where parameter values for aquifer hydraulic characteristics were allowed to vary across uniform distributions of their respective ranges. The larger simulations set used for the GW return flow model intended to reflect the much higher degree of uncertainty in those model parameters.

Each groundwater return flow simulation included a nine-year warmup period. Inclusion of a warm-up period enabled conditions to reach an equilibrium condition prior to assessing conditions under normal irrigation activities and/or after application of the water conservation treatment. GW return flows were simulated for normal year of operations at all parcels. A second set of model runs simulated the split-season irrigation curtailment enacted in 2020 at RSR T1 and RCR T2. No simulation was conducted for treatment fields subjected to full-season curtailment because field monitoring indicated that without irrigation, soil moisture rarely, if ever, exceeded field capacity during the summer months. In these circumstances, no water is expected to be abstracted from the stream nor is water expected to percolate to the aquifer or return to the stream as lagged groundwater returns. Modeling was not carried out to evaluate impacts on GW return flows from normal irrigation operations in a year following water conservation. The lagged impact of a water conservation on subsequent years' return flows is likely greatest where aquifer transmissivity is low. However, exploring such lagged impacts was beyond the scope of this effort.

The magnitude and timing of the impacts of water conservation activities on steamflow abstraction and groundwater return flows to streams was assessed by comparing simulation results under 'normal' irrigation operations year in 2021 with expected (full-season curtailment) and/or simulated results (split-season curtailment) under irrigation curtailment[14]. Treatment effects are calculated as the differences between the 'treatment' and 'normal' results. This calculation assumes that without the applied treatments, hydrologic and irrigation patterns on treatment fields in 2020 would have been equivalent to the conditions simulated under 'normal operations' which is based on conditions in 2021 (or 2022 at SPR-T1).

4 Results and Discussion

A primary goal of this investigation was to evaluate the utility of direct measurements for assessing the impacts of field-scale water conservation activities on local and regional streamflows. The field based and simulation modeling results produced from investigations of longitudinal streamflow

[14] SPR-T1 was simulated using 2022 data as the 'normal year' because there was no evidence of irrigation in 2021 in the soil moisture record likely due to water limitation at the parcel.

patterns and the differences observed in those patterns between the treatment year and the reference year on the Colorado River and Pass Creek provide some insights relevant to that goal.

4.1 Streamflow Field Observations

Longitudinal patterns in streamflow on the Colorado River reach were variable between measurement months and between years, as anticipated (Figure 4). We expect that some of this variability is driven by measurement error and some is driven by real differences in upstream-downstream streamflows. Nevertheless, no statistically significant differences in streamflows were detected across the reach during the relatively high flow period in August of 2020 and again during low flow period in October and November of 2021. Statistically significant differences in streamflow were detected between sites during other study months. The lower three sites were significantly different from both of the upper sites in September, 2020. Some or all of the lower three sites were not significantly different to one or both of the two upper sites, in October-November, 2020. August of 2021 followed a similar pattern, except that the upper site at Barger Gulch had the highest streamflows of any site. September, 2021 had a distinct pattern: significantly lower flows were observed at the Junction Butte Wetland but no significant differences were observed between the other four sites. Longitudinal patterns in median discharge in October and November of 2021 were similar to the same months in 2020 but the differences between sites were not statistically significant.

The general pattern of decreasing flows between Barger Gulch Fishing Access and Above Elktrout Lodge and then rebounding flows below that location is evident across both years and in most sampling months. This pattern may reflect localized groundwater exchange where significant amounts of streamflow move along subsurface pathways (e.g. gravel lenses in relict meander bend features) beneath SBR-T1, effectively bypassing the Elktrout Lodge measurement site. Alternatively, local site conditions may have produced a consistent bias toward lower streamflow measurements at the Above Elktrout Lodge site.

The observed longitudinal streamflow patterns on the Colorado River reach do not indicate treatment impacts driven by conservation program participation. While there were some significant streamflow changes bracketing the SRB-T1 parcel (between Barger Gulch and Junction Butte Wetland), the most reliable signal of increasing flows below the treatment field—a signal consistent with lagged groundwater return flow contributions—appeared in 2020 when conservation was taking place. That same signal was only evident in August of 2021. No statistically meaningful increase in streamflows was observed late in the 2021 irrigation season below SRB-T1. Streamflow measurements at the Hwy. 9 Fishing Access and the CO-Blue Confluence, sites intended to capture impacts of the RSR-T1 treatment parcel, yielded no statistically significant differences in any of the observed months. Even if the statistical significance of measured differences in flow are disregarded, the longitudinal pattern in median streamflows throughout the Colorado River reach suggests a stronger effect of lagged groundwater returns in the treatment year (Figure 9) rather than in the reference year—a counterintuitive result. Differences in patterns of irrigation on non-participating parcels and/or ditch diversions between 2020 and 2021 may confound inference into treatment effects. Differences in soil moisture conditions at the beginning of the 2020 and 2021 irrigation seasons may similarly confound results.

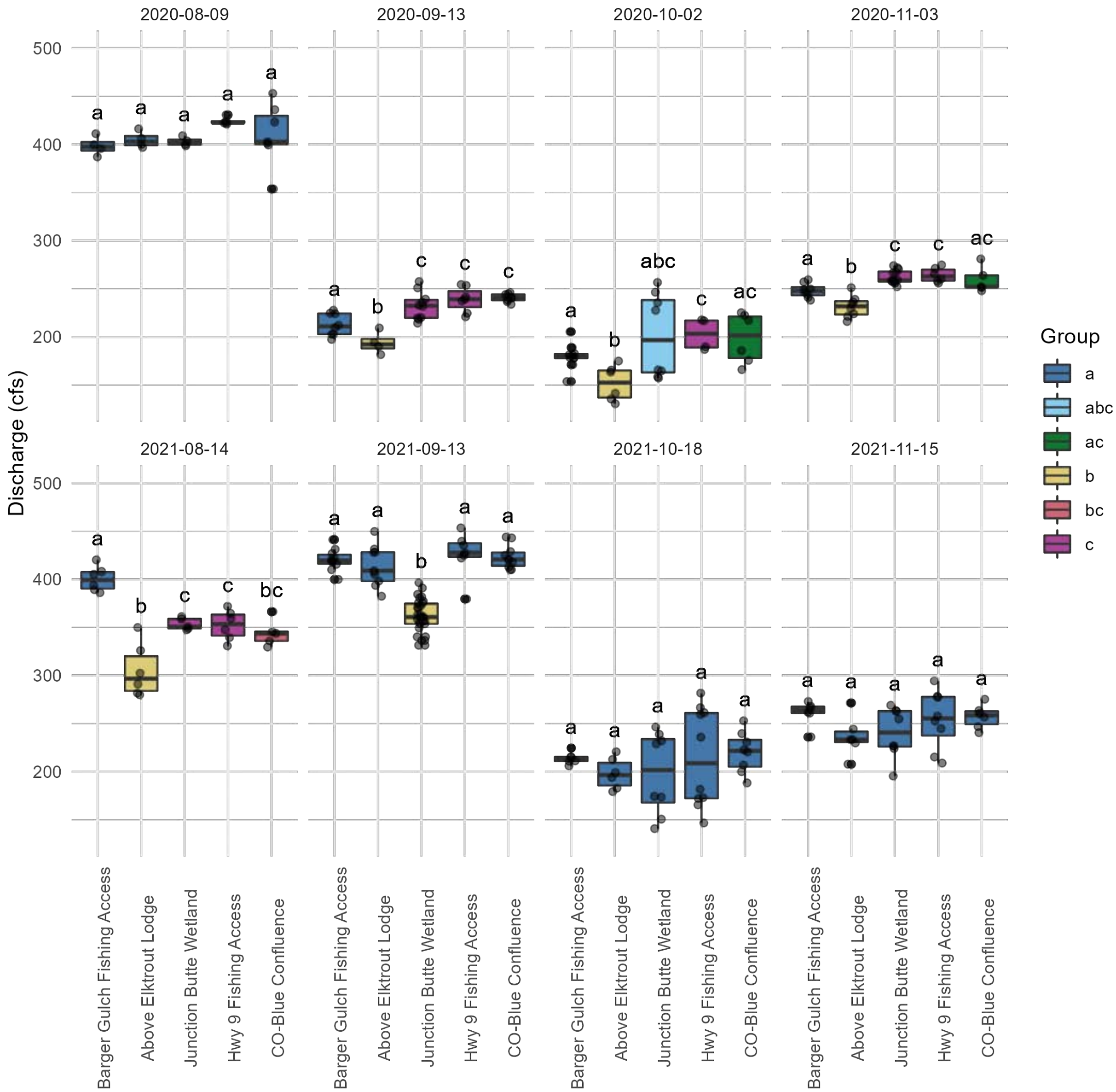

Figure 8: Longitudinal patterns in Colorado River streamflow by measurement date. Boxplots and points represent the distribution of dischage measurements collected at that site/date using the ADCP. Boxplots are colored and labeled with letters based indicating significantly different groupings identified with a pairwise wilcoxon rank sums tests for a given set of measurements. Distinct groups are given single letter codes (e.g., 'a' or 'b'). Multiple letter codes (e.g., 'abc') indicate cases where a set of measurements could not be differentiated from several other groups.

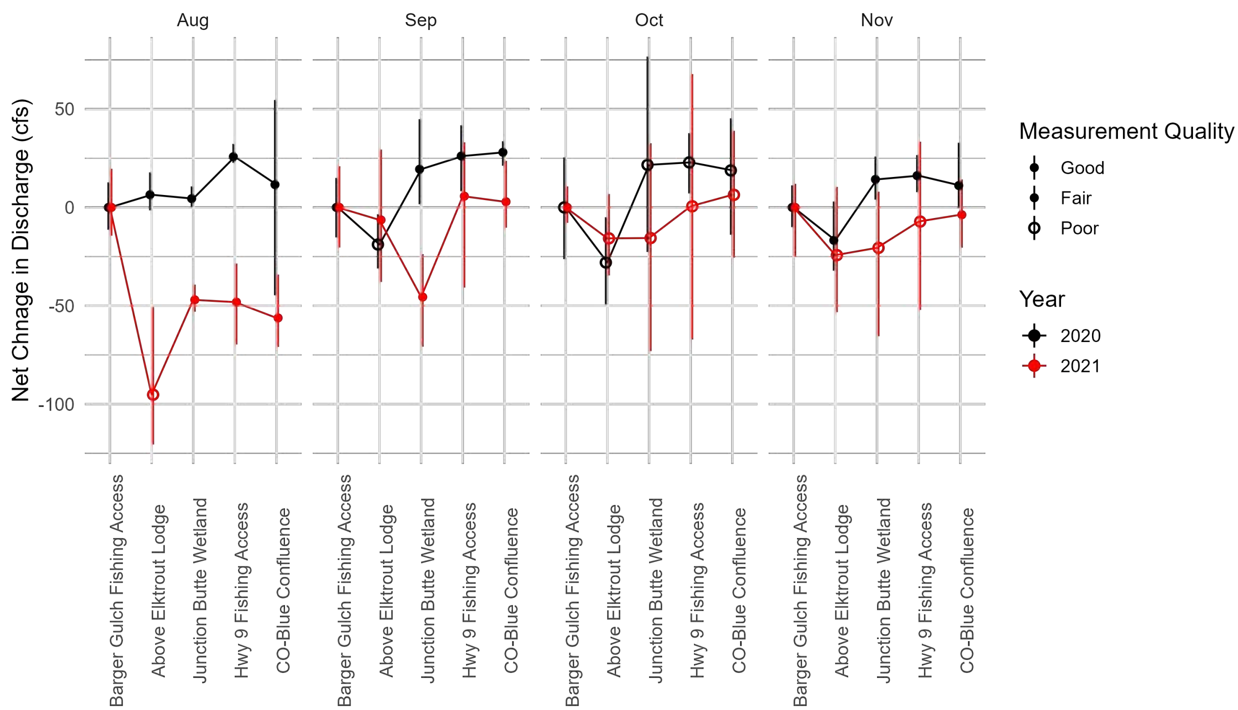

Figure 9: Net changes from the upstream site in Colorado River median streamflow estimates by month and year. Points represent deviations in median streamflow from a given site relative to the median streamflow estimate at the uppermost site on the reach (i.e., Barger Gulch Fishing Access). Vertical error bars represent the range of measurement results produced at each site. Filled circles indicate Good or Fair measurement quality ratings while open circles were rated as Poor.

Streamflow measurements at the two locations on Pass Creek were significantly challenged by the extremely low flows in the creek observed during both 2020 and 2021. In both years, the Pass Creek Ditch diversion point swept the stream immediately below McElroy reservoir. Flows in the creek at the upper measurement point were determined to be approximately zero. However, saturated conditions and ponding in a beaver complex downstream of the measurement site persisted in both years. Therefore, streamflows observed at the lower site might reflect a combination of surface and groundwater flows affected by irrigation on the GPR-T1 treatment parcel and the hydrology of the beaver complex on Pass Creek. Flows at the lower Pass Creek measurement location were ≤ 1.0 cfs on all measurement dates in 2020 and 2021. This flow rate produced very shallow water depths (~0-3 inches) in the creek bed. Shallow flows may have affected the accuracy of the velocimeter. Flows measured at the lower site were higher for all months in 2020 than in 2021 (Figure 10).

If we assume that the flows on upper Pass Creek are near zero, then the longitudinal differences observed in both years are consistent with the expectation of lagged groundwater return flow contributions. November streamflows between the two years were not substantially different given our assumption of 20% measurement error. The upstream-downstream difference in streamflows appears greater in the year when water conservation occurred than in the reference year when GPR-T1 underwent normal irrigation. This counterintuitive result is similar to the results produced for the Colorado River reach. We speculate that this could be related to several different possible factors including: differences in climatic conditions such as summer and fall precipitation;

groundwater return flows that may be lagged for more than several months; and/or differences in management of irrigation water on adjacent fields between the two years. An additional limitation of our study is that the assumption that surface topography effectively mirrors underlying groundwater gradients and that our measurement location on lower Pass Creek would capture and isolate irrigation return flow signals from GPR-T1. If this assumption does not hold, we cannot be certain that our measurement location is appropriate. It is possible that groundwater flows from the treatment parcels return to the river below the lower measurement point and/or may accrue directly to Wolford Reservoir. Similarly, groundwater flow from adjacent fields undergoing normal irrigation and assumed to accrue to Red Dirt Creek may actually accrue to Pass Creek, confounding our results.

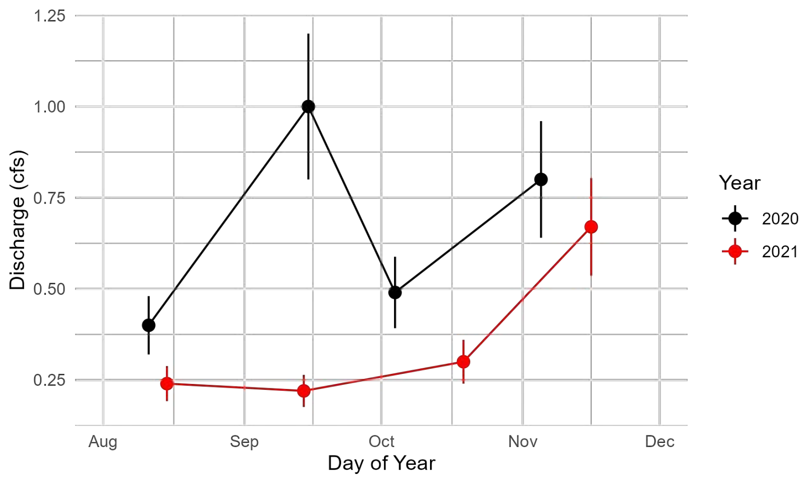

Figure 10: Patterns in 2020 and 2021 streamflow at the lower site at Pass Creek. Points indicate single discharge measurements and error bars reflect assumed 20% measurement error. No other quantitative or qualitative measurement quality ratings are available for these measurements.

Project results generated for the Colorado River reach and Pass Creek reach suggest that the upstream-downstream channel water mass-balance approach described here has limited capacity for identifying the impacts of irrigation curtailment on local streamflow patterns. We attribute the limitations of this approach primarily to 1) streamflow measurement uncertainty, 2) uncontrollable confounding variables, and 3) a high degree of uncertainty in aquifer characteristics and groundwater flow behavior. Each of these is discussed in turn below.

Uncertainty in measured streamflows can decrease the ability of statistical tests used to detect upstream-downstream differences in flow as it may be affected by conservation actions. Uncertainty associated with measurements collected on Pass Creek could not be assessed directly from the data but previously-noted challenges related to extremely shallow flows are expected to affect measurement accuracy and precision. The estimated 95% uncertainty for median discharge estimates on the Colorado River ranged from 3.3% to 18.4%. Estimated uncertainty was highest at lower flows with most measurements receiving a 'Poor' rating when discharge dropped below ~200 cfs (Figure 11). This may be particularly problematic in situations where the magnitude of return flows relative to the size of the receiving river/stream is expected to be small. In some cases, sites on the Colorado River with pairwise median streamflow differences as large as ~10-20 cfs were not found to be significantly different due to variability in repeat streamflow measurements. Any effect of conservation on streamflows falling below or within this range of measurement uncertainty was, thus, not detectable. Some sites generated low quality measurements with a greater frequency than others (e.g., Above Elktrout Lodge, Junction Butte Wetland, and Hwy. 9 Fishing Access). Measurement variability observed on the Colorado River during late summer conditions may be partially attributed to instrument interference caused by periphyton growing along the streambed, complex bed structures, shallow and/or turbulent flows, moving beds, etc. Field personnel observed dense periphyton mats at or near several of the measurement transects in 2020 and 2021. Attempts to remove these mats prior to measurement were only successful in the shallow channel margins.

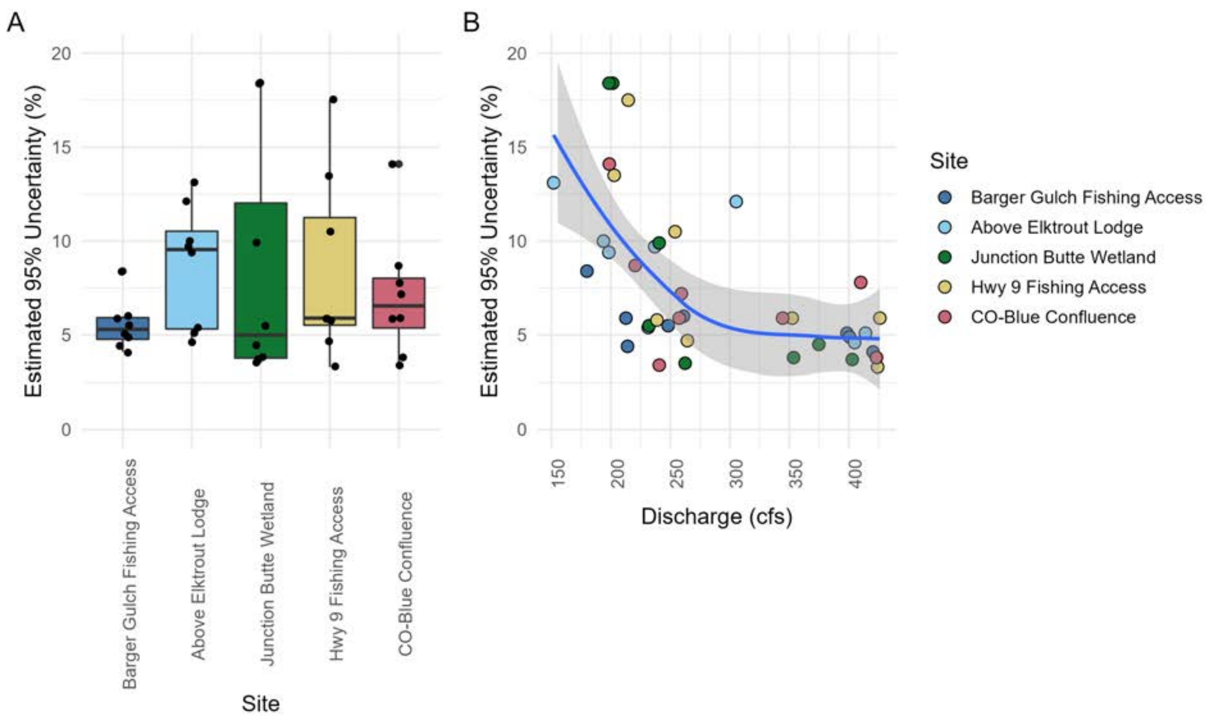

Figure 11: Streamflow measurement uncertainty along Colorado River by site (A) and by median discharge (B). Plots include measurements across both years. Estimated 95% uncertainty calculated by USGS QREV software.

In most cases, it will not be feasible to install a high-accuracy streamflow measurement station (e.g., a flume or an established gauging station with a robust rating curve) at each location that may require data for isolating the impacts of water conservation actions on streamflows. Expectations of measurement uncertainty for open-channel streamflow measurements are commonly set between 5-8%, even at established streamflow gauging stations. Therefore, if the magnitude of lagged groundwater return flow is expected to fall within 5-8% of late season streamflow, it may not be possible to directly measure lagged groundwater effects.

Several potentially-important environmental variables were not controllable by our assessment. We expect that analysis results for this study were confounded by the geographic arrangement of the treatment fields, the stream/river proximate to those parcels, and any non-participating parcels receiving typical irrigation. No true experimental control reach was available for comparison to locations where treatment effects were expected. Instead, identification of treatment effects required observing the same locations in two different year types: a treatment year and a reference year. This approach requires assumptions regarding the stationarity of environmental conditions between the two year types and/or the absence of non-linear behaviors in streamflow or groundwater as a function of changing environmental conditions.

The validity of the above-described assumptions could not be assessed by this effort. The behavior of all pumps and ditches and corresponding lagged groundwater return flow signals from irrigation on non-participating parcels along the reach was not assessed but may have masked the effects of water conservation on streamflows adjacent to the treatment fields. Variability in water application rates on non-participating parcels between 2020 and 2021 may also have occurred, violating the assumption of stationarity and precluding the use of 2021 as a reliable reference condition. Overcoming challenges associated with interannual variability and a lack of experimental control likely requires study designs where the effects of the treatment and the reference condition can be characterized across multiple years. This is probably not feasible in most settings and illustrates the need for alternative approaches for quantifying impacts of water conservation on streamflow.

4.2 Observable Impacts on Reservoirs

All four project fields in the area draining to Wolford Reservoir exhibited reduced evapotranspiration rates in 2020 relative to previous years for much of the growing season. Cumulative CCU summed across all fields was 550.8 af for the entire season (Apr-Oct 2020) with the highest monthly CCU rates in July, followed by June and August (Figure 1). Conserved diversion flows were observed at two ditches including Pass Creek Ditch which diverts water from Pass Creek and Herde Ditch which diverts water from Red Dirt Creek. Across both ditches, total CDF for the season was 2,026 af. Monthly CDF was highest in June which accounted for nearly half the total CDF, followed by May and July (Figure 12).

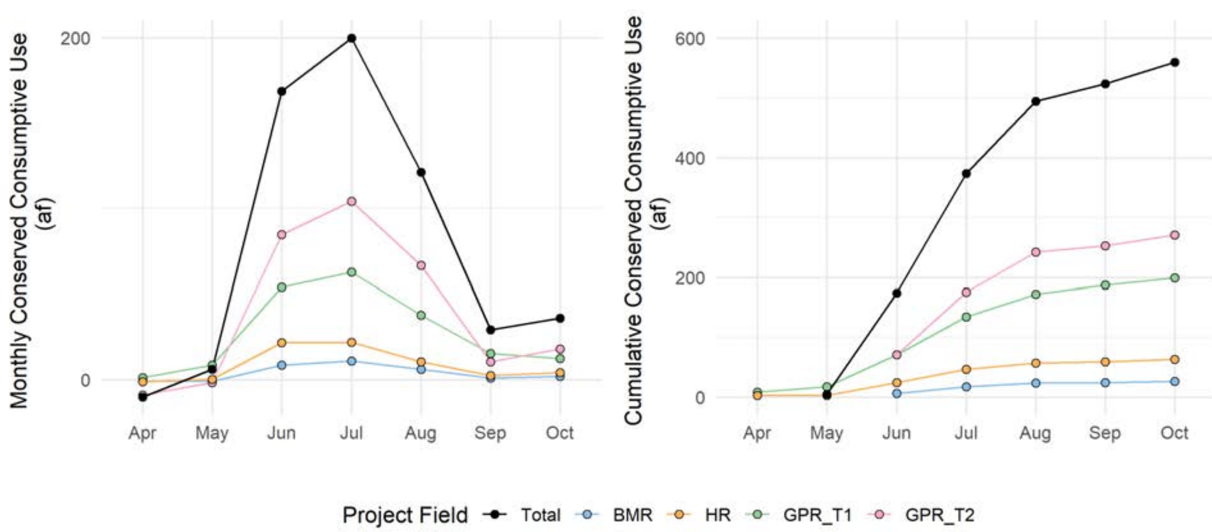

Figure 12. Conserved Consumptive Use (acre-feet) computed for the 2020 season for fields in the Red Dirt and Pass Creek watersheds.

Cumulative CDF was substantially higher than cumulative CCU because CDF accounts for diverted water that includes both consumptive and non-consumptive components. Peaks in CDF occurred during the May - July period, which was earlier than peaks in CCU (June – August). This pattern likely reflects the lag time between water diversion and water consumption on irrigated fields. Cumulative CDF appeared to represent a substantial portion of streamflow on Red Dirt and Pass creeks. Based on estimates of monthly streamflow in the two creeks, CDF accounted for ~24% of total cumulative flow exported to Wolford from the creeks between April-October (Table 3). CCU represents ~7% of total flow exported by the two creeks to Wolford. Estimates of late season streamflow on Pass Creek based on spot streamflow were only 30-60% of the flow estimates used in this analysis. If observed streamflow estimates are more representative of monthly flows on Pass Creek, then CDF and CCU accounted for a higher proportion of later season flow than reported here.

Table 3. Conserved Consumptive Use (CDU) and Conserved Diversion Flows (CDF) computed for 2020.

Month	CCU (af/month)	CDU (af/month)	CCU (% of Red Dirt + Pass Creek Flow)	CCU (% of Inflow)	CDF (% of Red Dirt + Pass Creek Flow)	CDF (% of Inflow)
April	-10	164	-1.5	-0.1	24.3	1.9
May	6	426	0.2	0.0	11.3	1.1
June	169	952	9.2	1.5	51.8	8.6
July	200	275	13.5	5.4	18.5	7.4
August	121	78.9	61.7	21.9	40.2	14.3
September	29	143	12.2	4.9	60.2	24.1
October	36	-12.5	15.6	6.5	-5.4	-2.2
Totals	***550.8***	***2026.4***	***6.5***	***0.8***	***24.0***	***3.1***

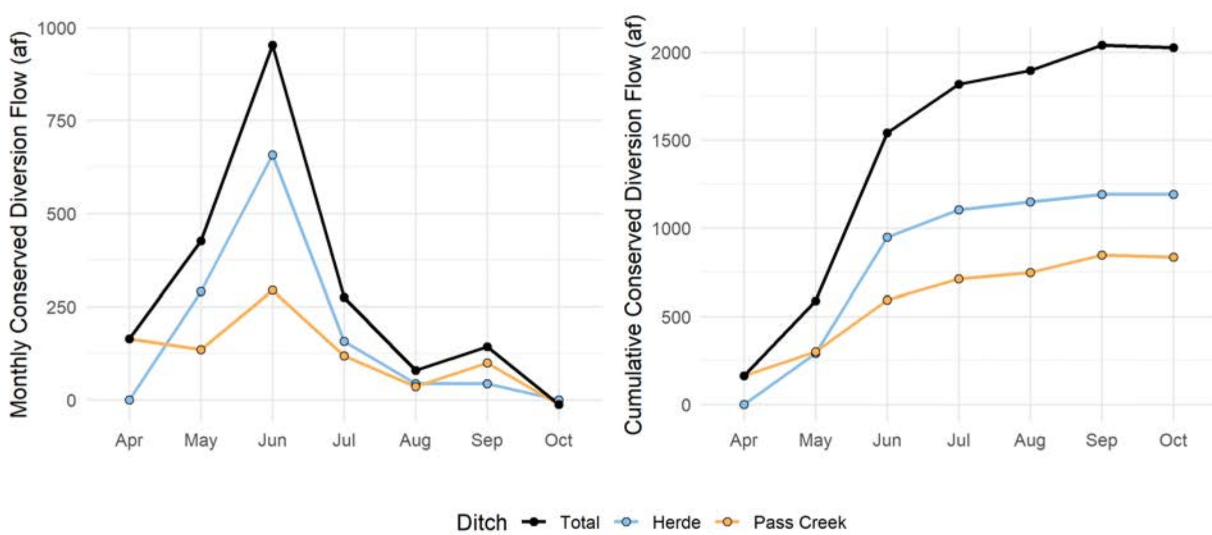

Figure 13. Conserved Diversion Flows (acre-feet) during 2020 computed for all fields participating in water conservation activities within Red Dirt and Pass Creek watersheds.

Watershed conditions in 2020 were compared to the full period of record (1997-2021) using the Muddy Creek above Antelope Creek streamflow gauge. Conditions in 2020 were characterized by unusually early high flows in early to mid-May, followed by low flows later in the season (Figure 14). Flow on Muddy Creek was near record lows in mid-August through late September. Calculated streamflows in Wolford tributaries across the period of record generally exhibit a more attenuated hydrograph with more gradual streamflow recessions through July and higher late season flows as compared to Muddy Creek. Tributary flows in 2020 were somewhat different. Tributary flow sharply peaked in mid-May, declined sharply in early June, plateaued until mid-July and then declined further through early August.

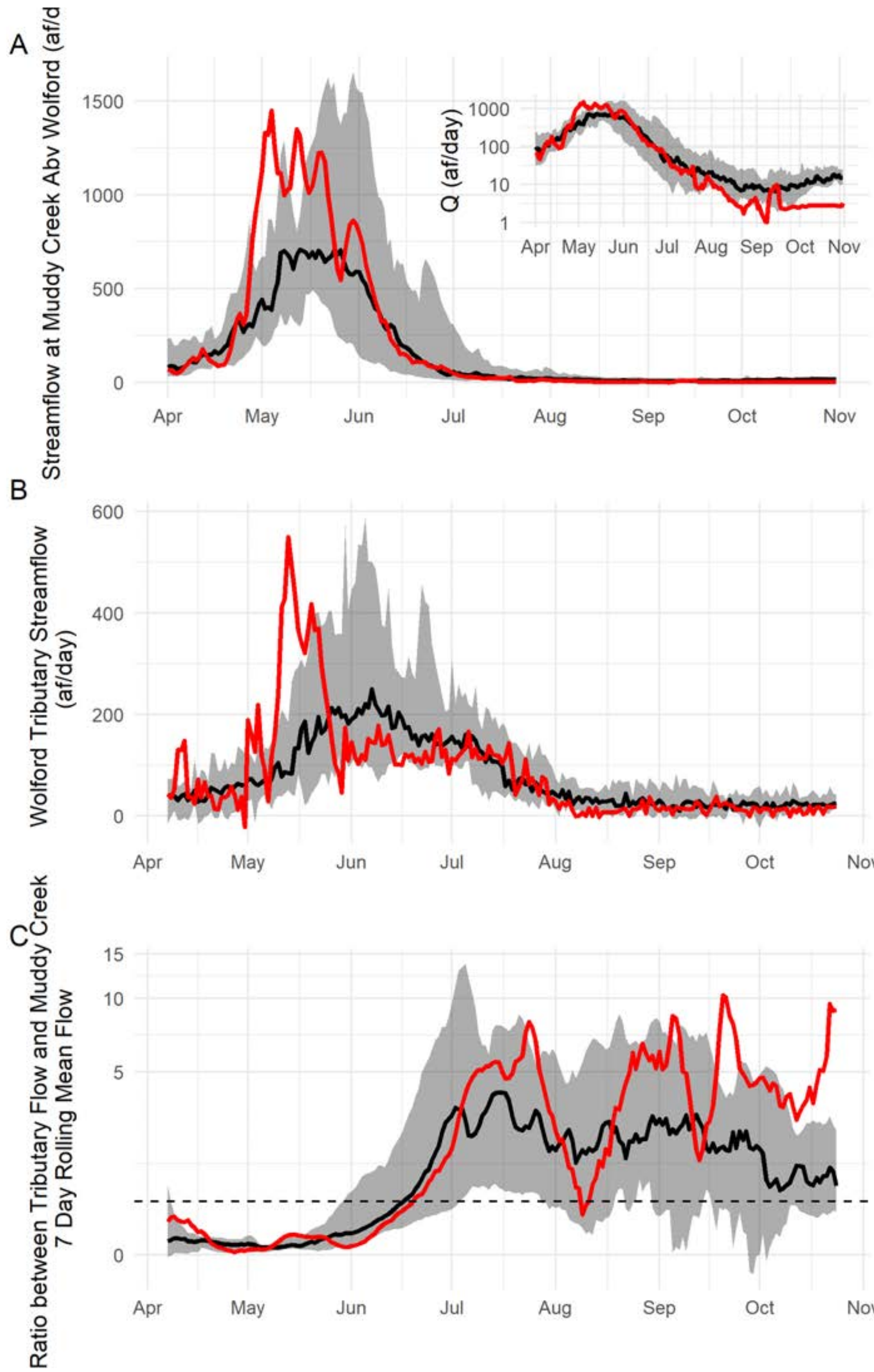

Figure 14. Hydrologic comparisons between 2020 (red line) and median (black line) and 10th to 90th percentile (grey shaded area) flows across the 1997-2021 period of record. A) Streamflow at Muddy Creek above Antelope Creek. B) Estimated inflows for all tributaries (inclusive of Red Dirt Creek, Pass Creek, and other tributaries). C) Ratio between streamflow at Muddy Creek above Antelope Creek and other tributary inflows.

Under median conditions, Wolford Reservoir fills to capacity in late May. Reservoir levels then decline slightly in early summer before dropping more sharply in August or September as inflows decline and late season outflows increase (Figure 15). Reservoir storage in 2020 rapidly increased in early May, reaching capacity levels by mid-May, nearly two weeks earlier than median conditions. Reservoir levels remained at or near capacity until mid-July when levels began to decline. Early in the season, reservoir outflows followed patterns of inflows with peak reservoir releases in mid- to late-May that were of a higher magnitude and several weeks earlier than median conditions. During a period from mid-August to mid-September, outflows in 2020 were near zero. Outflows during this same period in other years tend to rise as the reservoir releases water for late season streamflow augmentation needs.

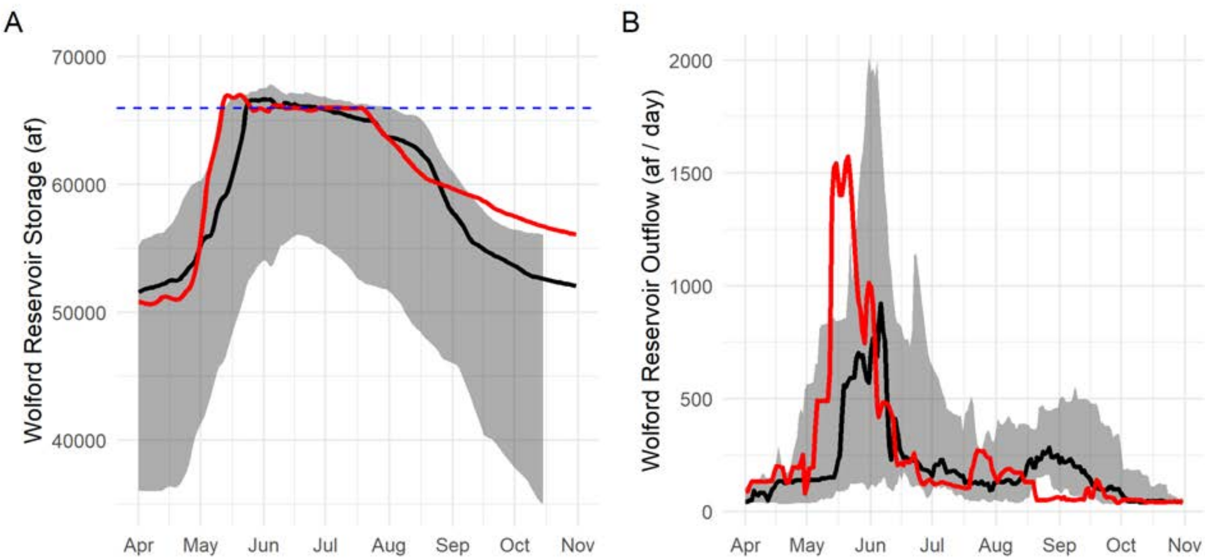

Figure 15. Wolford Reservoir storage (A) and outflow (B) observed in 2020 (red line) and compared to the median (black line) and 10th to 90th percentiles (grey shaded area) outflows for the full period of record (1997-2021). The dashed blue line represents the stated maximum reservoir capacity.

It was not possible to directly measure project impacts on Wolford due to the lack of complete streamflow records on project impacted creeks. As a proxy, we calculated CCU and CDF as a proportion of total reservoir inflows. These proportions provide an index of the potential scale of water conservation project impacts. Over the full season, impacts of water conservation were equivalent to only a small portion of total Wolford inflows. Reductions in consumptive use due to irrigation curtailment was equivalent to only ~0.8% of cumulative reservoir inflows while conserved diversion flows were equivalent to ~3.1% of cumulative reservoir inflows.

Monthly CCU and CDF represented a higher proportion of inflows later in the season. At its peak, CCU was equivalent to ~22% of August reservoir inflows. CDF was equivalent to ~24% of September reservoir inflows (Table 4, Figure 16). Tributary inflows to Wolford Reservoir were generally below historical median values during this period. Unlike Muddy Creek, inflows from other tributaries did not stay near all-time lows. It is possible the difference between Muddy Creek and other tributary inflows during this period could be the result of project-related conservation activities. Conversely, the pattern could be explained by typical lagged return flows from other irrigated fields on tributaries streams. It is not possible to determine if either explanation is correct without more streamflow data on the tributaries.

Table 4. Wolford Reservoir and tributary inflow records and estimates

Month	All Reservoir Inflows (af/mon)[a]	Tributary Inflows Only (af/mon)[a]	Pass Creek Field Measured Inflow (af/mon)[b]	Red Dirt Estimated Inflow (af/mon)[c]	Pass Creek Estimated Inflow (af/mon)[c]
April	8443	1382	-	401	274
May	40098	7721	-	2239	1529
June	11117	3766	-	1092	746
July	3704	3046	-	883	603
August	552	402	24.6	117	80
September	594	487	59.5	141	96
October	558	474	29.2	137	94
Totals	**65066**	**17278**		**5011**	**3421**

[a] Calculated from CRCWD records
[b] Based on spot discharge measurements on lower Pass Creek
[c] Estimated using proportional area of watersheds to all tributaries

Reservoir operations appeared strongly influenced by 2020 watershed conditions that resulted in high early streamflows that filled the reservoir. Once full, the reservoir released water approximately equal to inflows until mid-July. After mid-July, storage declined as outflows increased relative to inflows. When the reservoir is at capacity, there is little operational flexibility as any additional inflow must be released as outflow. An estimated 82% of conserved diversion flows occurred during the period when the reservoir was at or near capacity. Therefore, most project-related flows into the reservoir were presumably released downstream. The reservoir had more capacity to store conserved flows later in the summer in August and September. However, only ~11% of conserved diversion flows (approximately 221 af) occurred during this period. Even if we assume all of this water would be otherwise lost to consumptive use, it would account for ~0.4% of reservoir storage based on the mean historical reservoir storage during this period. These relatively low impacts help explain why project activities were not readily observed in the reservoir operational records.

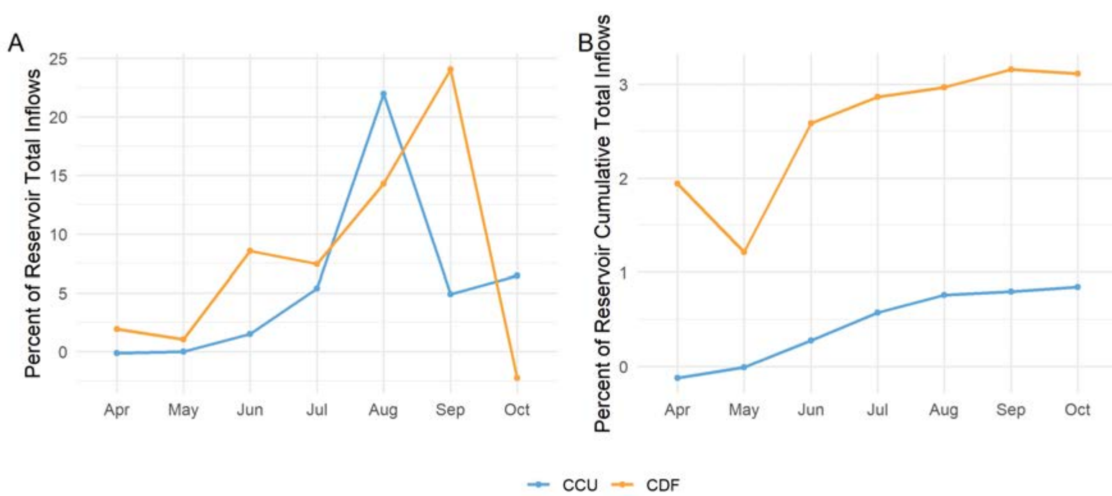

Figure 16. Percent of Project Impacts including CCU and CDF with respect to (A) monthly inflows and (B) cumulative seasonal inflows at Wolford Reservoir.

4.3 Simulations Modeling Results

The approach selected here for overcoming the challenges discussed above involved coupling a one-dimensional soil water balance model with an analytical solution for computing surface water abstractions and lagged groundwater accretions to stream channels. The modeling system was parameterized with the best-available site level data and reasonable value ranges established in academic literature. Modeling results were used to estimate the impacts of the ECCU project on local and regional streamflow, given some reasonable uncertainty in model parameter values. Soil water balance modeling helped bound expectations for conservation impacts on infiltration and deep percolation of water through the soil column. The Glover analytical solution, a method regularly employed by CDWR for approximating groundwater return flow behavior, was then used to simulate the lagged response of irrigation water accumulated in groundwater to nearby stream segments. Comparing simulated return flows from a year with normal operations to the lack/reduction of return flows during the treatment year provides a view into the potential impacts of water conservation activities on the most proximate stream and on downstream water bodies.

The modeled contribution of irrigation water to groundwater recharge (deep percolation) was variable across parcels due to differences in irrigation strategies, irrigation rates, and physical soil properties. Soil water balance Monte Carlo simulations produced an envelope of possible groundwater contributions at each site. This envelop represents the inherent uncertainty in modeling outputs given uncertainty in the values of infiltration rate and soil K_{sat}. The cumulative simulated deep percolation under normal operations across all parcels and simulations ranged from 1.2 to 14 ft of water (Table 5). The estimated annual volumetric streamflow abstraction at individual treatment parcels, calculated as infiltration minus precipitation multiplied by the parcel acreage, ranged from 98 - 124 acre-feet at BJM T1 to as much as an estimated range of 1038-1325 acre-feet at GPR T2. The estimated annual volumetric contributions to GW at individual treatment parcels, calculated as deep percolation multiplied by the parcel acreage, ranged from 68 - 95 acre-feet at BJM T1 to as much as an estimated range of 806 – 1041 acre-feet at GPR T2. Larger variability observed in some model ensembles reflect model sensitivities to physical soil parameters. Higher model ensemble variability was observed where infiltration rates and K_{sat} values were high relative to irrigation contribution rates (Table 2). At these locations, groundwater contributions were primarily limited by physical constraints on water moving from the surface through the soil column. Parcels with low irrigation rates relative to infiltration/K_{sat} were observed to have low ensemble variability. Groundwater contributions at these locations were primarily limited by the irrigation rate. Describing the impact of uncertainty in irrigation rates was beyond the scope of the effort here and is not included in our model simulations.

The bulk of GW contributions generally entered the groundwater concurrent with periods of irrigation water application; although, deep percolation was observed to continue for a period of several days to more than a week after irrigation ceased in some locations (Figure 17). These lags in deep percolation are most pronounced at locations exhibiting relatively low soil column K_{sat}.

Modeled GW return flow results can best be considered in light of the high uncertainty associated with the physical characteristics of the underlying aquifer. Ensembles of model results were grouped by simulations testing high, medium, and low aquifer transmissivities—a measure of the rate at which GW flows horizontally through an aquifer. Envelopes of simulation results for the ensembles within each transmissivity class reflect uncertainty in other soil and aquifer parameter values across their respective ranges.

Table 5: Soil water balance model estimates of streamflow abstraction and groundwater contributions at treatment parcels during a year with normal operations. Minimum and maximum estimates are the range derived from Monte Carlo model ensembles.

Parcel	Parcel Size (acres)	Cumulative Streamwater Abstraction (ft) (min – max)	Volumetric Streamwater Abstraction (acre-feet) (min - max)	Cumulative Deep Percolation (ft) (min - max)	Volumetric Contribution to GW (acre-feet) (min - max)
BJM T1	32.1	3.1- 3.9	98 – 124	2.1 – 3.0	68.4 – 95
GPR T1	202.6	4.5 – 6.0	901 – 1206	3.6 – 5.1	735- 1041
GPR T2	345.9	3 – 3.8	1038 – 1325	2.3 – 3.2	806 – 1095
HSR T1	86.5	3.1 – 3.9	266 - 336	2.1 – 2.9	180- 251
RCR T2	7	14.6 – 14.6	102 – 102	14 – 14	97 – 97
RSR T1	125.5	2.2 – 3.2	277 – 398	1.2 – 2.2	149 – 271
SBR T1	69.2	6.2 – 9.8	430 – 480	4.8 – 8.4	332 – 580
SPR T1	220	3.7 – 3.7	811 - 811	3.3 – 3.3	719 – 719

Simulations within the high aquifer transmissivity class generated relatively high peak GW return flow rates and limited lag times in GW return flows. In these circumstances, GW returns to the stream initiate and peak concurrent with irrigation water application and generally tail off within 1-3 weeks after the cessation of irrigation (Figure 17 & Appendix A). More moderate aquifer transmissivities generated conditions with attenuated peak GW return flow rates and a more sustained contribution to nearby streams that persisted for several weeks or longer following the cessation of irrigation. Low aquifer transmissivities generated substantially more attenuated GW return flows. In these circumstances, groundwater contributions to streams were lower and less variable but persisted into the fall or, in some cases, continued at a low level throughout the calendar year.

Groundwater return flow rates at individual parcels were highly variable (Appendix A). Intuitively, larger fields (including GPR T1, GPR T2, and SPR T1) generated the highest GW return flow rates. Fields exhibiting lower infiltration rates (SBR T1, RSR T1), smaller acreage (RCR T2, BSR T1, HSR T1) and/or shorter irrigation windows (RCR T2) produced relatively-small GW return flows.

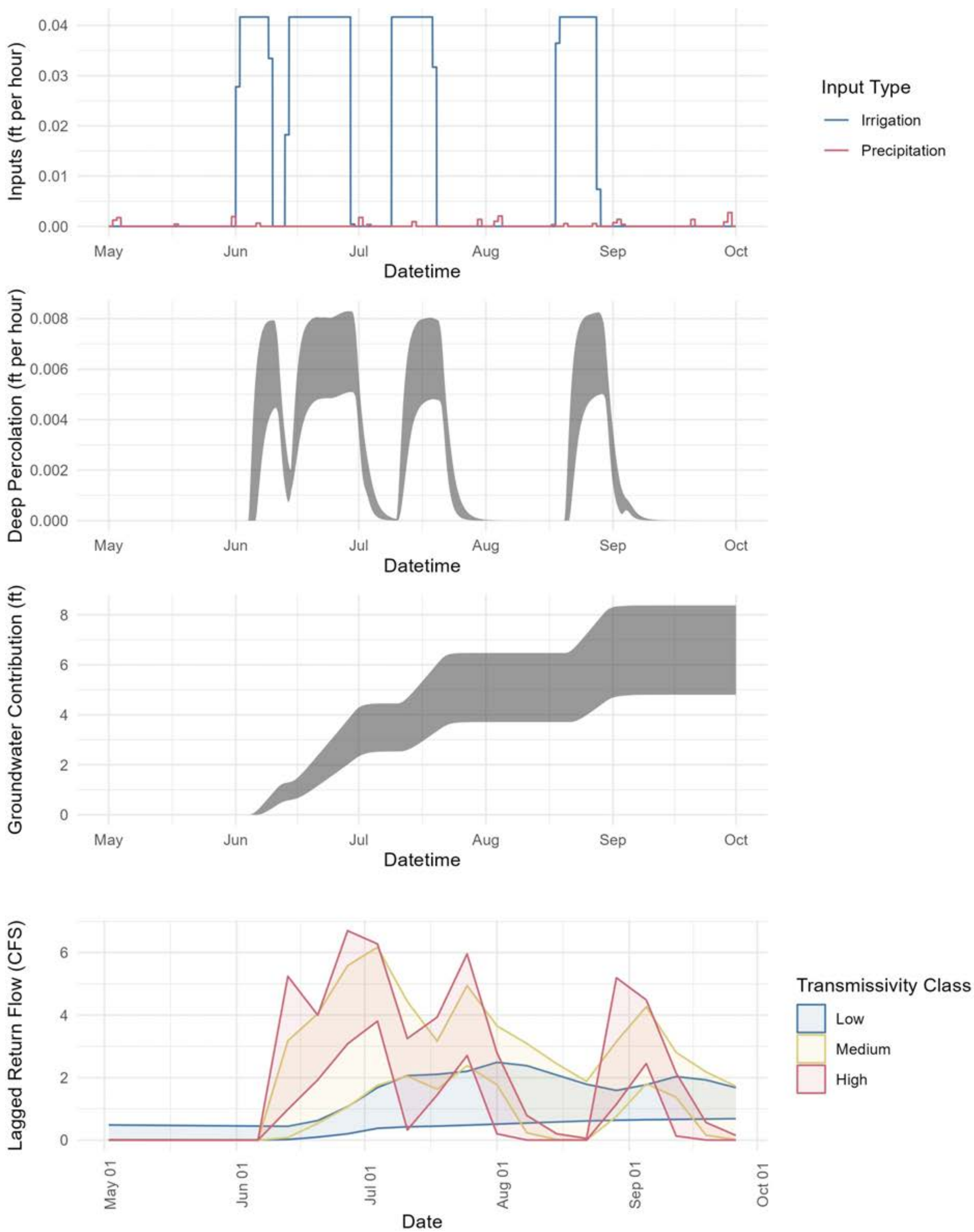

Figure 17: Simulation results for a year with normal operations at SBR T1 including hydrological inputs (top), deep percolation rates (second row), cumulative groundwater contributions for any unit area (third row), and lagged GW return flows (bottom row). Simulation envelopes for deep percolation and cumulative groundwater contribution reflect uncertainty in the soil water balance model parameters. Lagged return flow simulation results are summarized for three aquifer transmissivity classes: high (>1000 m^2/day, red), medium (100-1000 m^2/day, yellow), and low (<100 m^2/day, blue). Lagged return flow simulation envelopes depict combined uncertainty of soil water balance and groundwater return flows models.

5 Cumulative Impacts on Downstream Water Bodies

The challenges associated with directly measuring project impacts on streams and reservoirs downstream of fields enrolled in conservation projects was discussed at length previously. As a result, the overall impacts of water conservation activities on the Colorado River, Wolford Reservoir and Williams Fork Reservoir were estimated using the simulation modeling framework. Aggregate net treatment impacts were evaluated as the combined impacts of streamwater abstractions and GW return flows during the treatment year minus those simulated during a normal year. As noted previously, water diversions and GW return flows during the treatment year were assumed negligible if a parcel underwent full irrigation curtailment. In such cases, the treatment impact was assumed of equivalent magnitude and opposite sign to the modeled results of the normal year. Treatment impacts were aggregated all project parcels where GW returns flows were expected to accrue to each waterbody. Impacts of water conservation on parcels upstream of Wolford and Williams Fork Reservoirs not also considered to cumulatively impact Colorado River flows due to flow regulation by those reservoirs. Unavoidable uncertainty in assessing treatment impacts was accommodated by considering ensembles of model results classified by high, medium, and low aquifer transmissivities. Note that treatment impacts reported below as positive values reflect an increase in streamflow contributions during the treatment year while negative values reflect a decrease in streamflow contributions.

5.1 Colorado River

Contributions from three parcels (RCR T2, SBR T1, and RSR T1) were identified as directly impacting Colorado River flows. Aggregate treatment net impacts ranged from –11.5 to +8 cfs under high transmissivity, -8.5 to +8 cfs under medium aquifer transmissivity and remained between –4 to +8 cfs under low aquifer transmissivity. Patterns in treatment impacts oscillated several times between negative and positive values during the season, reflecting the impacts of multiple periods of irrigation throughout the year during normal operations on the contributing parcels. During the low-flow period from August onward, aggregate treatment impacts not below -5 cfs across all three transmissivity classes but did spike as high as +8 cfs under high transmissivity in late August. This spike corresponds to late summer irrigation that occurs under normal operations at all three parcels.

These treatment net impacts on the Colorado River represent a small proportion of overall streamflows measured on the Colorado in 2020. Net impacts of 8 cfs represent just 2-5% of measured streamflows observed at measurement sites on the Colorado River from August through early November 2020 (observed flows ranged from ~150–400 cfs). Such small changes to flow are unlikely to be observable in streamflow records. This may help explain why clear treatment impacts to discharge were not observed through longitudinal measurement field measurements on the Colorado River.

5.2 Wolford Reservoir

Contributions from four parcels (GPR-T1, GPR-T2, HSR-T1, and BJM-T1) were identified as impacting Wolford Reservoir. Topographic and field analysis suggest that some or all of GW return flows from GPR-T1 may first accrue to Pass Creek while return flows from GPR-T2 may first accrue to an unnamed tributary of Pass Creek on the south of the parcel. Groundwater return flows from HSR-T1 and BJM-T1 likely accrue directly to Wolford Reservoir.

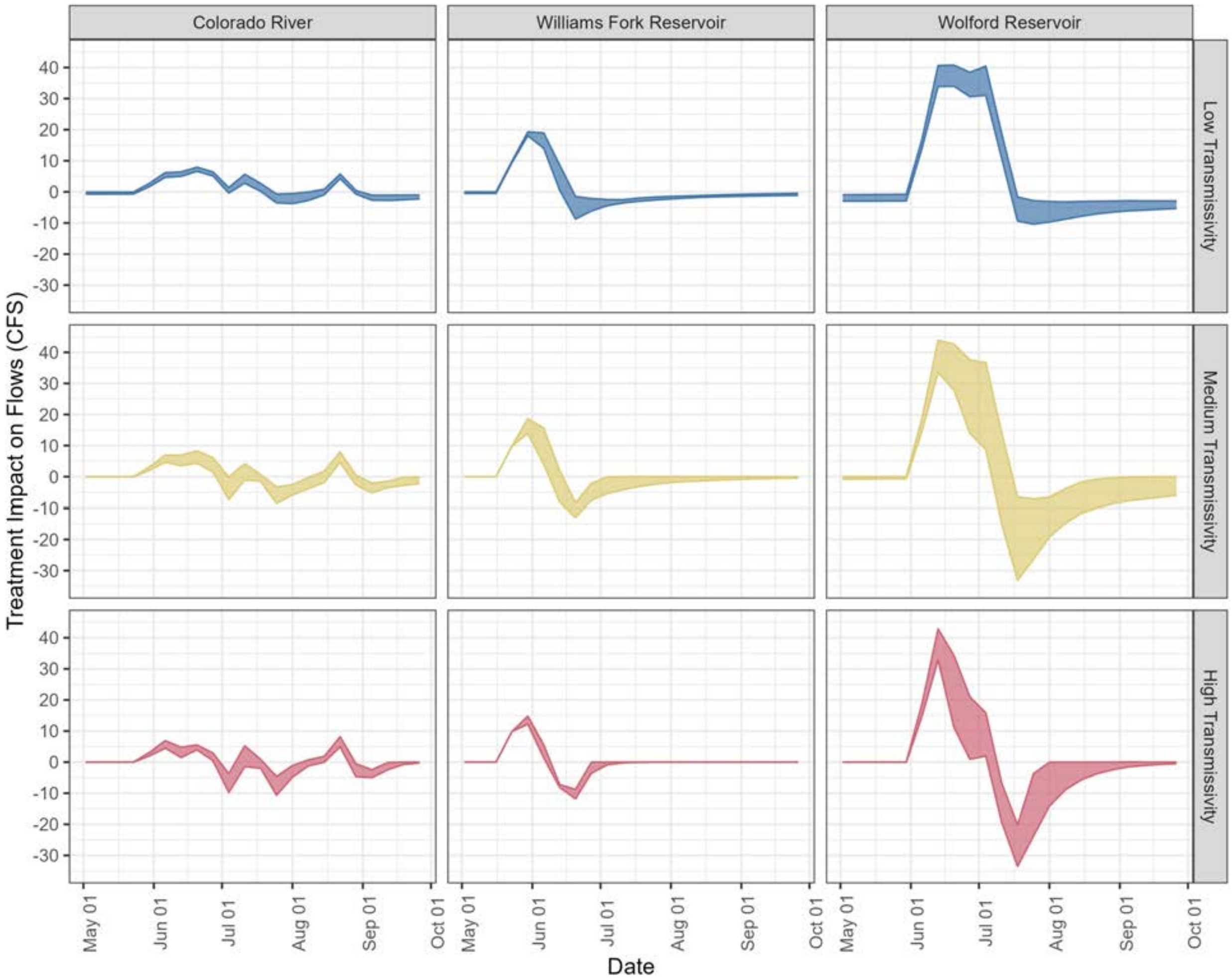

Figure 18: Aggregated Treatment Net Impacts on Streamflow. Net impacts are calculated as the difference between the combined effects of water abstractions and lagged return flows under normal operations and under treatment conditions. Results are aggregated to impacted downstream water bodies (columns) and shown for low, medium, and high aquifer transmissivity classes (rows). Values are calculated as the weekly net impact of the treatment year differenced by the net impacts during a normal year. Sites with full curtailment were considered to have no water abstractions or return flows during the treatment year. Simulation envelopes depict combined uncertainty of the soil water balance and lagged groundwater return flow models.

Aggregate treatment net impacts to Wolford Reservoir ranged from -42 to +44 cfs for a high transmissivity aquifer, from -36 to +44 cfs for an aquifer with medium transmissivity, and from -10 to +44 cfs for a low transmissivity aquifer (Figure 18). Positive treatment impacts on streamflow occurred in late May through early July, peaking in June. Negative treatment impacts on flow occurred in mid-July through the end of September, diminishing throughout the late summer period.

Alteration of flows to Wolford Reservoir during water conservation periods may represent a meaningful influence on overall reservoir inflows, with a potential greater influence later in the summer when combined reservoir inflows are low (Figure 13)[15]. The monthly alterations in flows to Wolford represented ~0-3% of Wolford Reservoir's capacity but constituted a significant fraction of the historical monthly inflows late in the summer. Simulated increased flows to Wolford due to reduced surface water abstractions were largest during June for aquifers with Medium and High transmissivities, and July for aquifers with Low transmissivity. Increases in June represent a relatively small to moderate proportion of overall inflows to Wolford Reservoir. Simulated decreases to Wolford Reservoir inflows during the treatment year occurred in July-September due to the lack of groundwater return flows and were most pronounced in August and September. Impacts occurred sooner for higher transmissivity classes.

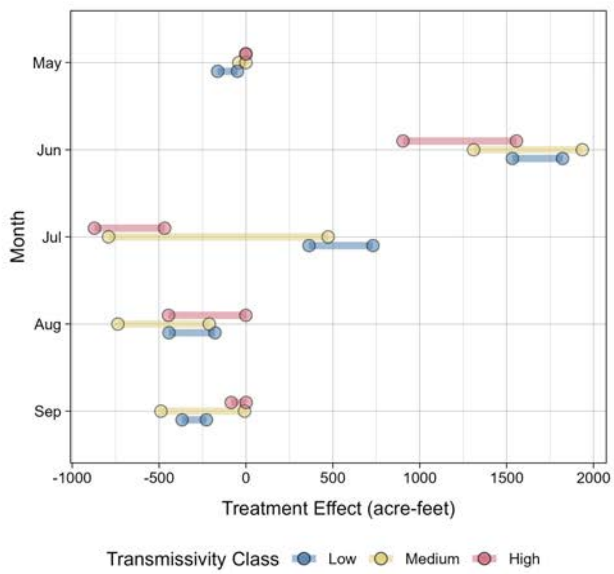

Figure 19: Monthly Aggregated Volumetric (acre-feet) Net Treatment Effects on Flows to Wolford Reservoir. Points and connecting lines indicate minimum, maximum and range of values across simulation envelopes for a given transmissivity class.

These results indicate that meaningful changes to Wolford Reservoir inflows due to the water conservation program activities may have occurred in 2020. Impacts were likely most apparent in the later season when the reservoir was not completely full and inflows were otherwise low. The positive gains simulated in June/July represent a relatively small fraction of overall inflows. Analysis of Wolford Reservoir water surface elevation records indicate that the reservoir is generally at capacity through at least the end of June and was at capacity through mid-July in 2020. Therefore, any boost to inflows driven by reductions in surface water diversions was likely released downstream and not stored in the reservoir. Reductions in late-summer groundwater return flows during the conservation year could have reduced the amount water supplied to Wolford Reservoir in the late summer when storage space existed. This effect were strongest for moderate or low

[15] Wolford reservoir operation records were obtained from Colorado River Water Conservation District. Wolford Reservoir Outflows on Muddy Creek are measured at USGS streamflow gage Muddy Crk blw Wolford (#09041400). The upper streamflow gauge above Wolford is located at Muddy Crk Abv Antelope Crk (USGS # 09041090), ~1 mile north of Wolford. Several ungauged tributaries join Muddy Creek below the gauge prior to the reservoir inflow and/or feed directly into Wolford. Inflows are therefore calculated by CRWCD through a mass balance approach using changes in storage capacity, outflow discharge and modeled reservoir evaporation.

aquifer transmissivities. The cumulative reductions in late-season (August-September) water supply to the reservoir could have reached as high as 1000 acre-feet, which may have impacted reservoir storage and planning for late season releases. As a comparison, the total Aug-Sep releases from the reservoir in 2020 were ~6000 acre-feet. It is also worth considering that if aquifer transmissivities are on the very low end of the simulated range, then lagged groundwater return flows derived from the 2019 irrigation season may have buffered the estimated impact of 2020 water conservation activities on late-summer inflows to the reservoir.

5.3 Williams Fork Reservoir

Contributions from a single parcel (SPR-T1) were identified as impacting Williams Fork Reservoir. Topographic analysis suggests that some or all of GW return flows from this location may accrue first to Bull Run Creek, confluence into Battle Creek and, subsequently, into the reservoir.

Simulated aggregate monthly treatment impacts on groundwater return flows ranged from -12 to +12 cfs under high aquifer transmissivities, from -13 to +19 cfs under medium aquifer transmissivities and from -9 to +19 cfs under low aquifer transmissivities. Positive impacts to flows were generally simulated in mid-May through early June while negative impacts peaked in mid to late June and then declined through the remainder of the season. From late July onward, reductions to Williams Fork Reservoir inflows were estimated below 3 cfs across under low and medium aquifer transmissivities and less than 1 cfs under high aquifer transmissivities.

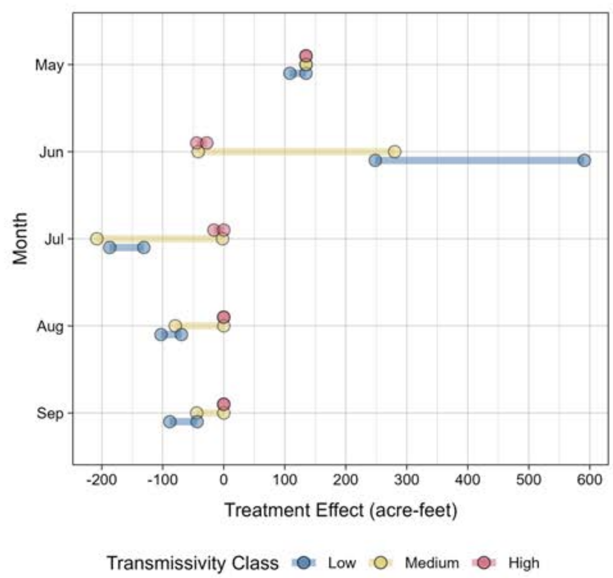

Figure 20: Monthly Aggregated Volumetric (acre-feet) Net Treatment Effects on Flows to Williams Fork Reservoir. Points and line indicate minimum, maximum and range of values across simulation envelopes for a given transmissivity class.

Monthly estimated alterations of inflows to Williams Fork Reservoir from water conservation activities represented a negligible to small change to the reservoir, accounting for less than 1% of th reservoir's capacity and between -9 to +3 % of the historical monthly inflows. Simulated increased inflows due to reduced surface water abstractions were largest during May or June. The largest positive flow impacts were simulated in June under a low transmissivity aquifer. Simulated decreased inflows to Wolford during the water conservation period occurred from July through

September. In the July-September period, these declines in flow represented between 0–9% of the historical monthly reservoir inflows[16]. Simulation results suggest that that water conservation-induced changes to Williams Fork Reservoir inflows in 2020 had a negligible impact on reservoir operations.

6 Key Takeaways

- Direct measurement and observation of water conservation activity impacts on streamflows was challenged by unexpected water management activities on participating and non-participating parcels, unique site-specific groundwater and surface water return flow pathways, and the expected size of the streamflow effect relative to unavoidable streamflow measurement uncertainty/error.

- Overcoming challenges to direct measurement of water conservation impacts driven by interannual variability and a lack of experimental control likely requires study designs where the effects of the water conservation treatment and the reference condition can be characterized across multiple years. Such study designs may also require additional data collection to address confounding effects of irregular irrigation patterns on non-participating parcels and normal interannual variability in tributary streamflows. Studies must also overcome the masking effect of streamflow measurement error on small treatment impacts. This is probably not feasible in most settings and illustrates the need for alternative approaches for quantifying impacts of water conservation on streamflow.

- Project results generated for the Colorado River, Wolford Reservoir and Williams Fork suggest that the coupled modeling approach described has the capacity to provide general insights into the impacts of irrigation curtailment on the hydrology of down-gradient streams and reservoirs.

- The simulated effects of water conservation activities in the Kremmling area include an increase to Wolford Reservoir and Williams Fork Reservoir inflows early in the runoff season and a modest decrease in those inflows later in the summer. Increased inflows in the runoff period likely resulted in a larger reservoir spill in the early summer. Decreased inflows later in the summer may have limited opportunities for additional water storage, particularly in Wolford Reservoir.

- The simulation of water conservation activities on streamflows in the Colorado River indicate modest and variable effects across the irrigation season. Simulated flow differences resulting from conservation (□ 10 cfs) relative to late summer streamflows (200-400 cfs) confirm the challenges posed for direct measurement of water conservation treatment impacts where streamflow measurement error on the order of 5-8% is typical.

- Refining estimates of specific treatment impacts on timing and magnitude of streamflow alteration due to water conservation activities in the Kremmling area would require data collection to further constrain irrigation rates and application patterns, physical soil parameters and aquifer properties.

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[16] Williams Fork Reservoir inputs (site id: WILPARCO) and outputs (site id: WILFORCO) records were obtained from the Colorado Division of Water Resources streamflow portal. https://dwr.state.co.us/Tools/Stations.

- Uncertainty in model outputs is primarily driven by a lack of local data describing of soil infiltration rates, hydraulic conductivity, porosity, and aquifer transmissivity. Soil characteristics can be better constrained via field data collection but adequate characterization of aquifer characteristics will likely remain a prohibitively costly and complex undertaking at most locations.

- Monte Carlo style simulation modeling approaches will likely remain the best approach for estimating the range of potential consequences associated with a planned or implemented water conservation activities similar to those conducted in the Kremmling area.

Appendix A: Modeling Results by Location

Study Site: BJM T1

Table 6: Soil Water Balance Physical Parameters by Layer

Soil Layer	Root Distribution	Initial Water Content	Porosity	Field Capacity	Wilting Point
1	0.3	0.28	0.41	0.39	0.19
2	0.24	0.3	0.48	0.43	0.25
3	0.23	0.35	0.45	0.38	0.25
4	0.23	0.35	0.45	0.38	0.25
5	0	0.45	0.54	0.45	-

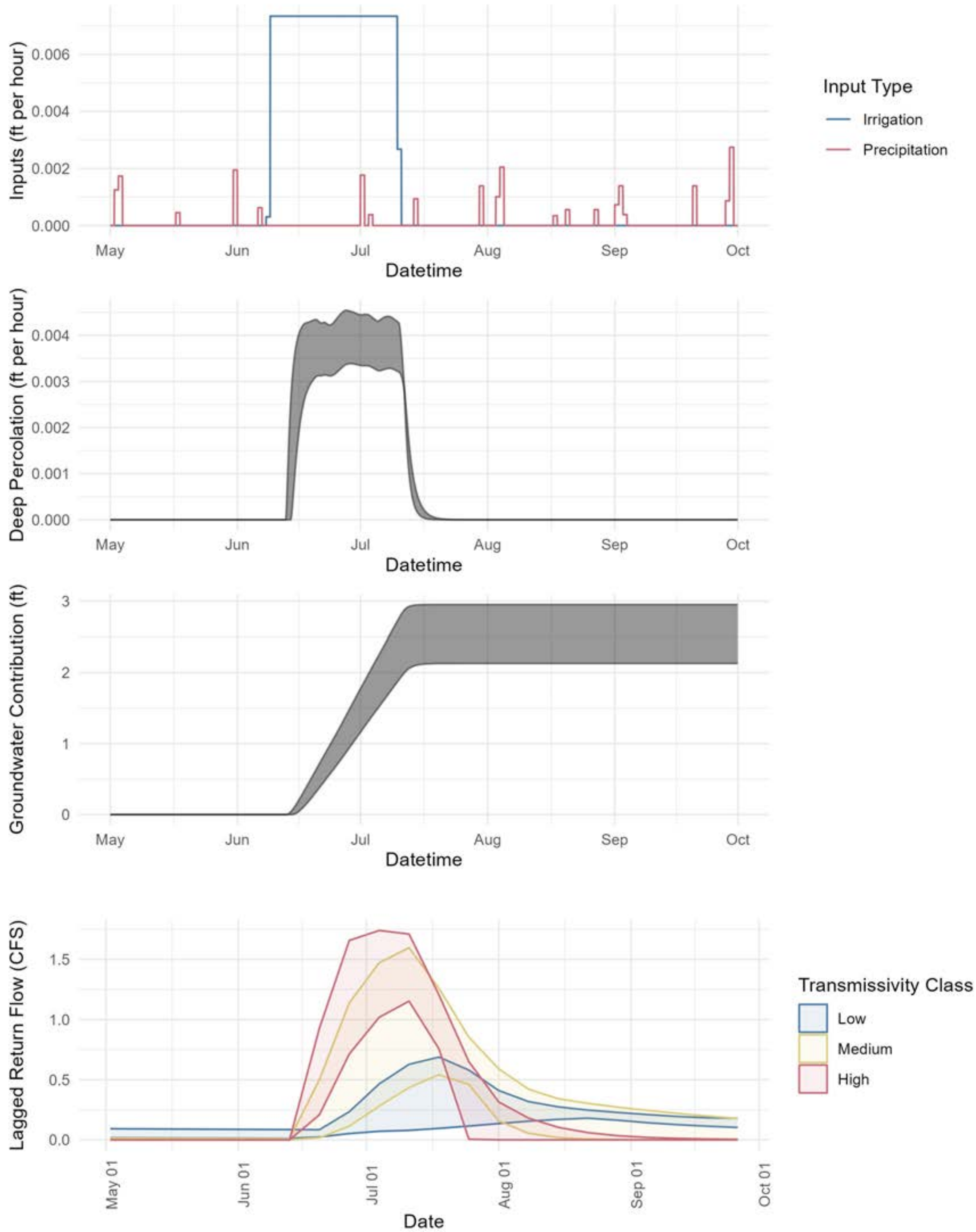


Figure 21: Simulated results for a year with normal operations including hydrologic inputs (ft/hr), deep percolation rates (ft/hour), cumulative groundwater contributions (ft), and lagged return flows (cfs). Envelopes in deep percolation and cumulative groundwater contribution depict uncertainty in the soil water balance model. Lagged return flow simulation envelopes are shown for different aquifer transmissivity classes including high (>1000 m²/day, red), medium (100-1000 m²/day, yellow), and low (<100 m²/day, blue). Lagged return flow simulation envelopes depict combined uncertainty of soil water balance and groundwater return flows models.

Study Site: GPR T1

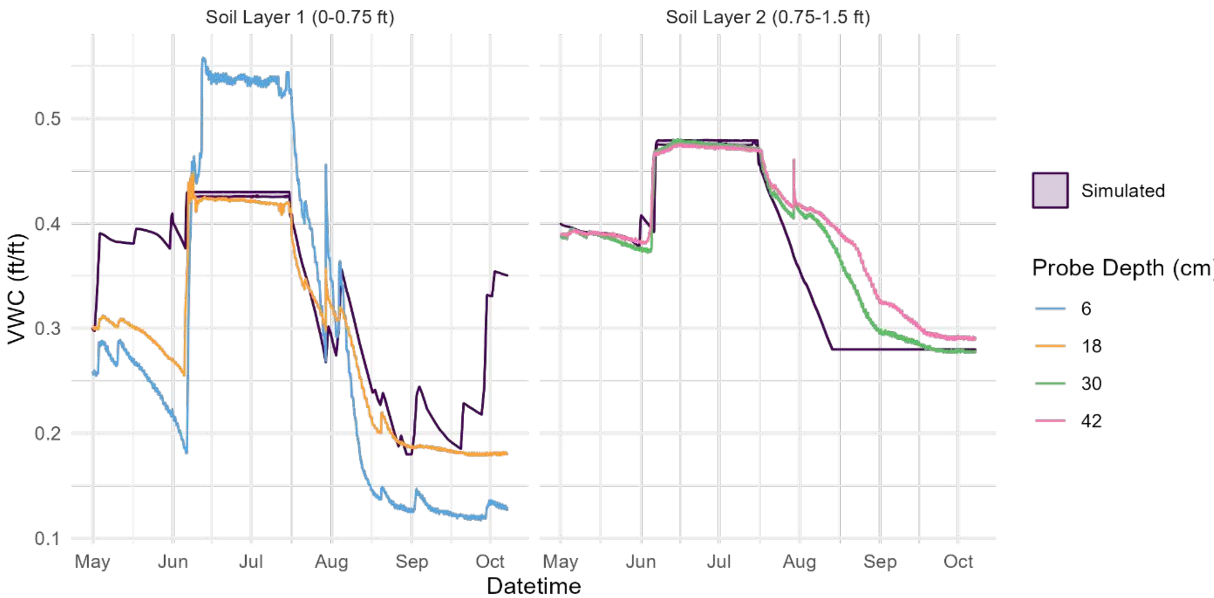


Figure 22: Observed vs simulated soil water balance for the top two soil layers in the soil water balance model. Probe depth was not deep enough for comparison with deeper soil layers in the model. Simulated envelope describe uncertainty in physical soil parameters including infiltration and saturated hydraulic conductivity.

Table 7: Soil Water Balance Physical Parameters by Layer

Soil Layer	Root Distribution	Initial Water Content	Porosity	Field Capacity	Wilting Point
1	0.4	0.3	0.43	0.4	0.18
2	0.25	0.4	0.48	0.45	0.28
3	0.18	0.35	0.48	0.45	0.28
4	0.17	0.35	0.48	0.45	0.28
5	0	0.45	0.54	0.45	-

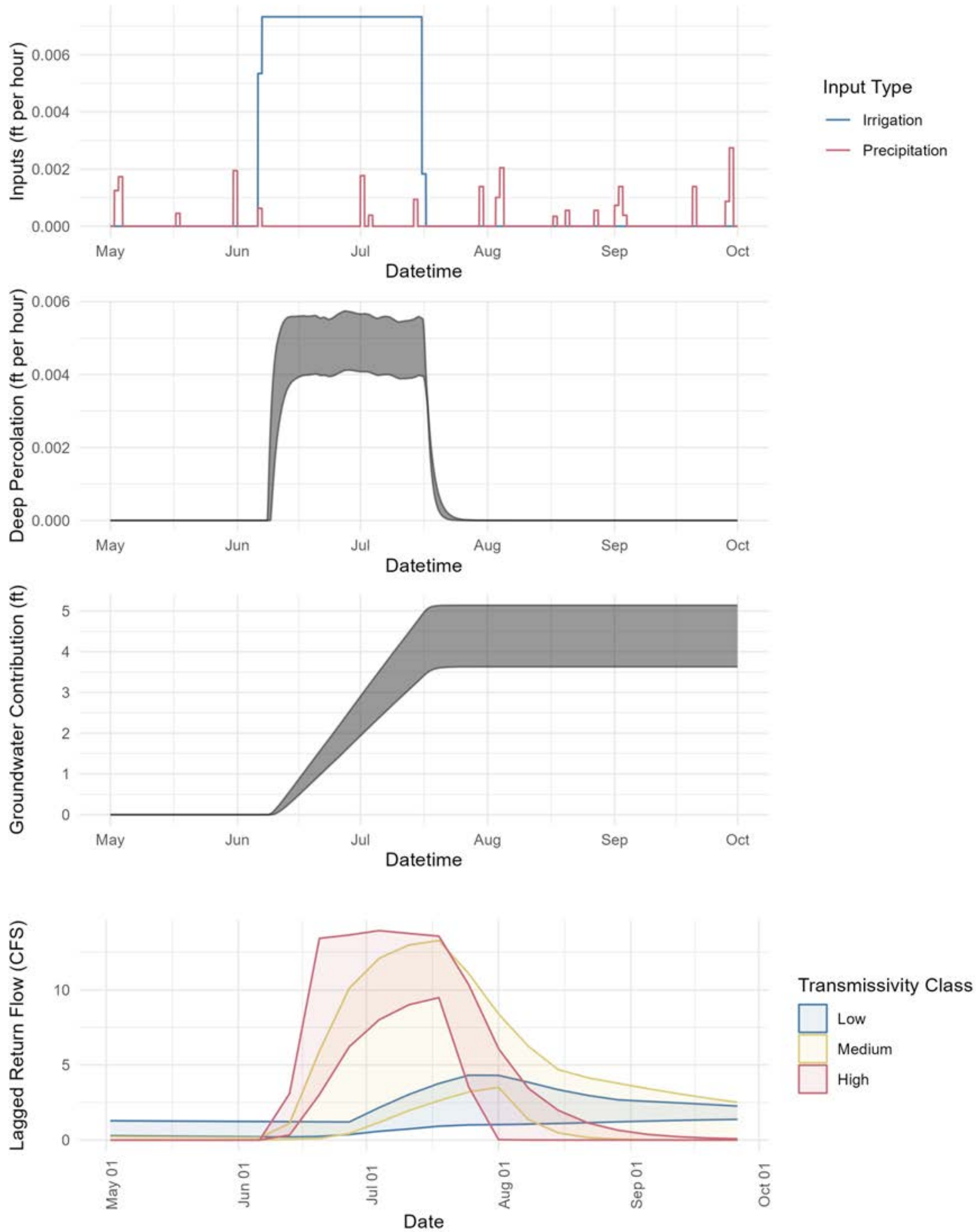


Figure 23: Simulated results for a year with normal operations including hydrologic inputs (ft/hr), deep percolation rates (ft/hour), cumulative groundwater contributions (ft), and lagged return flows (cfs). Envelopes in deep percolation and cumulative groundwater contribution depict uncertainty in the soil water balance model. Lagged return flow simulation envelopes are shown for different aquifer transmissivity classes including high (>1000 m^2/day, red), medium (100-1000 m^2/day, yellow), and low (<100 m^2/day, blue). Lagged return flow simulation envelopes depict combined uncertainty of soil water balance and groundwater return flows models.

Study Site: GPR T2

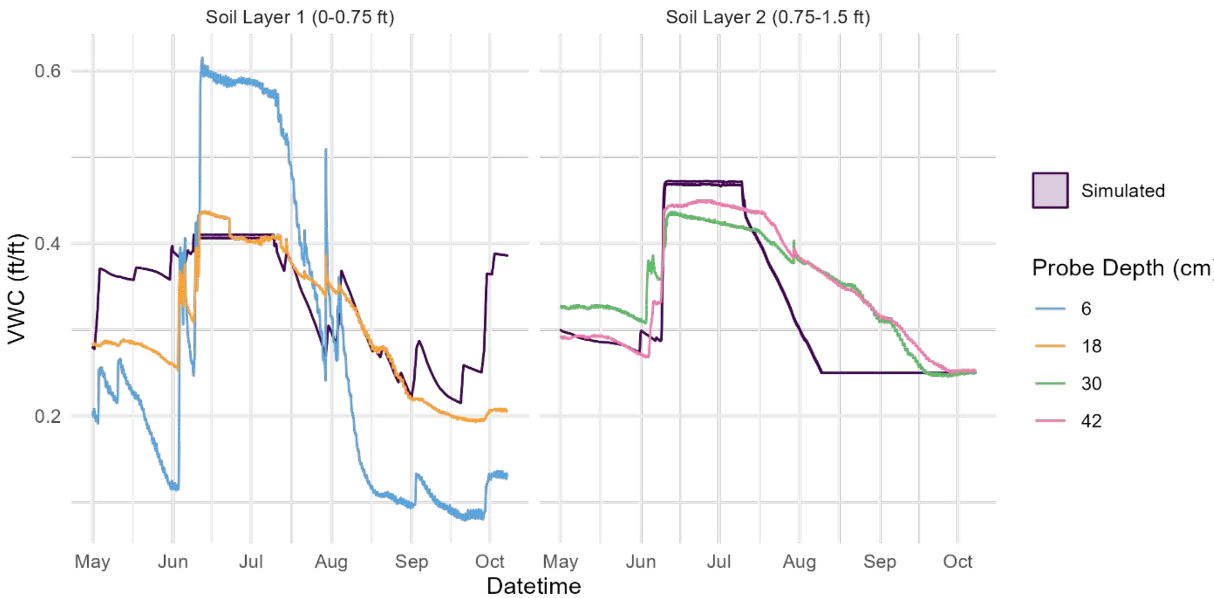


Figure 24: Observed vs simulated soil water balance for the top two soil layers in the soil water balance model. Probe depth was not deep enough for comparison with deeper soil layers in the model. Simulated envelope describe uncertainty in physical soil parameters including infiltration and saturated hydraulic conductivity.

Table 8: Soil Water Balance Physical Parameters by Layer

Soil Layer	Root Distribution	Initial Water Content	Porosity	Field Capacity	Wilting Point
1	0.3	0.28	0.41	0.39	0.19
2	0.24	0.3	0.48	0.43	0.25
3	0.23	0.35	0.45	0.38	0.25
4	0.23	0.35	0.45	0.38	0.25
5	0	0.45	0.54	0.45	-

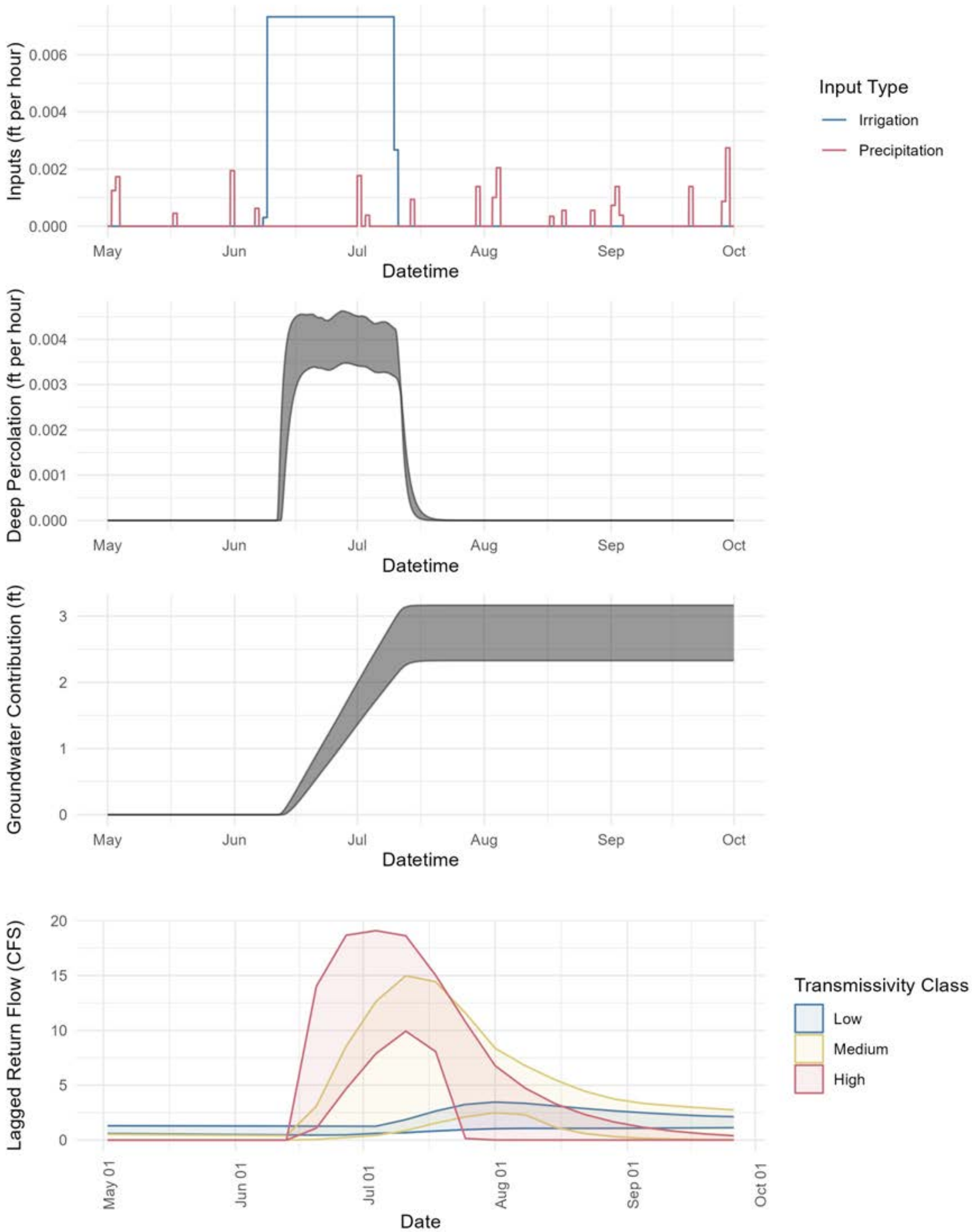


Figure 25: Simulated results for a year with normal operations including hydrologic inputs (ft/hr), deep percolation rates (ft/hour), cumulative groundwater contributions (ft), and lagged return flows (cfs). Envelopes in deep percolation and cumulative groundwater contribution depict uncertainty in the soil water balance model. Lagged return flow simulation envelopes are shown for different aquifer transmissivity classes including high (>1000 m^2/day, red), medium (100-1000 m^2/day, yellow), and low (<100 m^2/day, blue). Lagged return flow simulation envelopes depict combined uncertainty of soil water balance and groundwater return flows models.

Study Site: HSR T1

Table 9: Soil Water Balance Physical Parameters by Layer

Soil Layer	Root Distribution	Initial Water Content	Porosity	Field Capacity	Wilting Point
1	0.3	0.28	0.41	0.39	0.19
2	0.24	0.3	0.48	0.43	0.25
3	0.23	0.35	0.45	0.38	0.25
4	0.23	0.35	0.45	0.38	0.25
5	0	0.45	0.54	0.45	-

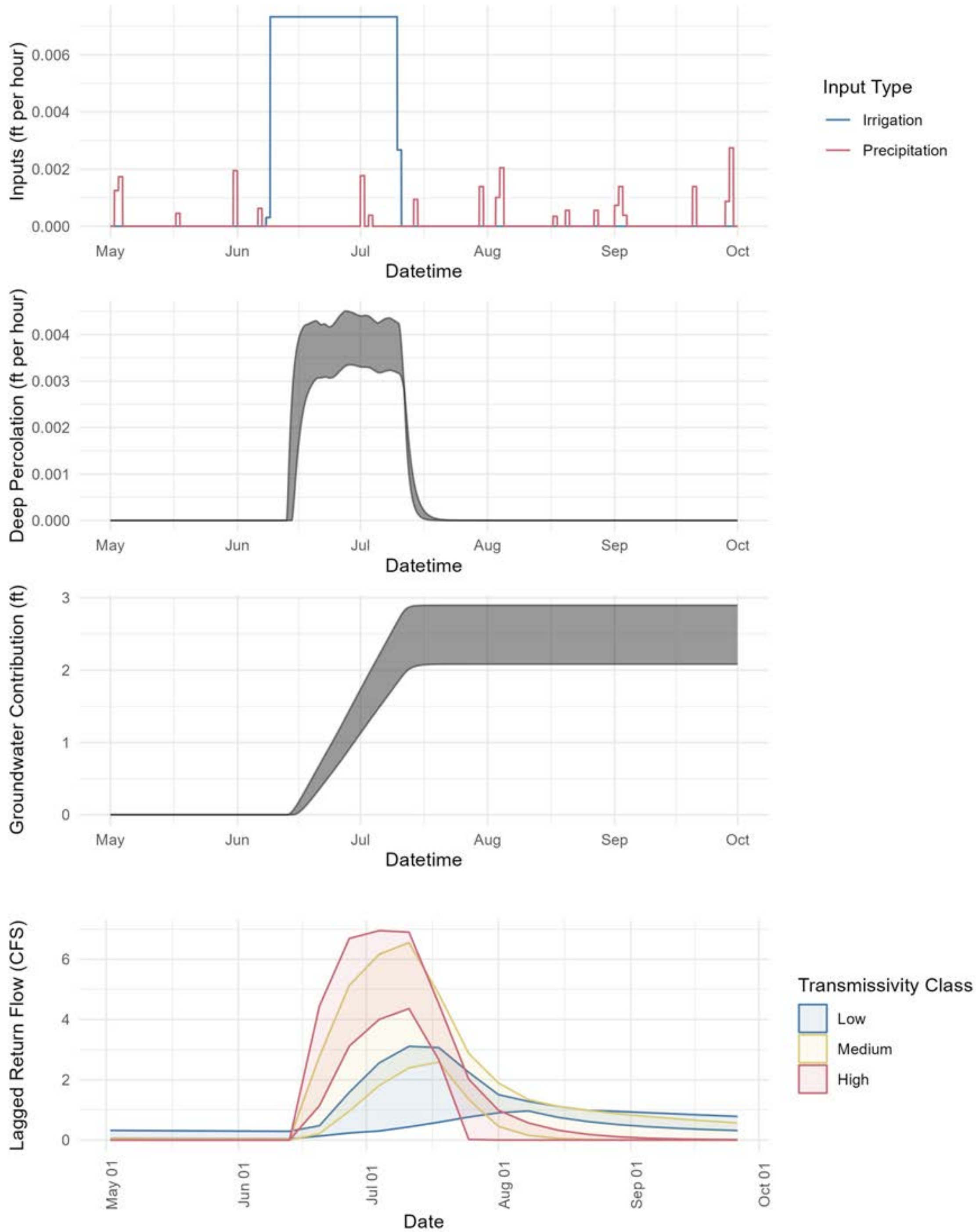


Figure 26: Simulated results for a year with normal operations including hydrologic inputs (ft/hr), deep percolation rates (ft/hour), cumulative groundwater contributions (ft), and lagged return flows (cfs). Envelopes in deep percolation and cumulative groundwater contribution depict uncertainty in the soil water balance model. Lagged return flow simulation envelopes are shown for different aquifer transmissivity classes including high (>1000 m^2/day, red), medium (100-1000 m^2/day, yellow), and low (<100 m^2/day, blue). Lagged return flow simulation envelopes depict combined uncertainty of soil water balance and groundwater return flows models.

Study Site: RCR T2

Table 10: Soil Water Balance Physical Parameters by Layer

Soil Layer	Root Distribution	Initial Water Content	Porosity	Field Capacity	Wilting Point
1	0.5	0.25	0.47	0.3	0.15
2	0.25	0.3	0.47	0.3	0.15
3	0.15	0.3	0.47	0.3	0.15
4	0.1	0.3	0.47	0.3	0.15
5	0	0.3	0.47	0.3	-

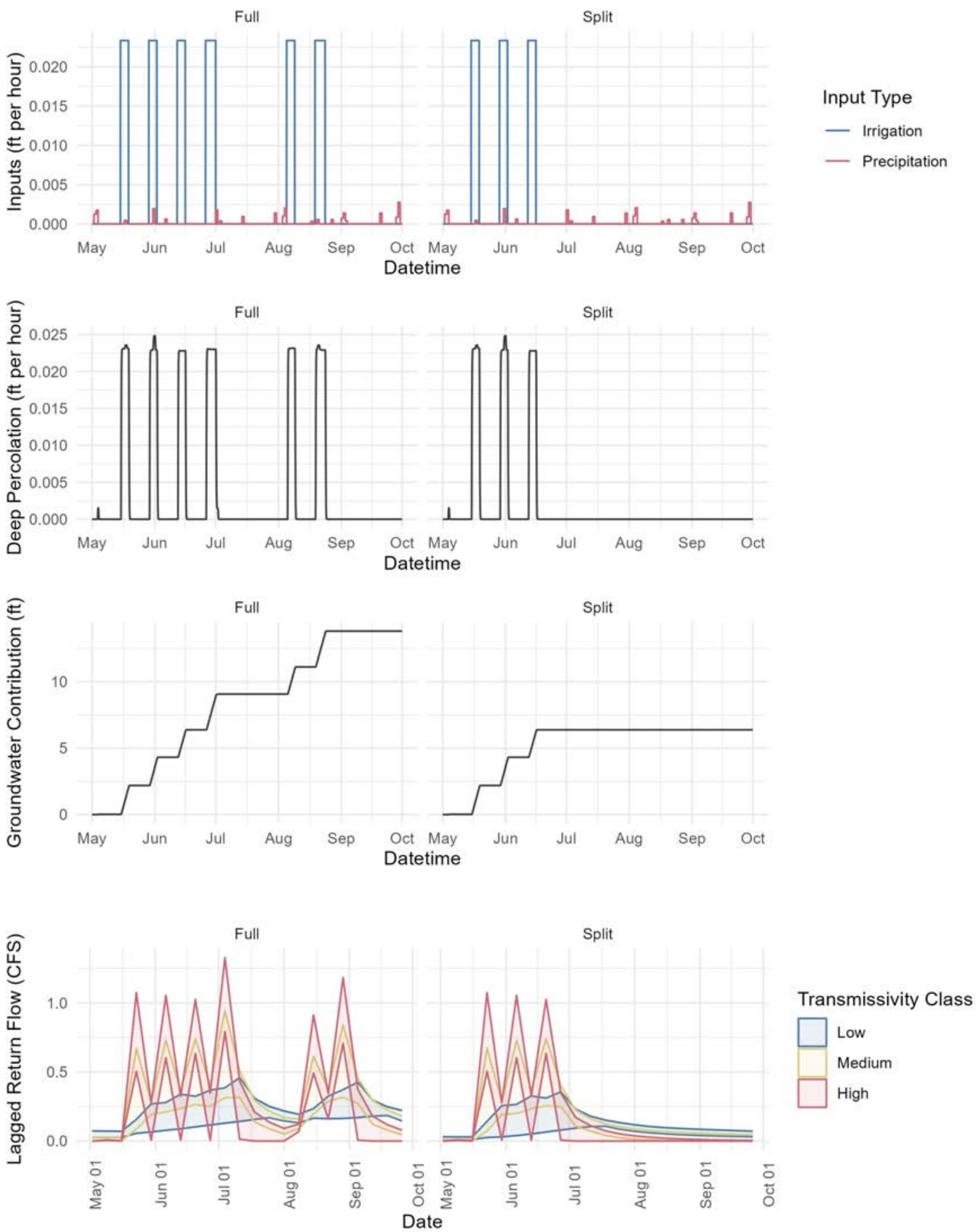


Figure 27: Simulated results for years with normal ('full') operations and split season curtailment including hydrologic inputs (ft/hr), deep percolation rates (ft/hour), cumulative groundwater contributions (ft), and lagged return flows (cfs). Envelopes in deep percolation and cumulative groundwater contribution depict uncertainty in the soil water balance model. Lagged return flow simulation envelopes are shown for different aquifer transmissivity classes including high (>1000 m^2/day, red), medium (100-1000 m^2/day, yellow), and low (<100 m^2/day, blue). Lagged return flow simulation envelopes depict combined uncertainty of soil water balance and groundwater return flows models.

Study Site: RSR T1

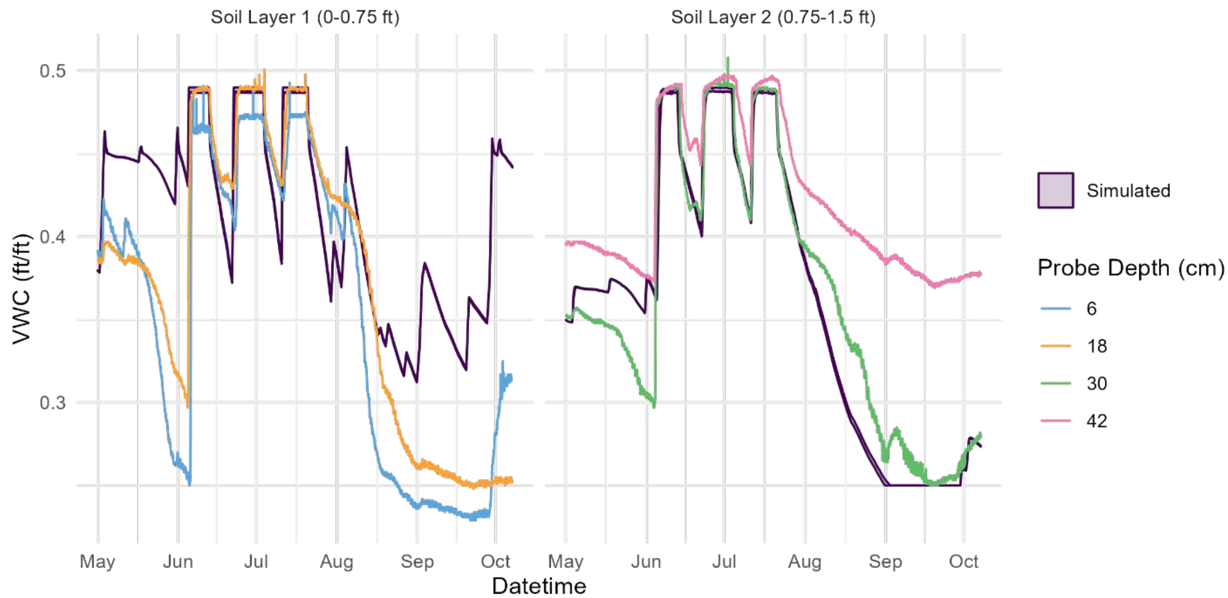


Figure 28: Observed vs simulated soil water balance for the top two soil layers in the soil water balance model. Probe depth was not deep enough for comparison with deeper soil layers in the model. Simulated envelope describe uncertainty in physical soil parameters including infiltration and saturated hydraulic conductivity.

Table 11: Soil Water Balance Physical Parameters by Layer

Soil Layer	Root Distribution	Initial Water Content	Porosity	Field Capacity	Wilting Point
1	0.3	0.28	0.41	0.39	0.19
2	0.24	0.3	0.48	0.43	0.25
3	0.23	0.35	0.45	0.43	0.25
4	0.23	0.35	0.45	0.38	0.25
5	0	0.45	0.54	0.45	-

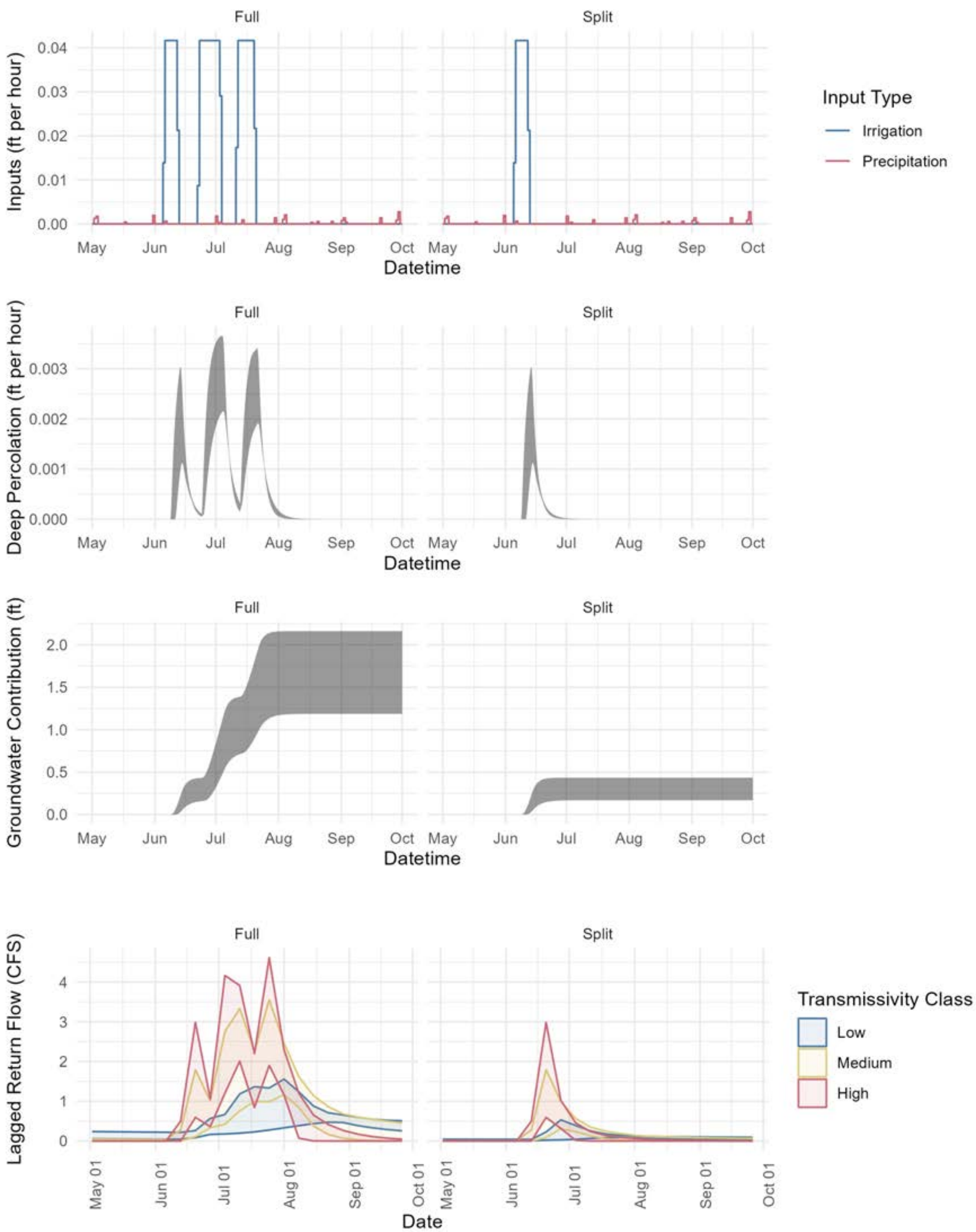


Figure 29: Simulated results for years with normal ('full') operations and split season curtailment including hydrologic inputs (ft/hr), deep percolation rates (ft/hour), cumulative groundwater contributions (ft), and lagged return flows (cfs). Envelopes in deep percolation and cumulative groundwater contribution depict uncertainty in the soil water balance model. Lagged return flow simulation envelopes are shown for different aquifer transmissivity classes including high (>1000 m^2/day, red), medium (100-1000 m^2/day, yellow), and low (<100 m^2/day, blue). Lagged return flow simulation envelopes depict combined uncertainty of soil water balance and groundwater return flows models.

Study Site: SBR T1

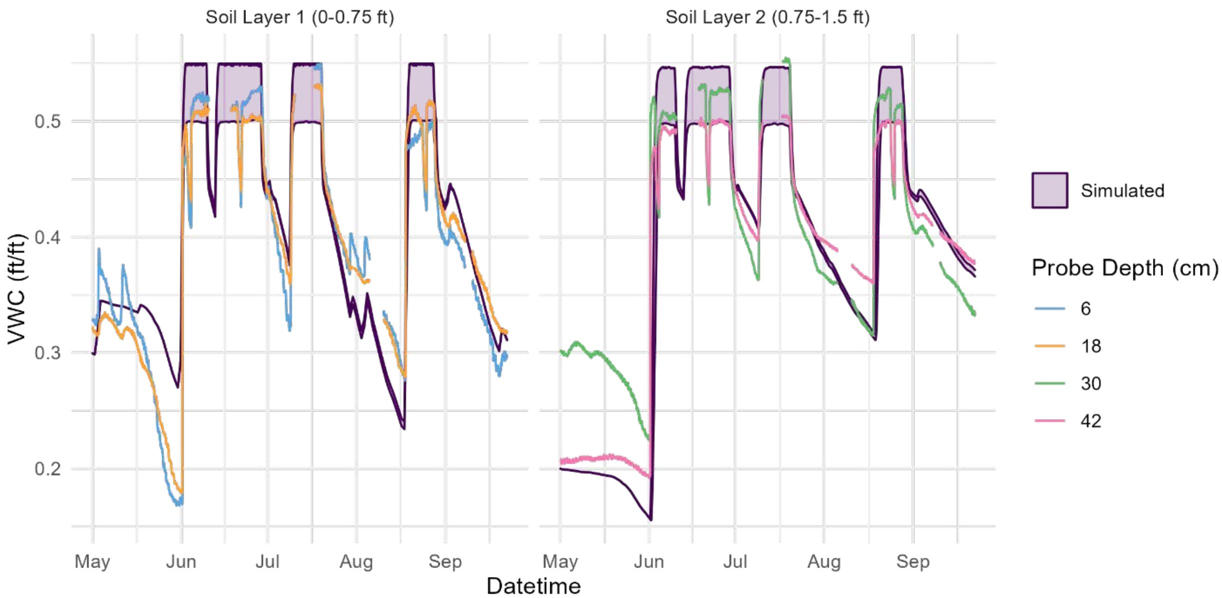


Figure 30: Observed vs simulated soil water balance for the top two soil layers in the soil water balance model. Probe depth was not deep enough for comparison with deeper soil layers in the model. Simulated envelope describe uncertainty in physical soil parameters including infiltration and saturated hydraulic conductivity.

Table 12: Soil Water Balance Physical Parameters by Layer

Soil Layer	Root Distribution	Initial Water Content	Porosity	Field Capacity	Wilting Point
1	0.55	0.3	0.55	0.44	0.15
2	0.25	0.2	0.55	0.44	0.15
3	0.15	0.35	0.55	0.44	0.15
4	0.05	0.35	0.55	0.44	0.15
5	0	0.44	0.55	0.44	-

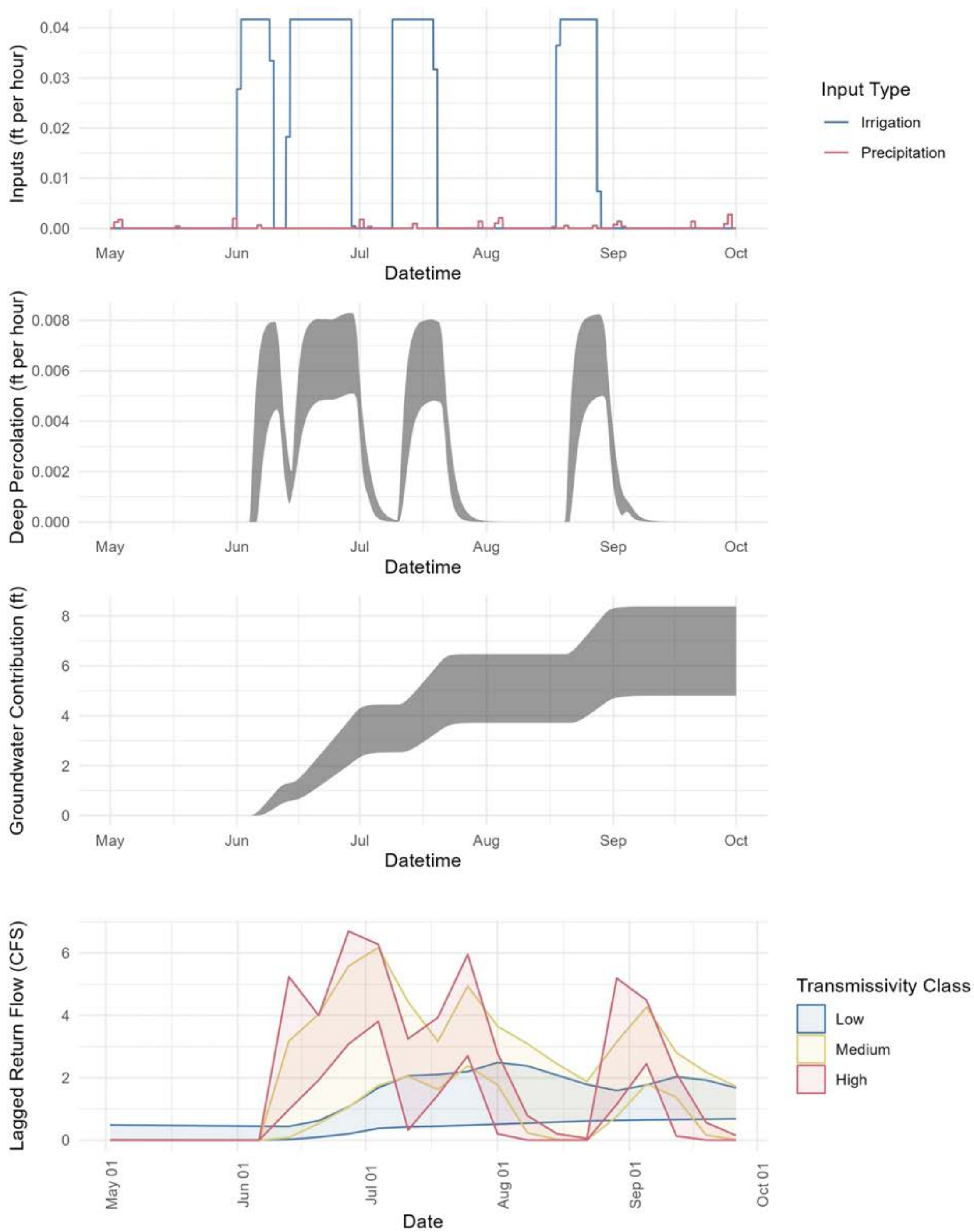


Figure 31: Simulated results for a year with normal operations including hydrologic inputs (ft/hr), deep percolation rates (ft/hour), cumulative groundwater contributions (ft), and lagged return flows (cfs). Envelopes in deep percolation and cumulative groundwater contribution depict uncertainty in the soil water balance model. Lagged return flow simulation envelopes are shown for different aquifer transmissivity classes including high (>1000 m^2/day, red), medium (100-1000 m^2/day, yellow), and low (<100 m^2/day, blue). Lagged return flow simulation envelopes depict combined uncertainty of soil water balance and groundwater return flows models.

Study Site: SPR T1

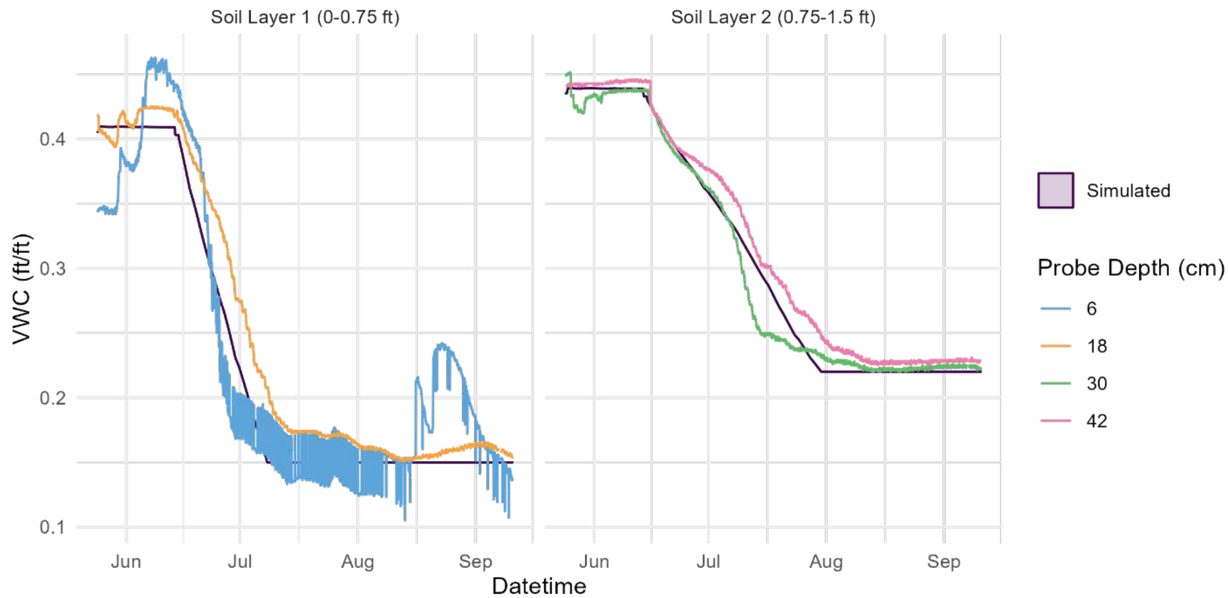


Figure 32: Observed vs simulated soil water balance for the top two soil layers in the soil water balance model. Probe depth was not deep enough for comparison with deeper soil layers in the model. Simulated envelope describe uncertainty in physical soil parameters including infiltration and saturated hydraulic conductivity.

Table 13: Soil Water Balance Physical Parameters by Layer

Soil Layer	Root Distribution	Initial Water Content	Porosity	Field Capacity	Wilting Point
1	0.5	0.37	0.42	0.4	0.15
2	0.2	0.43	0.44	0.43	0.22
3	0.15	0.4	0.44	0.4	0.22
4	0.15	0.4	0.45	0.4	0.22
5	0	0.4	0.45	0.4	-

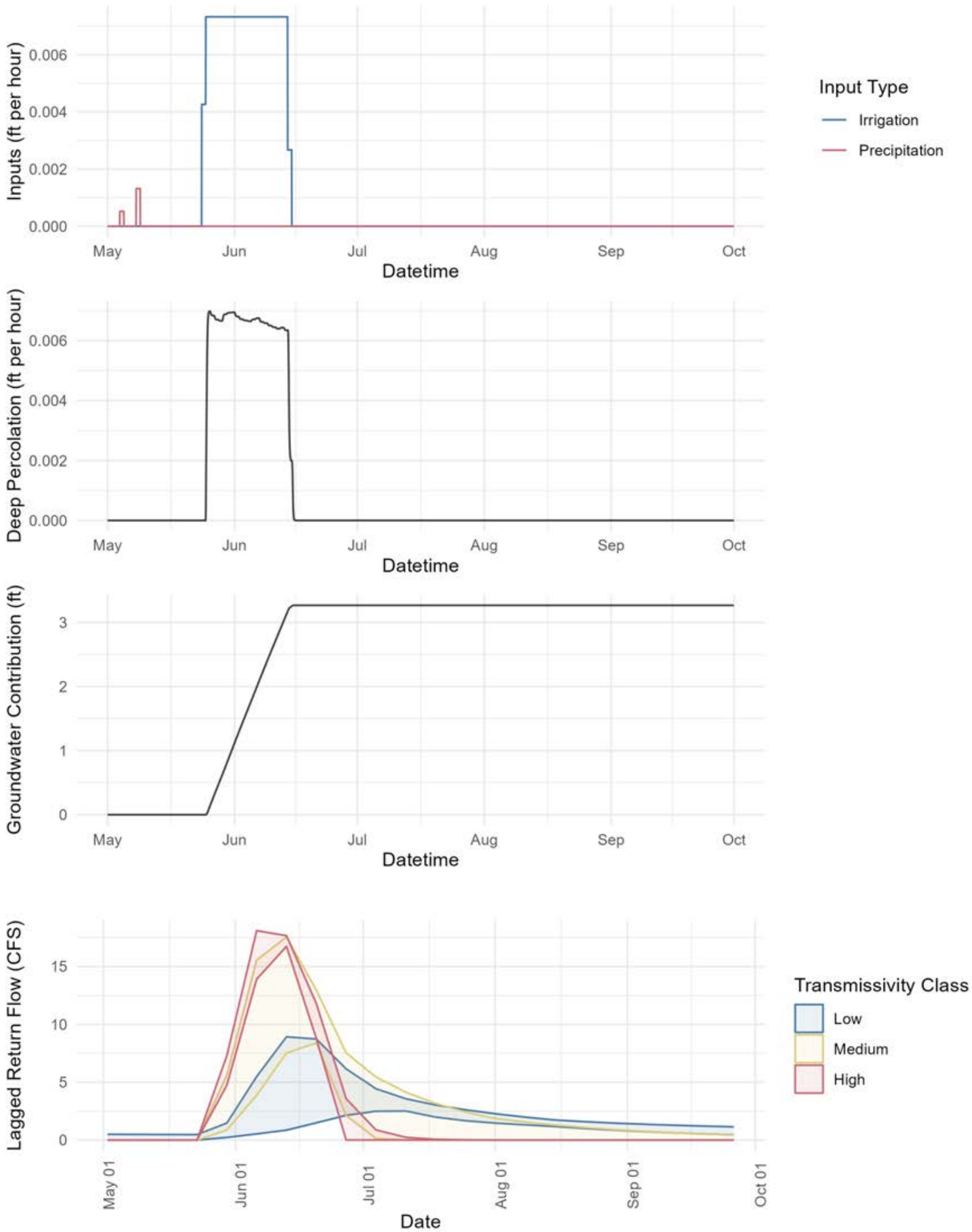
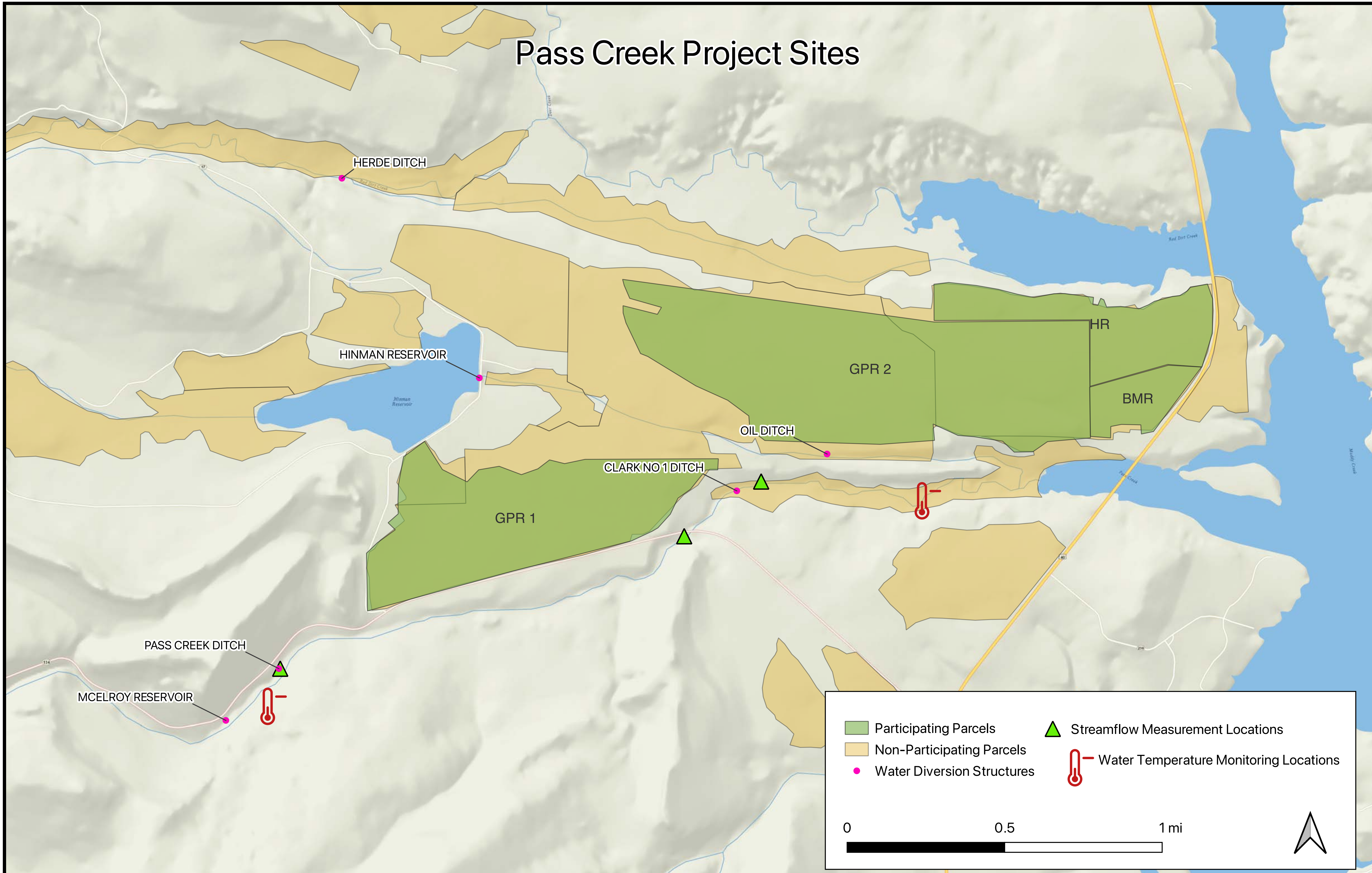


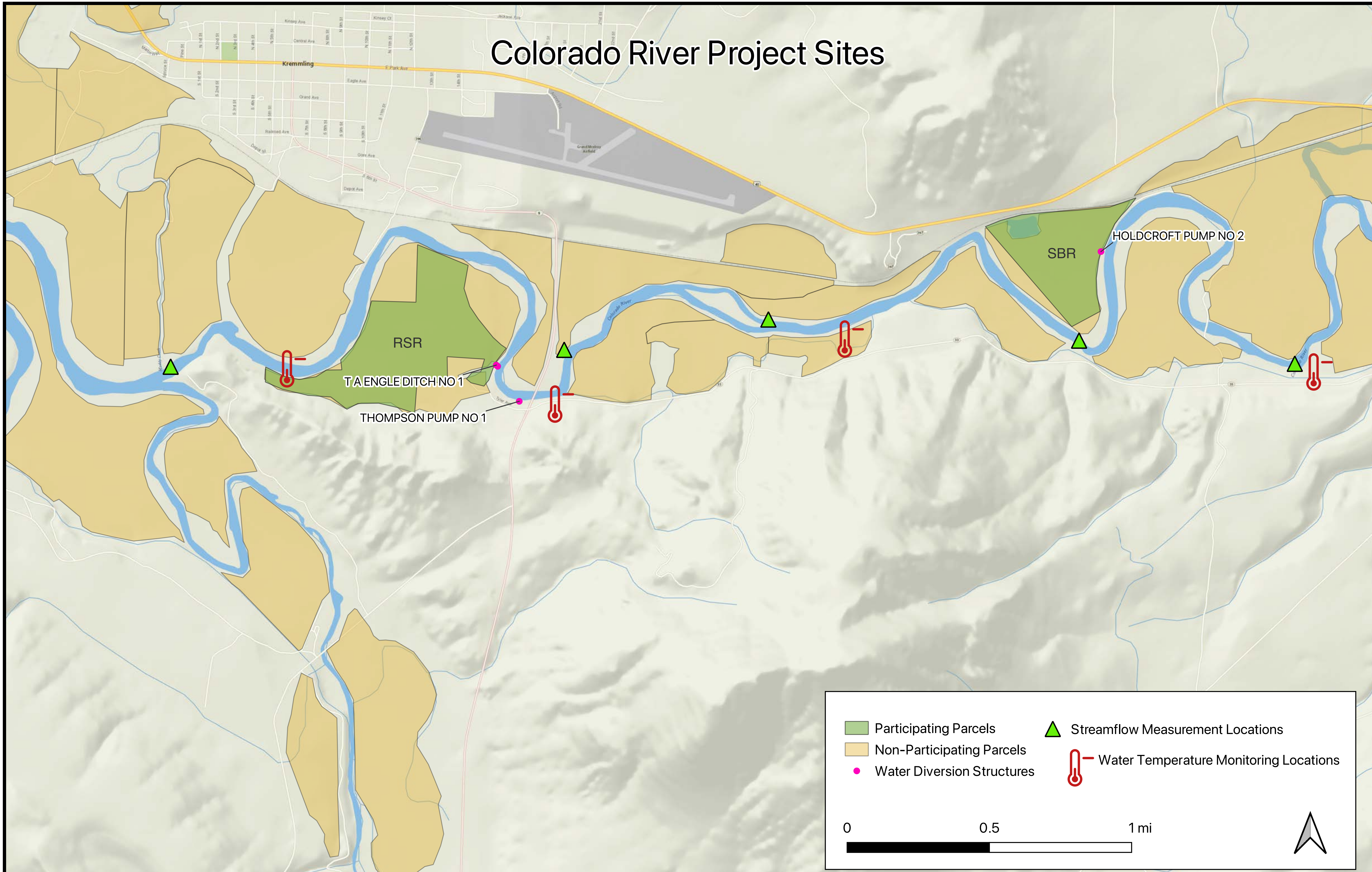
Figure 33: Simulated results for a year with normal operations including hydrologic inputs (ft/hr), deep percolation rates (ft/hour), cumulative groundwater contributions (ft), and lagged return flows (cfs). Envelopes in deep percolation and cumulative groundwater contribution depict uncertainty in the soil water balance model. Lagged return flow simulation envelopes are shown for different aquifer transmissivity classes including high (>1000 m^2/day, red), medium (100-1000 m^2/day, yellow), and low (<100 m^2/day, blue). Lagged return flow simulation envelopes depict combined uncertainty of soil water balance and groundwater return flows models.

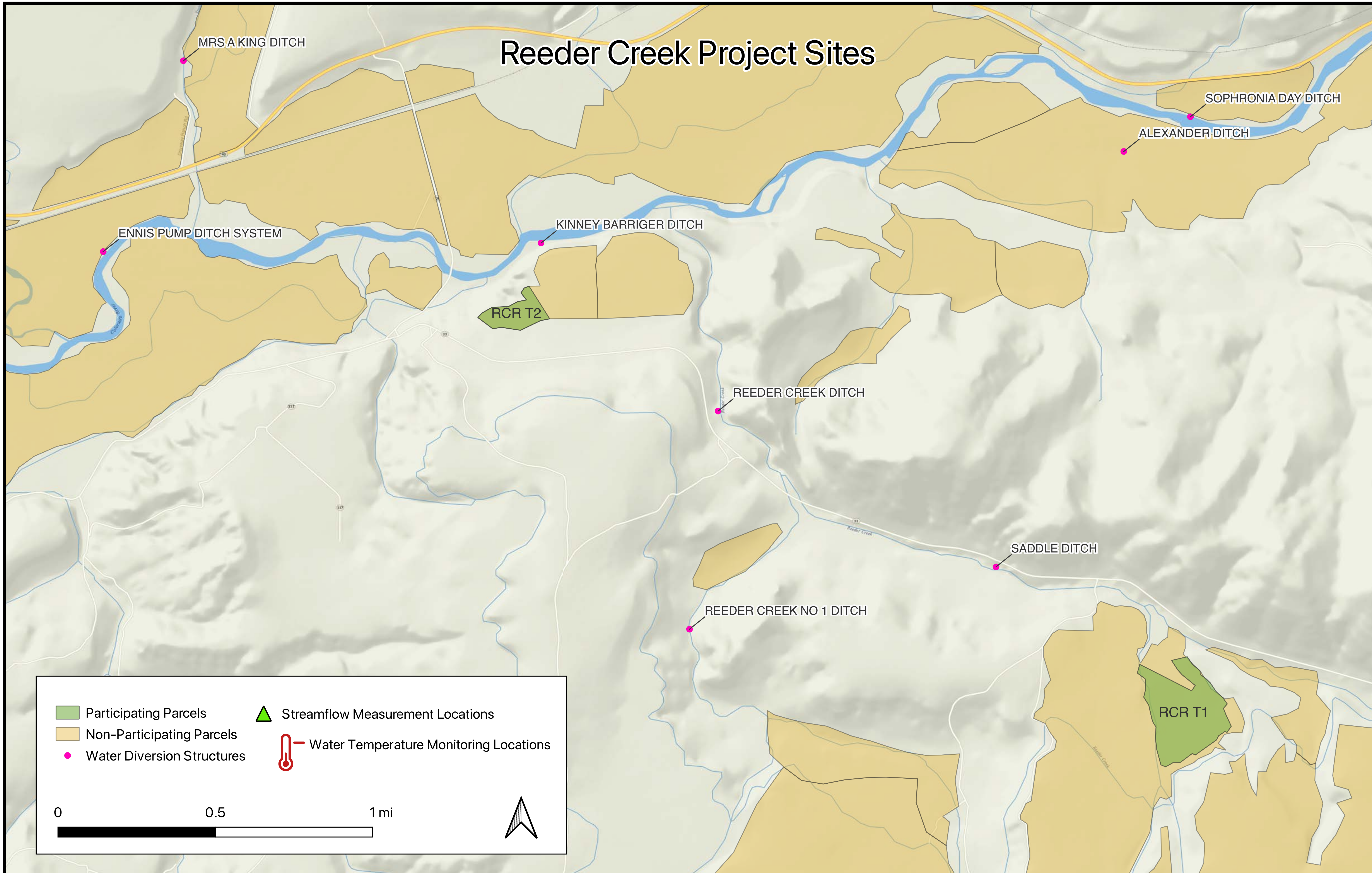
APPENDIX B: SITE MAPS

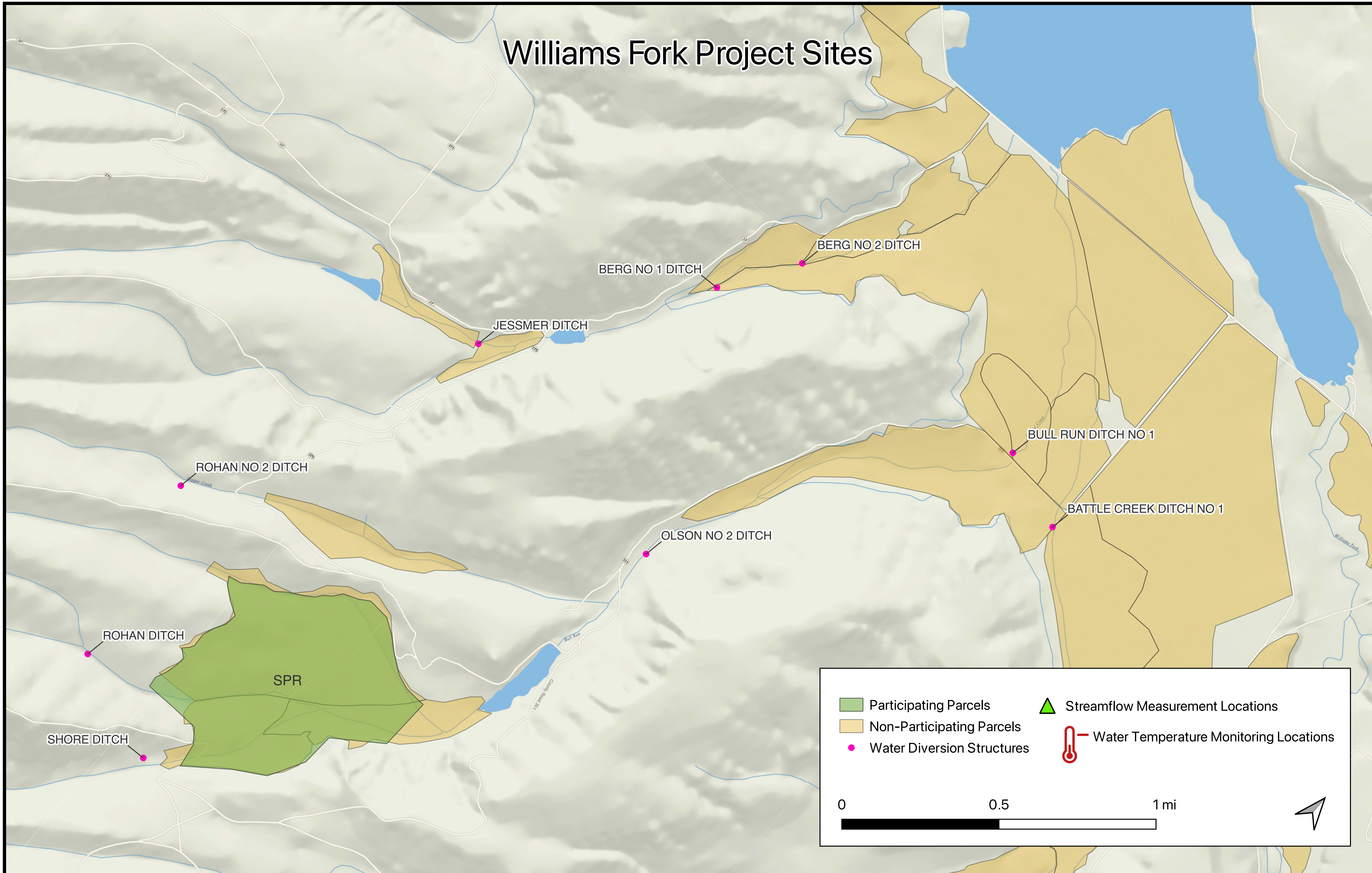


Pass Creek Project Sites
HERDE DITCH
HINMAN RESERVOIR
GPR 2
HR
BMR
OIL DITCH
CLARK NO 1 DITCH
GPR 1
PASS CREEK DITCH
MCELROY RESERVOIR
Participating Parcels
Non-Participating Parcels
Water Diversion Structures
Streamflow Measurement Locations
Water Temperature Monitoring Locations
0
0.5
1 mi

Colorado River Project Sites




Reeder Creek Project Sites
MRS A KING DITCH
SOPHRONIA DAY DITCH
ALEXANDER DITCH
ENNIS PUMP DITCH SYSTEM
KINNEY BARRIGER DITCH
RCR T2
REEDER CREEK DITCH
SADDLE DITCH
REEDER CREEK NO 1 DITCH
RCR T1
Participating Parcels
Non-Participating Parcels
Water Diversion Structures
Streamflow Measurement Locations
Water Temperature Monitoring Locations
0
0.5
1 mi


Williams Fork Project Sites
BERG NO 2 DITCH
BERG NO 1 DITCH
JESSMER DITCH
BULL RUN DITCH NO 1
BATTLE CREEK DITCH NO 1
ROHAN NO 2 DITCH
OLSON NO 2 DITCH
ROHAN DITCH
SPR
SHORE DITCH
Participating Parcels
Non-Participating Parcels
Water Diversion Structures
Streamflow Measurement Locations
Water Temperature Monitoring Locations
0
0.5
1 mi

APPENDIX C: CODE REPOSITORY

https://github.com/lotichydrological/soilwaterbalance.git