THESIS

QUANTIFYING THE HYDROLOGICAL EFFECTS OF CONVERTING FROM FLOOD IRRIGATION TO SPRINKLER IRRIGATION IN A SEMI-ARID STREAM AQUIFER SYSTEM

Submitted by

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ASTRACT

QUANTIFYING THE HYDROLOGICAL EFFECTS OF CONVERTING FROM FLOOD IRRIGATION TO SPRINKLER IRRIGATION IN A SEMI-ARID STREAM AQUIFER SYSTEM

Flood irrigation is commonly practiced in many semi-arid alluvial river valleys, particularly in the Upper Colorado River Basin. Due to high inefficiencies, particularly regarding field runoff and deep percolation, this practice can be seen as wasteful at the field scale, leading to calls for a switch to sprinkler irrigation. However, the hydrologic and ecosystem impacts of such a switch is not well understood. This thesis seeks to understand the hydrologic implications of a regional conversion from flood irrigation to sprinkler irrigation in a semi-arid alluvial aquiver system. The region of interest in this study is the area in and around Meeker, Colorado (180 km^2), which lies along the White River and its alluvial aquifer system, within the Upper Colorado River Basin. Hydrologic fluxes subject to change include ditch diversions, ditch seepage, irrigation runoff, irrigation recharge, and groundwater-river exchange. To accomplish this objective, we use a MODFLOW groundwater model, modified to include an irrigation package that accounts for all major hydrologic flows in the study region, for the 2019-2024 period. The model is calibrated and tested against measured values of groundwater head, ditch seepage, river flow, and groundwater return flows, with the latter performed for three sections of the White River. From model results, we conclude that during the period of study, approximately 90% of water diverted from the White River for irrigation is replenished by groundwater discharge. Irrigation efficiency is very low (40%), but the “lost” water recharges the aquifer, increasing groundwater storage and groundwater gradients, thereby inducing discharge to the

White River and its tributaries. From the scenario of converting all fields to sprinkler irrigation, we conclude the following:

1) Converting from flood to sprinkler irrigation results in a re-timing of river flow, as river flow increases in the summer months due to lower ditch diversions but decreases in the fall and winter months due to a decrease in groundwater return flows. On average, groundwater return flows to the White River decrease by 70%.

2) Converting from flood to sprinkler irrigation results in a drastic decrease in groundwater levels, with average declines of 5 ft in riverine wetlands, and 5% of total wetland area experiencing a decrease of over 5 ft.

These changes occur due to an overall decrease in hydrologic fluxes and water storage in the soil and aquifer. Less water is diverted from the White River to ditches, which leads to a decrease in ditch seepage recharge, applied irrigation, deep percolation, and groundwater recharge, leading to a decline in groundwater levels, groundwater storage, and groundwater gradients, resulting in less groundwater discharging to the White River and its tributaries, particularly during late-season months. This re-timing of river flow, i.e., less river water in the winter months, can have profound impacts on downstream hydropower and aquatic ecosystems. Furthermore, the decline in water table will result in the eventual drying of wetlands, impacting associated habitat and ecosystem services. This study highlights the importance of understanding unique hydrologic circumstances of regions when making major decisions about changing an area’s long-standing agricultural practice.

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1. Introduction

1.1 Background

Irrigation is the most common method for supplying water to agriculture in semi-arid regions. The dry climate requires water sources outside of weather to supply necessary crop water demands. Flood irrigation is the longest-standing and most common form of irrigation on the planet (FAO 1991; WaterHistory n.d.; Irrigation of World Agricultural Lands 2020). This method of irrigation offers several notable advantages to its users. Flood irrigation is versatile in scalability, covering both large and small areas of land. It requires simple maintenance and less consistent labor. Consisting of simple infrastructure and gravity as the primary driver of flow delivery, flood irrigation offers the benefits of low installation and energy consumption costs (WaterHistory n.d.). However, there are notable drawbacks to flood irrigation as well. One of the largest disadvantages to a flood-based system is the notable lack of efficiency in water delivery compared to other irrigation systems (El-Banna et al. 2025). The high volume of water flooding the fields often exceeds the field capacity of the soil, leading to water being lost to runoff or deep percolation to the aquifer (Seibert et al. 2018; Tulip et al. 2022). Additionally, flood irrigation often diverts higher amounts of water from nearby sources, which can decrease water and flow levels in the area (Ferencz and Tidwell 2022). Due to these drawbacks, users often face incentives to convert existing flood irrigation systems to more efficient irrigation systems including sprinkler systems or drip systems (for higher value crops). Often, the increase in efficiency is the driving factor for switching irrigation systems (El-Banna et al. 2025; Seibert et al. 2018). However, potential hydrologic consequences can be faced when undergoing this conversion, and the effects are not often considered or quantified. In many regions, irrigation systems are widely used and play significant roles in the area's hydrological cycle, contributing groundwater levels, groundwater return flows, water body levels, and river flow rates (Ferencz and Tidwell 2022; Zhu et al. 2018).

Notable studies have been conducted attempting to understand hydrologic impacts due to irrigation changes. Some studies have shown that a switch from flood irrigation to a more efficient system increases efficiency but decreases groundwater storage in the area due to less deep percolation. A 2021 study attempted to use modeling to quantify this when investigating a switch from flood to drip irrigation in a semi-arid Mediterranean region. The study found that groundwater recharge saw a 10% drop when flood irrigation was replaced with drip irrigation (Pool et al., 2021). Another study in 2019 used a SWAT-MODFLOW model to identify system responses of irrigation reduction, which would be implied in a flood to sprinkler system switch. This study highlighted that just a 10% reduction in irrigation would see notable reductions in surface runoff, evapotranspiration, groundwater recharge. The study also found that groundwater return flows increased when undergoing this reduction, but crop yields decreased by 9%. However, this irrigation was sourced from the aquifer, not surface water (Wei, Bailey, 2019). Another study sought to understand the specific importance of flood irrigation in a flood-irrigated stream-aquifer system (Gordon et al., 2020). This study found that lost water in flood irrigation replenishes the stream both during and after irrigation. The results showed that 29% of water would return to the stream as runoff, with another 18% of the water returning to the stream via return flows after irrigation had stopped.

Multiple studies have undergone research specifically related to flood to sprinkler conversion, with similar trends being identified amongst the results. A major finding was that a switch from flood to sprinkler irrigation resulted in increased river flow during peak seasons but decreased late-season flow and annual groundwater storage within the stream-aquifer system.

Studies conducted by Ven et al. (2004), Sando et al. (1988), and Peterson (2011) all reported these similar findings. Additionally, these studies investigated return flows due to the flood to sprinkler change and found that return flows also saw decreases in later seasons.

Return flows and irrigation practices have been noted to be very important to maintaining both groundwater levels and streamflow throughout the year. Findings from Cai and Zeng (2013), Caldwell and Eddy-Miller (2014), and Winter (2007) all discuss that return flows play a crucial role in delivering water to nearby streams in arid or semi-arid systems during late seasons. A study conducted by Ferencz and Tidwell (2022) specifically wanted to investigate impact from irrigation management strategies on return flows. The study was conducted in a stream-aquifer system located in an irrigated alluvial valley. Results from the study found that return flows that specifically originating from irrigation are crucial to providing supplementary streamflow to the river. This supplementary streamflow proves important in providing water to the river in locations where snowmelt-dominated streamflow sees sharp declines in late seasons. Findings from these studies all imply importance in monitoring how these hydrologic fluxes change with changes in irrigation systems and water management. Groundwater modeling has shown significant potential to be useful in quantifying hydrological impacts due to irrigation. Multiple previously mentioned studies used modeling to draw their conclusions including Ferencz and Tidwell (2022), Bailey and Wei (2019), Peterson (2011), and Cai and Zeng (2013).

A recent modeling effort aimed at quantifying hydrologic fluxes within a river valley dominated by flood irrigation was conducted by Bailey (2025), who developed a new irrigation package for MODFLOW that accounts for all major hydrological fluxes in flood irrigated systems, such as daily ditch diversions, ditch seepage, irrigation, runoff from rainfall and irrigation, crop ET, recharge, and groundwater-river exchange. The irrigation package uses a soil water balance to simulate runoff, ET, soil water storage, and recharge to the water table. The study focused on a region along the White River located in Meeker, Colorado, and tested the model against groundwater-river exchange rates for three sections along the White River and general groundwater levels. The model simulation period is 2019-2023, and runs on a daily time step. From modeling results, the author concluded that 75% of the water diverted from the White River for irrigation returns to the river via groundwater recharge, groundwater flow through the unconfined aquifer, and then discharge to the river. Also, these return flows to the river occur primarily in the fall and winter months, thereby sustaining river flow during post-irrigation months, which can have beneficial effects for downstream hydropower, riparian ecosystems, and fish populations. However, although the study proposed likely hydrologic impacts if flood irrigation were changed to sprinkler irrigation, it did not quantify this conversion. The model also did not account properly for ditch seepage, a major component of the hydrologic cycle within the study region. The study also did not assess the impact of flood irrigation on ecosystem services, such as wetland development and maintenance within the region.

1.2 Purpose

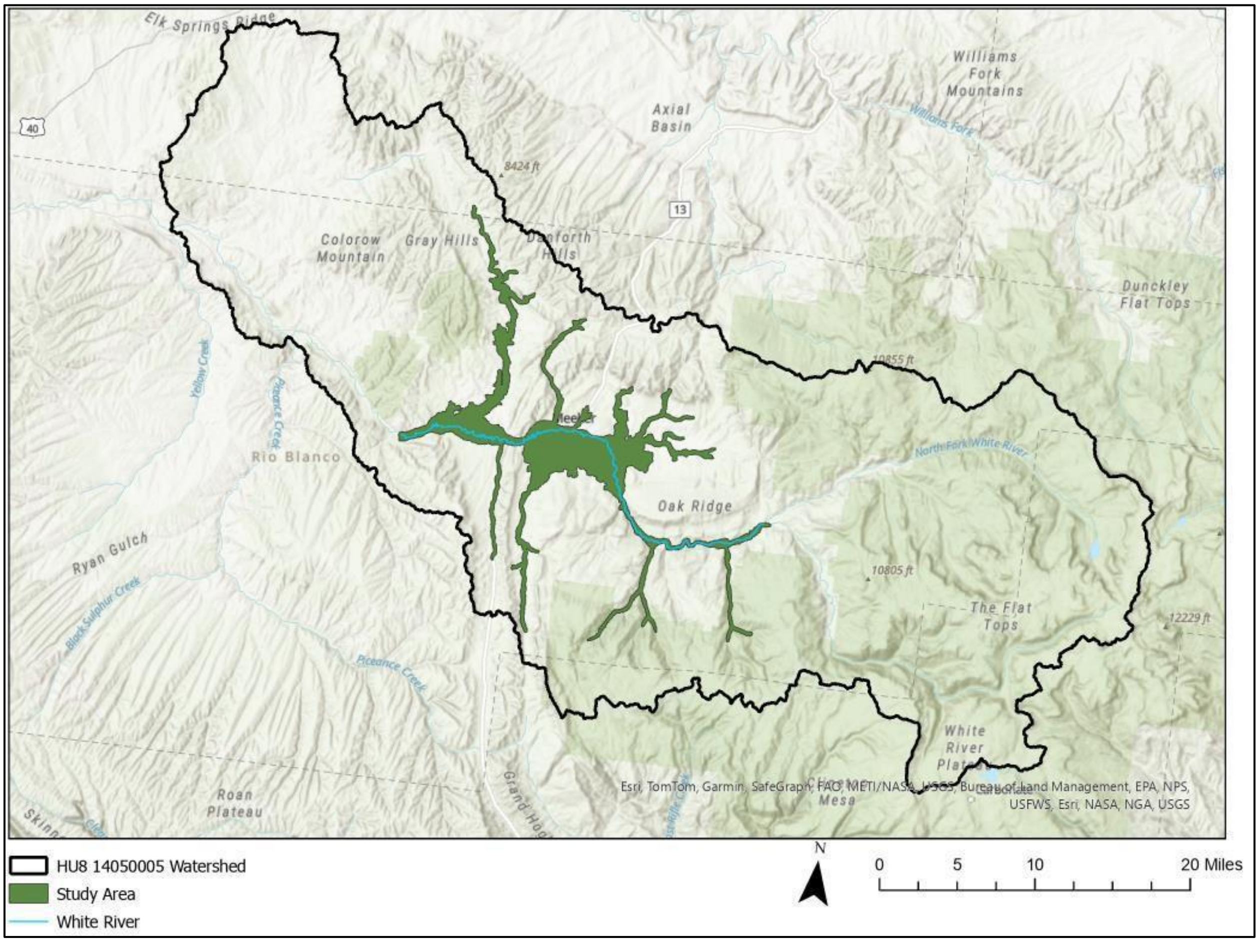
The objective of this thesis is to quantify the hydrologic and ecological effects of converting from flood irrigation to sprinkler irrigation in a semi-arid region. Effects being analyzed include spatio-temporal changes in groundwater recharge, groundwater storage, groundwater table elevation, and groundwater return flows and river exchange. Additionally, a focus will be put on understanding specific impacts within wetland environments, specifically the change in water table elevation and how that might affect wetland development and/or maintenance. To accomplish these objectives, the existing MODFLOW model for the White River Valley (Bailey 2025) was extended through the 2024 irrigation season, calibrated and tested against groundwater-river exchange rates and measured groundwater head from a network of monitoring wells, and then run through a variety of sprinkler conversion scenarios. Conversion to sprinkler irrigation consisted of both a decrease in river diversions, since sprinkler irrigation requires less water, and a decrease in runoff from applied irrigation. Model results were analyzed for change in groundwater return flows, timing and magnitude of river flow rate, and groundwater head magnitude and fluctuations.

In this thesis we do not analyze the economic cost of conversion from flood to sprinkler irrigation. The findings from this study can be used to guide decisions on irrigation type and conversion impact for the study region and other flood irrigated river valleys within the Upper Colorado River Basin. The model can be used generally as a decision support tool for irrigation management considerations within the study region and other areas of similar climate and geography. The developed MODFLOW model can also be applied to similar regions to aid in their specific management practices as well.

2. Materials and Methods

2.1: Study Region

The region of interest in this study is the White River Valley within the vicinity of Meeker, Colorado, located within the Upper White watershed (USGS HUC8 14050005) within the Upper Colorado River Basin. Specifically, we focus on a segment of the White River that spans 32.8 miles in length within the region (Figure 1)



Esri, TomTom, Garmin, SafeGraph, FAO, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, USFWS, Esri, NASA, NGA, USGS

Figure 1: Map of White River Basin and Study Area

The climate is semi-arid and sits on the western slope of the Rocky Mountains. The regional climate includes moderate rainfall throughout the year and earlier snowmelt than average. In 2024, the average daily temperature was 6.5 degrees Celsius (43.7 degrees Fahrenheit) and the average maximum daily temperature reached 16.4 degrees Celsius (61.5 degrees Fahrenheit) (CoAGMET, 2025). Average precipitation in the region is approximately 409 mm/yr (16.1 in/yr) (US Climate Data, 2025). Peak streamflow often occurs in May and June because of early snowmelt. The river valley contains a shallow, highly transmissive unconfined alluvial aquifer originating from alluvium deposits from the White River (Van Liew and Gesink, 1985). Tributaries to the White River, such as Miller Creek, Coal Creek, Flag Creek, and Strawberry Creek also flow through narrow alluvial channels, overlying alluvial aquifer material.

Recharge to the aquifer is largely due to irrigation, rainfall, and ditch seepage, which maintain high groundwater levels and groundwater gradients that induce groundwater flow to the White River and its tributaries (Van Liew and Gesink, 1985; Bailey, 2025). Based on the field study of the region from Van Liew and Gesink (1985), hydraulic conductivity (K) of the aquifer material ranges from 20 to 470 m/day and specific yield ranges from 0.1 to 0.3. From the modeling study of Bailey (2025), K values were refined to a range of 70 to 1550 ft/day, with the region divided into aquifer units based on a dataset of material type from a network of 414 drilled boreholes in the region (CDWR; https://dwr.state.co.us/Tools/WellPermits, accessed November 2023). However, the values of K were estimated based on a small set of groundwater head values, and likely can be determined with more certainty through additional model calibration.

Irrigation within the study area for the 322 fields is predominantly flood-based (approximately 95%; CDWR, 2020). Dominant crops include grass hay and alfalfa (90% grass, 10% alfalfa) (CDSS, 2025). Irrigated fields are often used for grazing cattle in the area as well. Irrigation water is supplied by a network of 30 ditches that divert water from the White River. Ditch water either seeps to the aquifer or is applied to fields. Applied water can run off the field (and can be captured by downgradient ditches for reuse), be used by crops, add to soil water storage, or percolate through the soil profile to become recharge for the aquifer. As found by Bailey (2025), recharge is approximately 60% of applied water, which increases groundwater storage and establishes groundwater gradients that induce significant flow to the White River. The ratio of groundwater discharge to ditch diversions is approximately 80%, based on both a water balance study of the river and results from the MODFLOW simulations (Bailey, 2025). A map of irrigated field diversions is shown in Figure 2.

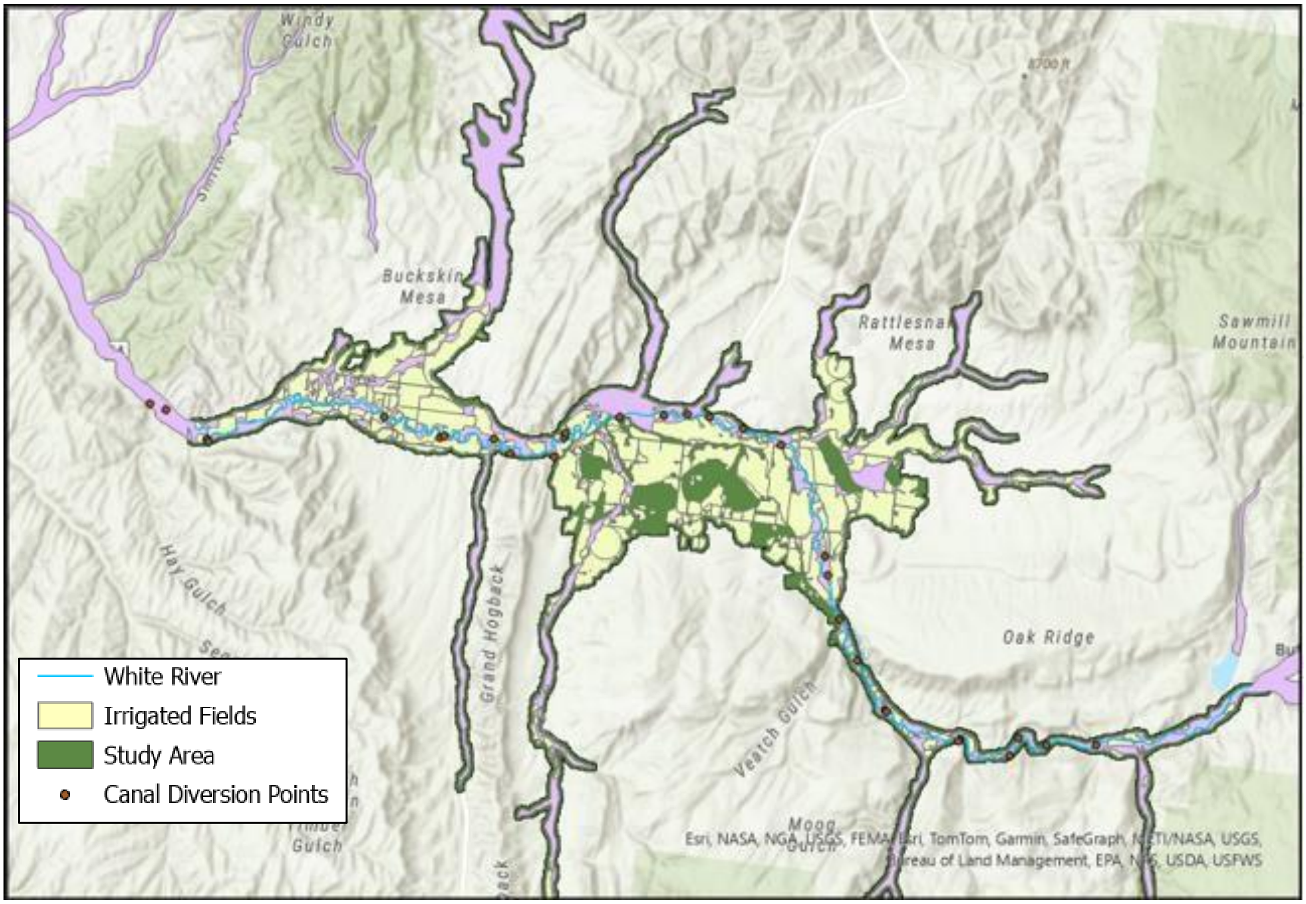
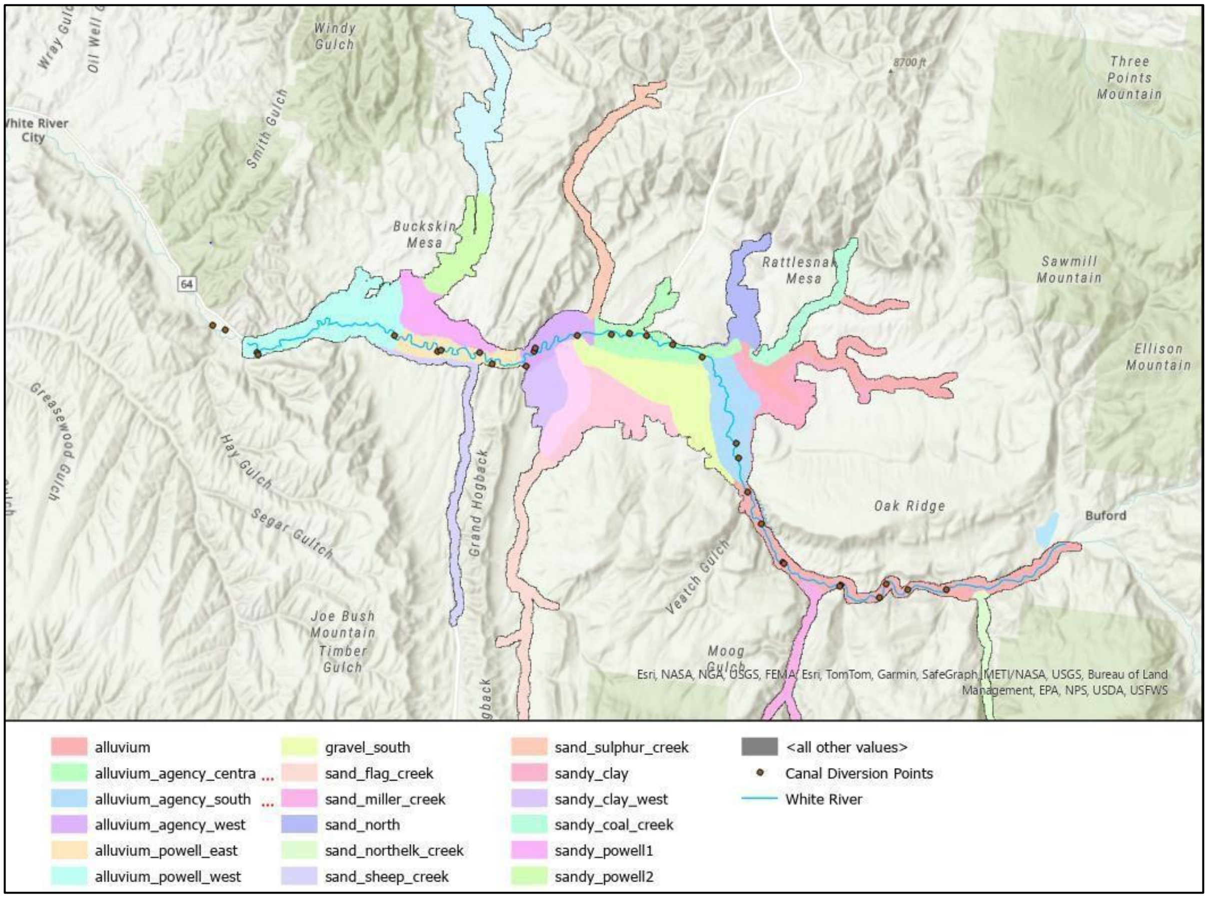


Figure 2: Map of canal diversion points, irrigated fields, and the alluvial aquifer located within the study period

2.2 MODFLOW Model with Irrigation Package

2.2.1 MODFLOW Model Construction

For this study we used the MODFLOW model published by Bailey (2025), in which an irrigation package is developed to simulate the unique hydrological features of flood irrigation. The base model is constructed using MODFLOW-NWT (Niswonger et al., 2011). MODFLOW simulates the storage and multi-dimensional flow of groundwater within a multi-layer aquifer system subject to boundary conditions and a variety of groundwater inflows and outflows. The MODFLOW grid consists of 977 rows and 836 columns, using 200 ft cells, resulting in 48,627 active cells (i.e., cells within the alluvial aquifer system of the region). Each grid cell was provided with groundwater surface (ft) using a 10-m DEM; bedrock elevation (ft) using interpolated values from drill logs of 414 boreholes; and initial values of hydraulic conductivity K (ft/day) and specific yield S_y for 21 geologic units, with unit boundaries based on material type from the 414 boreholes. Due to the shallow depth of the alluvial aquifer, the aquifer system was represented by a single layer. Cells that intersect ditches, the White River, and river tributaries were designated as “River Cells” for which groundwater-surface water exchange is simulated using the River Package. This resulted in 3,478 River Cells, of which 2,235 are cells that intersect irrigation ditches. The model also simulates groundwater pumping for municipal water supply. The town of Meeker has 8 pumping wells that extract groundwater from the alluvial aquifer within the immediate vicinity of the White River. The town of Meeker provided monthly pumped volumes, which were included in the model using the Well Package. The model is run on a daily time step for the 2019-2023 period. Maps of the geologic units in the MODFLOW grid and irrigated fields can be seen in Figure 3 and Figure 4



Esri, NASA, NGA, USGS, FEMA, Esri, TomTom, Garmin, SafeGraph, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, USDA, USFWS

Figure 3: Geologic units in the MODFLOW grid

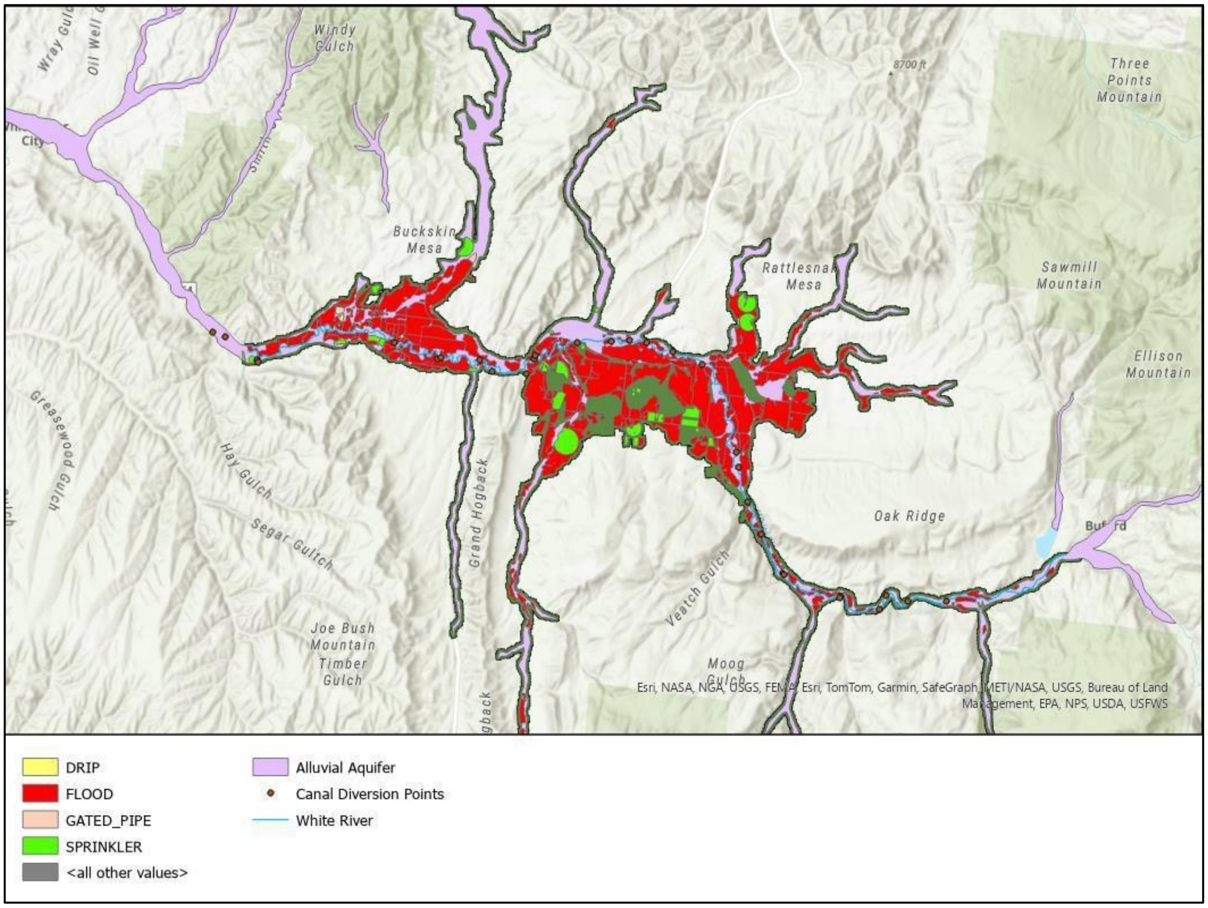
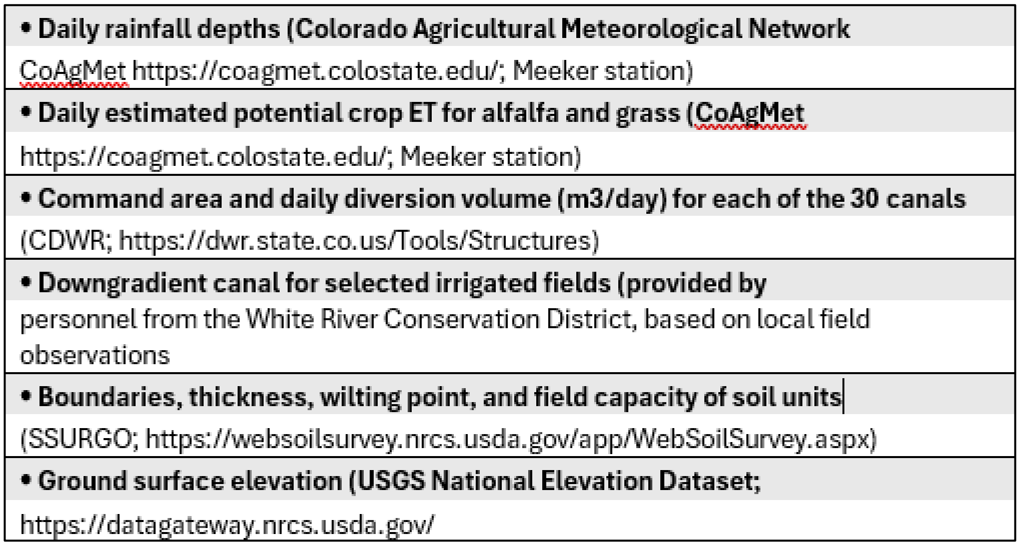


Figure 4: Irrigation systems for each irrigated field in the study area

2.2.2 Irrigation Package for MODFLOW

Bailey (2025) prepared a new irrigation package for MODFLOW-NWT, which simulates a ditch water balance for each irrigation ditch and a soil water balance for each designated hydrologic response unit (HRU), with each HRU consisting of a unique combination of soil type, irrigated field, natural vegetation areas, and topographic slope. Table 1 lists data sources for irrigation package inputs.



• Daily rainfall depths (Colorado Agricultural Meteorological Network CoAgMet https://coagmet.colostate.edu/; Meeker station)
• Daily estimated potential crop ET for alfalfa and grass (CoAgMet https://coagmet.colostate.edu/; Meeker station)
• Command area and daily diversion volume (m3/day) for each of the 30 canals (CDWR; https://dwr.state.co.us/Tools/Structures)
• Downgradient canal for selected irrigated fields (provided by personnel from the White River Conservation District, based on local field observations
• Boundaries, thickness, wilting point, and field capacity of soil units (SSURGO; https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx)
• Ground surface elevation (USGS National Elevation Dataset; https://datagateway.nrcs.usda.gov/

Table 1: Source list for irrigation package inputs

The ditch water balance consists of water diverted from the White River (input, *div*), ditch seepage (output, *seep*), groundwater discharge (input, *gw*), irrigation application (output, *irr*), and runoff water collected from upgradient fields (input, *ro*), and ditch water storage. For each ditch, the daily change in ditch water volume V_{ditch} (L^3) is given as:

$$\frac{\Delta V_{ditch}}{\Delta t} = Q_{div} - Q_{irr} + Q_{gw} - Q_{seep} + Q_{ro} \qquad (1)$$

Daily diversions Q_{div} (L^3) are input to the model for each ditch in the model domain, with values obtained from CDWR. The volume of irrigation Q_{irr} is based on a user-defined fraction, with the option of leaving a portion of water in the ditch to be released at the downstream end into a tributary. Q_{gw} and Q_{seep} are aggregated values from all grid cells that intersect the ditch, with exchange rates calculated using the River Package. Runoff Q_{ro} is estimated using the soil water balance for HRUs (see Equation 2). In the irrigation package input files, the connection between upgradient ditches and downgradient ditches is specified by the user. For example, runoff from irrigated fields within the Miller Creek Ditch irrigation command area is given to the Highland

Ditch, which can then seep to the aquifer or be applied to fields within the Highland Ditch command area.

The soil water balance consists of inputs of rainfall (*rain*) and irrigation (*irr*) and outputs of runoff (*ro*), crop ET (*ET*), and deep percolation (*dp*). The daily change in soil water volume V_{soil} (L^3) is given as:

$$\frac{\Delta V_{soil}}{\Delta t} = Q_{rain} + Q_{irr} - Q_{ro} - Q_{ET} - Q_{dp} \qquad (2)$$

Daily rainfall is provided by the local CoAgMet (https://coagmet.colostate.edu/) Meeker weather station. Irrigation is provided from the HRU's designated source ditch, with the daily ditch volume applied to fields based on the surface area of each field within the ditch command area. Runoff is determined using specified runoff fractions obtained from locally collected data, with flood irrigation and sprinkler irrigation set to 15% and 5%, respectively, of applied irrigation water. Crop ET is estimated each day using potential ET calculated by the CoAgMet weather station data, and the simulated available water storage V_{soil} within the soil profile. Crop ET is lost to the system (atmosphere), whereas field runoff can be captured by downgradient ditches (input in Equation 1) and deep percolation becomes recharge to the underlying aquifer. Recharge from HRUs is mapped to the MODFLOW grid cells, for the Recharge Package, using area average weighting. The geographic intersection between HRUs and MODFLOW grid cells is performed using GIS, with intersection information stored in an input file and read into the Irrigation Package routines for use throughout the MODFLOW simulation.

During the MODFLOW simulation, the Irrigation Package provides outputs water balance volumes for the entire domain, for each ditch, and for each HRU on a daily, monthly, yearly, and total basis. These outputs are used to analyze fluxes for each water balance component. Irrigation Package inputs are generic so that it can be applied to any irrigated region with a MODFLOW model.

The model from Bailey (2025) was tested against groundwater-river exchange (White River) and general groundwater head values. Groundwater-river exchange for field conditions was estimated for three sections of the White River using a daily water balance. The three sections are (Figure 5):

(1) USGS gage 09304115 (White River below North Elk Creek) to USGS gage 0934200 (White River above Coal Creek, near Meeker) (18.1 km)

(2) USGS gage 09304200 to USGS gage 09304500 (White River near Meeker) (5.7 km)

(3) USGS gage 09304500 to USGS 09304800 (White River below Meeker) (29.1 km)

For each section, the following water balance is used:

$$\frac{\Delta V_{river}}{\Delta t} = Q_{inflow} + Q_{trib} + Q_{gw} - Q_{outflow} \qquad (3)$$

Daily inflow and outflow are provided by the USGS gages; tributary inflow (*trib*) is estimated using a SWAT+ (Bieger et al., 2017) model for the Upper White watershed, which uses daily weather, land use, soil type, and topographic slope to simulate rainfall-runoff-infiltration processes. The overall hydrologic fluxes for the model agree well with regional values approximate by Reitz et al. (2017). By setting Equation 3 = 0 by assuming that for a given day the volume of water in the river section does not change (i.e., steady flow conditions), then the volume of groundwater entering the river section can be estimated:

$$Q_{gw} = Q_{outflow} - Q_{inflow} - Q_{trib} \qquad (4)$$

These daily values are then compared to the model simulated values from MODFLOW, with the groundwater-river exchange rates for each of the three river sections computed by aggregating results from all River Cells within the section.

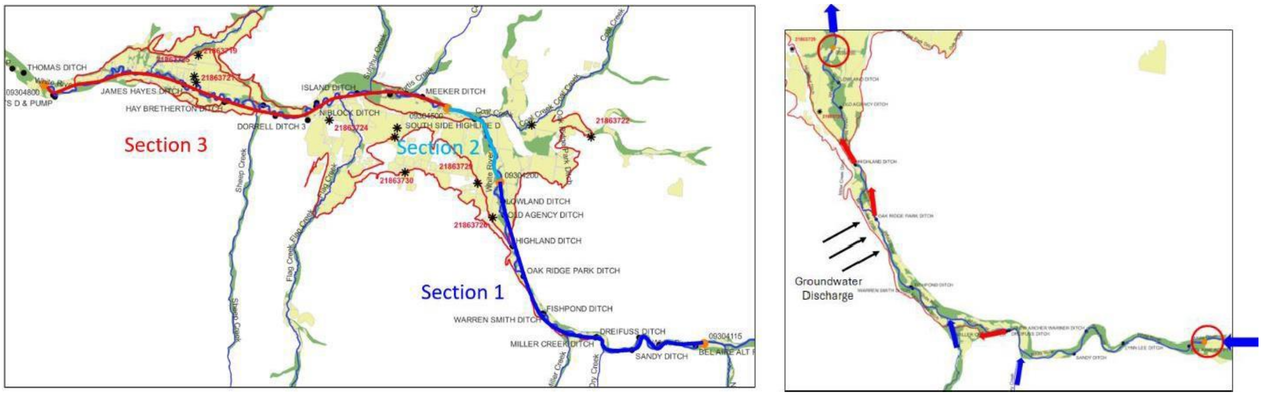


Figure 5. (left) River sections for which a water balance approach was used to estimate groundwater return flow rates; (right) Map of Section 1 of the White River, showing the components of the river water balance approach.

Simulated groundwater head values were compared loosely with measured head values from a network of 11 monitoring wells. However, only two months of data were used, since the monitoring wells became operations in November 2023 and the model simulation period ends in 2023. Therefore, although general groundwater levels are accurate, the model could not be compared to temporal changes in groundwater head, as would be expected during the spring and summer months due to rainfall and irrigation inputs and outputs.

To provide a reasonable match between measured and simulated groundwater-river exchange and groundwater head, Bailey (2025) used PEST (White et al., 2020) to estimate aquifer properties (K, S_y) and riverbed conductance.

2.3 Model Expansion

2.3.1 Extending the model to 2024

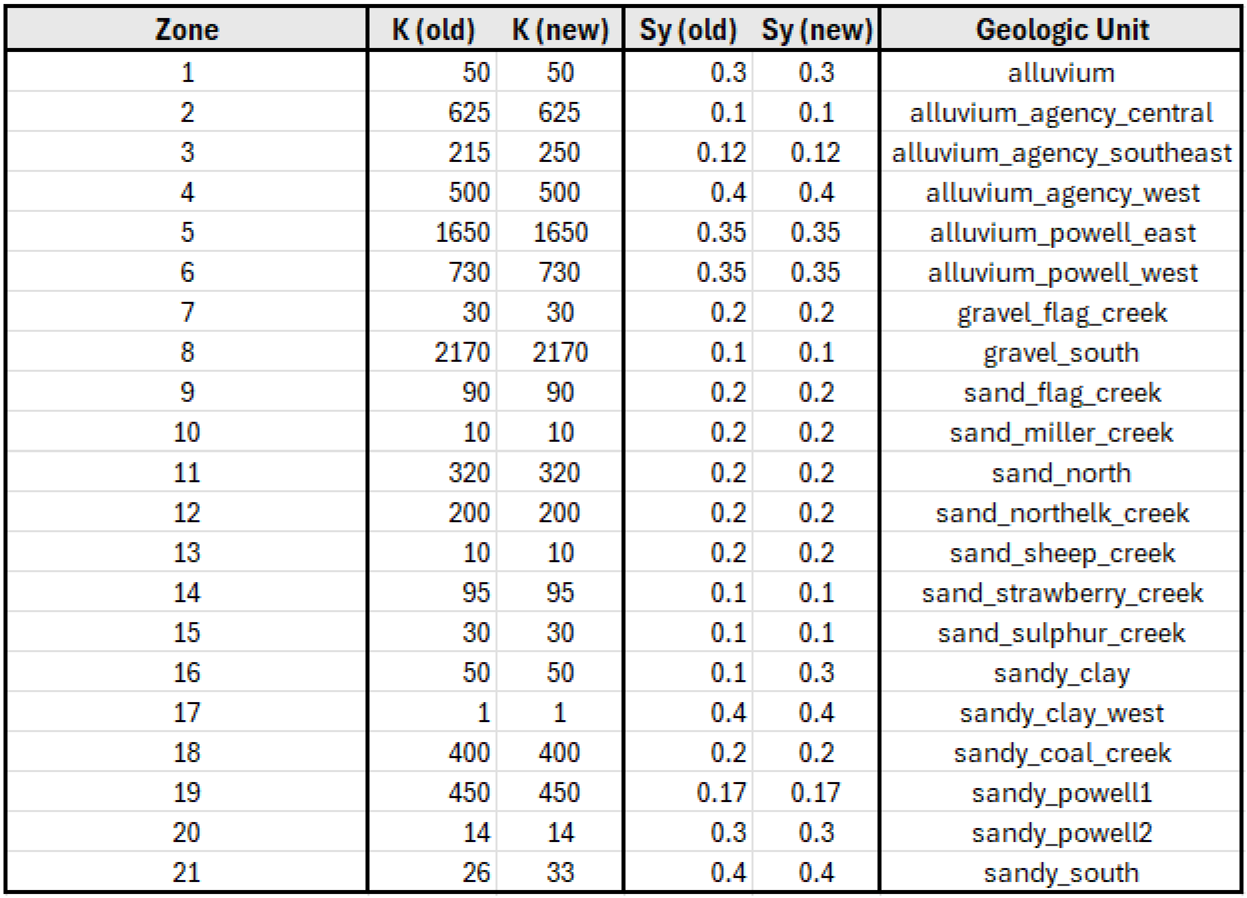
In this study, we extend the model to include the 2024 irrigation season, which also allows us to test the model against additional groundwater-river exchange data and measured groundwater head from a network of 11 monitoring wells, installed in November 2023. In addition, we can compare simulated ditch seepage rates with rates measured in a field study in summer 2024 conducted by the Farmer Conservation Alliance. To extend the MODFLOW model and Irrigation Package to 2024, we prepared the following for 2024 and amended the Irrigation Package input files:

- Daily rainfall and potential ET depths from CoAgMet, Meeker station
- Monthly pumping volumes for the 8 municipal wells for the town of Meeker
- Daily ditch diversion volumes for the 30 ditches

In addition, we fixed a mistake that occurred in the Bailey (2025) study. The previous version of the MODFLOW model used a fixed river stage for each cell in the River Package. In this study, we amended the River Package to include time-varying river stage for each cell using gage data from the USGS gaging stations. This will provide a more accurate estimation of groundwater-river exchange for the various seasons of the year.

2.3.2 Model Calibration and Testing

The updated model was calibrated and tested using monthly average groundwater head (ft) from the 11 monitoring wells for the period of November 2023 to October 2024. Manual calibration was performed by adjusting aquifer K, aquifer S_y, and riverbed K, for the various geologic units. The final calibrated values are provided in Table 2. Additional model testing includes 1) monthly average groundwater-river exchange rates for the three river sections, 2) ditch seepage for the Highline Ditch and the Oak Ridge Ditch, 3) flow rates in Flag Creek and Strawberry Creek, two major tributaries to the White River for which flow is made up of groundwater return flows from irrigated areas during most of the year, and 4) flow rates in the White River at USGS gaging locations, with the simulated hydrographs constructed using groundwater-river exchange rates, groundwater-tributary exchange rates, and tributary inflows from the upstream end of the model domain to the downstream end. Old and newly adjusted parameters are listed in Table 2



Zone	K (old)	K (new)	Sy (old)	Sy (new)	Geologic Unit
1	50	50	0.3	0.3	alluvium
2	625	625	0.1	0.1	alluvium_agency_central
3	215	250	0.12	0.12	alluvium_agency_southeast
4	500	500	0.4	0.4	alluvium_agency_west
5	1650	1650	0.35	0.35	alluvium_powell_east
6	730	730	0.35	0.35	alluvium_powell_west
7	30	30	0.2	0.2	gravel_flag_creek
8	2170	2170	0.1	0.1	gravel_south
9	90	90	0.2	0.2	sand_flag_creek
10	10	10	0.2	0.2	sand_miller_creek
11	320	320	0.2	0.2	sand_north
12	200	200	0.2	0.2	sand_northelk_creek
13	10	10	0.2	0.2	sand_sheep_creek
14	95	95	0.1	0.1	sand_strawberry_creek
15	30	30	0.1	0.1	sand_sulphur_creek
16	50	50	0.1	0.3	sandy_clay
17	1	1	0.4	0.4	sandy_clay_west
18	400	400	0.2	0.2	sandy_coal_creek
19	450	450	0.17	0.17	sandy_powell1
20	14	14	0.3	0.3	sandy_powell2
21	26	33	0.4	0.4	sandy_south

Table 2: Old and new parameter values for hydraulic conductivity (K) and specific yield (Sy) from model calibration

2.4 Quantifying the Impact of Conversion to Sprinkler Irrigation

Using the calibrated and tested model, we quantified the hydrologic and ecosystem impact of converting from flood irrigation to sprinkler irrigation, for each of the 322 fields within the study region. The 40 fields which were originally sprinkler irrigated were maintained as sprinkler irrigation.

Within the modeling framework, converting from flood irrigation to sprinkler irrigation consists of two changes to model inputs: 1) within the “irg.field_db” file, changing the irrigation type from “FLOOD” to “SPRINKLER”, thereby using irrigation runoff fractions of 0.05 rather than 0.15; and 2) within the “irg.irrig” file, decreasing the daily volume of ditch diversions from the White River. For the latter, this is instituted because sprinkler irrigation uses less water, and therefore less water is required for diversion from the river. However, the degree to which diversions will decrease under a sprinkler regime is not known with certainty. To estimate this, decrease, we ran the MODFLOW model for 9 scenarios, with diversion amounts ranging from 10% to 90% of the original diverted volumes. For each scenario, we compared the simulated total crop ET volume with the baseline crop ET, to determine the threshold diversion volume at which crop ET begins to decline (Figure 6). Based on these results, a large change in crop ET occurs between the 30% and 40% diversion changes. Assuming that farmers will not allow crop ET to decline but also use as little water as possible, we used the 40% scenario (i.e., diversion is 40% of the original diverted volume) as the target diversion fraction.

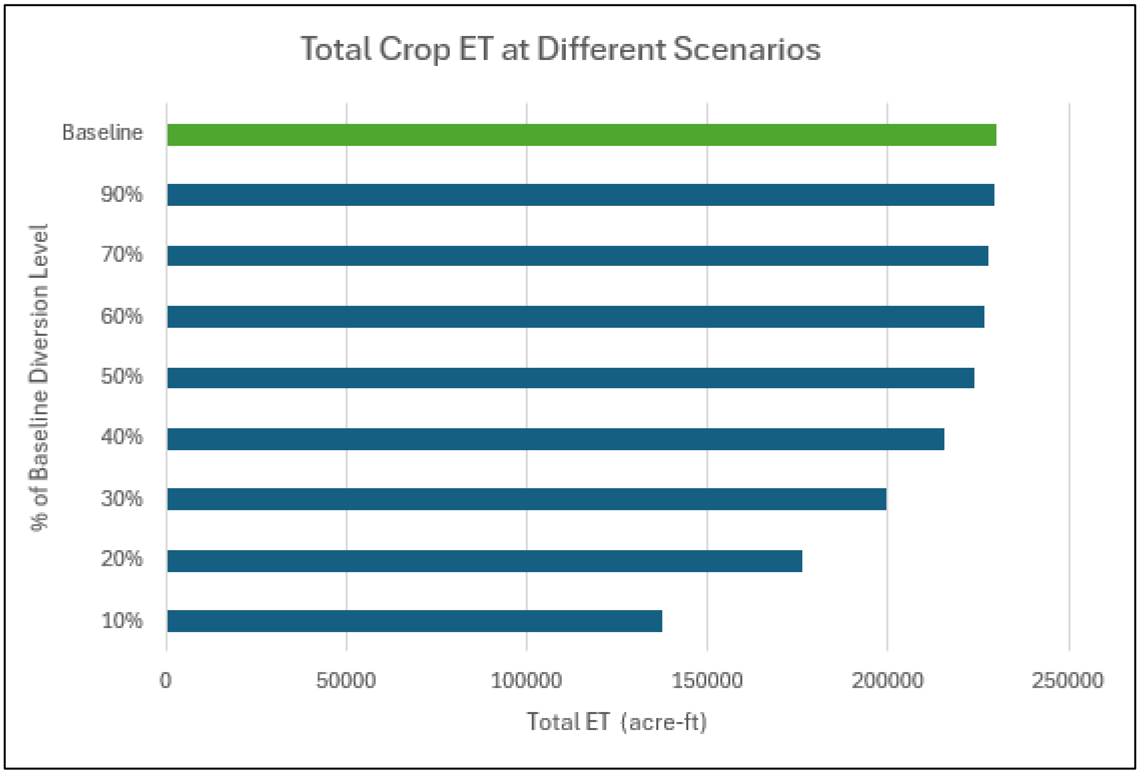


Figure 6: Cumulative crop ET across all scenarios and baseline conditions

For this scenario of 40% of original diversion volume and changing all fields to sprinkler irrigation, we compared model results with the baseline (flood irrigation) model to determine hydrological effects of irrigation conversion. Return flow results were used to quantify cumulative annual, monthly, and seasonal groundwater return flows along the White River. The return flow results were also used in conjunction with tributary inflows to estimate river flow rate at each point along the White River, to create hydrographs at key points along the White River. Finally, changes in groundwater head between the scenario and the baseline were mapped for wetland areas (National Wetlands Inventory; https://www.fws.gov/program/national-wetlands-inventory, accessed March 2025), to determine impact of sprinkler irrigation on their development and maintenance. We hypothesis that many of the wetland areas are groundwater dependent, and likely artificial ("human-influenced") due to the use of flood irrigation over the past 100 years. Analysis was performed for the four types of wetlands in the study region: Freshwater Emergent Wetland, Freshwater Forested/Shrub Wetland, Freshwater Pond, and Riverine.

3. Results and Discussion

3.1 Baseline Results

3.1.1 General Water Balance

Shown in Figure 7 are the average annual hydrologic fluxes (1,000 ac-ft / yr) as simulated by the baseline MODFLOW model. Figure 8 displays a column chart of soil and aquifer hydrologic fluxes (ft^3/day) trends for the aquifer-river system of canals and irrigated fields, from the baseline model.

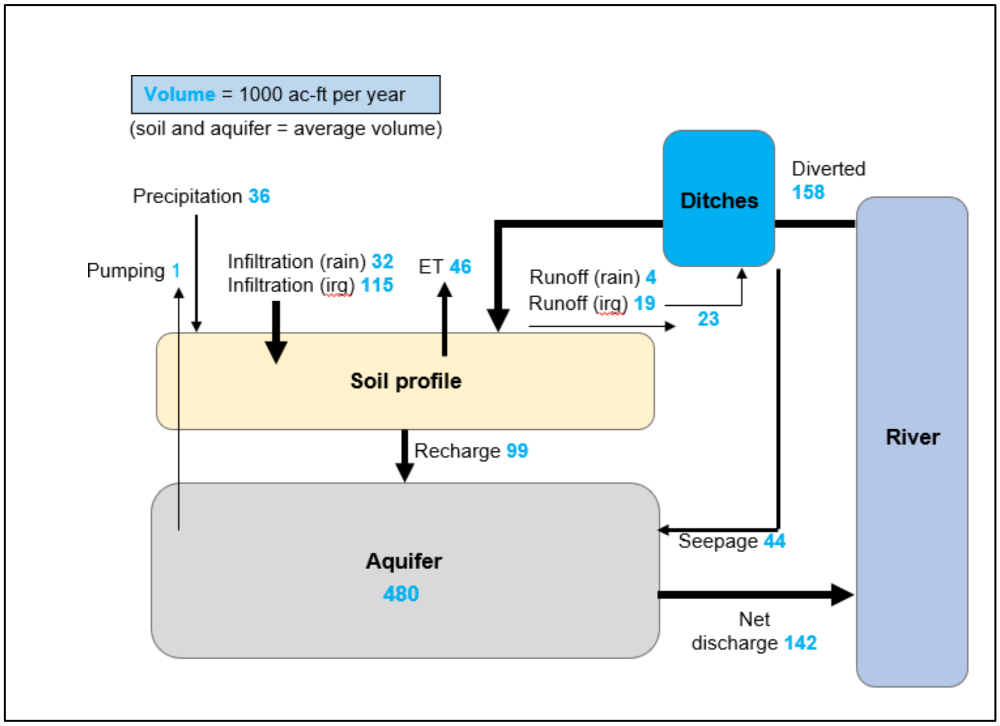


Figure 7: General water balance graphic (including irrigation) for the study region

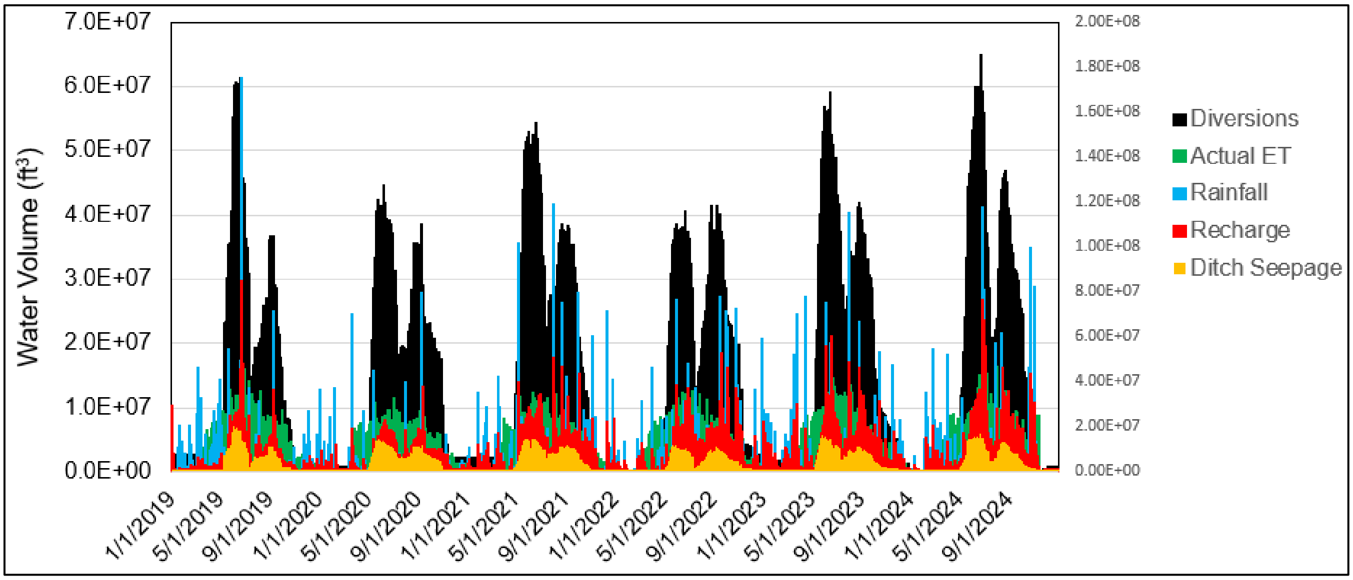


Figure 8: Seasonal fluxes for soil and aquifer

General conclusions from the water balance show the following results:

- *Groundwater fraction*: The ratio of net groundwater discharge (**142**) to diverted water (**158**) is 90%. This shows that for the entirety of the model, 90% of water diverted from the river for irrigation will return via return flows.
- *Irrigation*: Recharge from irrigation **(95)** implies that 60% of diverted water for irrigation recharges to the aquifer via deep percolation. If irrigation runoff is factored in (**19)**, then 72% of diverted flows return to either a ditch or the White River.
- *Ditch seepage:* approximately 28% (**44/158**) of diverted ditch water seeps to the aquifer.
- *Region-wide irrigation efficiency*: (**46**/(**158-44**)) = 40%. Although very low compared to other irrigated valleys, the majority of "lost" water recharges the aquifer, **returning to the river slowly** via groundwater return flows.

For an average year, volumes of canal diversion, recharge, and groundwater discharge rates are equivalent to approximately 20% of aquifer groundwater storage. The water balance determines that the aquifer acts as a conveyor system for unused river water that percolates through the soil profile, recharges the aquifer, returns to the river and its tributaries.

Total groundwater storage over time can be seen in Figure 9. Observable trends show increased storage twice a year during irrigation seasons. Additionally, groundwater storage over time shows a linear increase, with the trendline being observable in the chart. Findings from these results show that the aquifer and groundwater storage have yet to reach a point of steady-state conditions during the testing period.

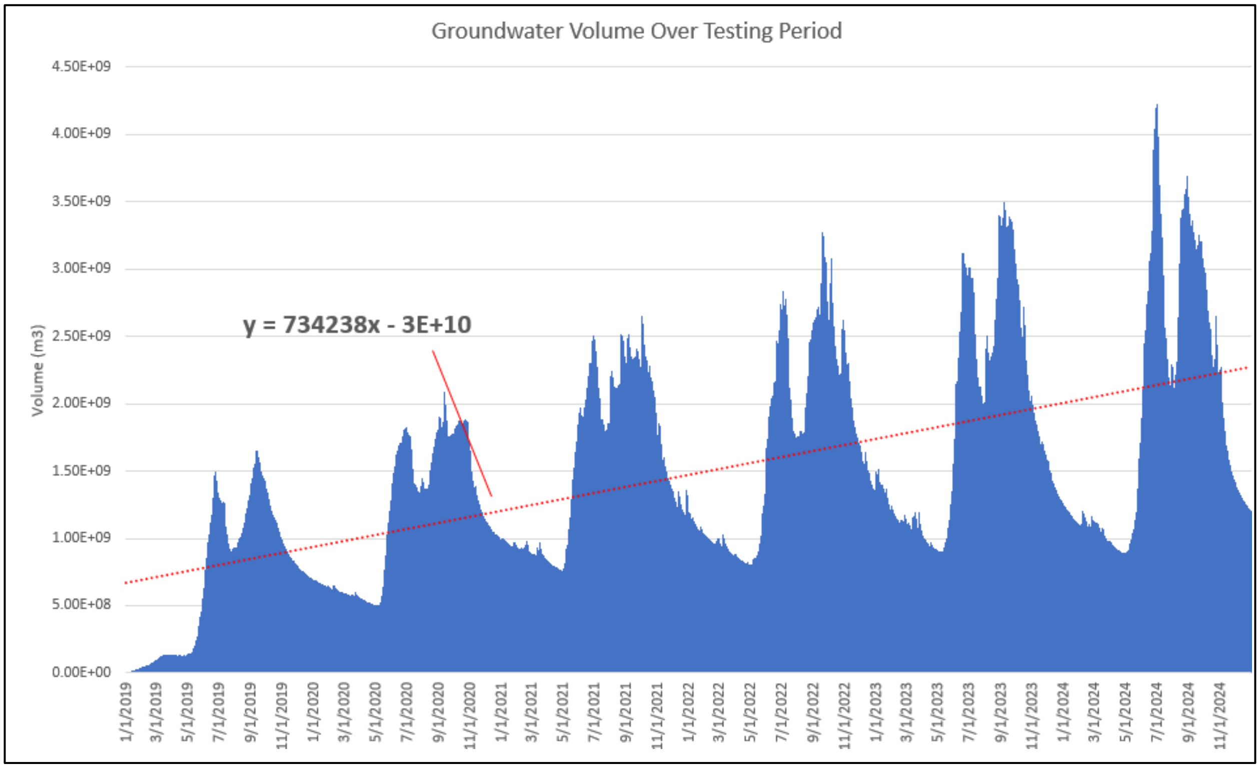


Figure 9. Total groundwater storage (m3) over time in the study area

3.1.2 System-Response Variables

Presented in the following section are results of modeled vs observed results after calibrations, along with their approximate Nash-Sutcliffe Efficiency coefficient (NSE). Figure 9 displays groundwater head results from calibration. The average approximate NSE for all four wells is 0.74. Results show that the model is cable to capture the magnitude and seasonal fluctuation of the observed groundwater levels.

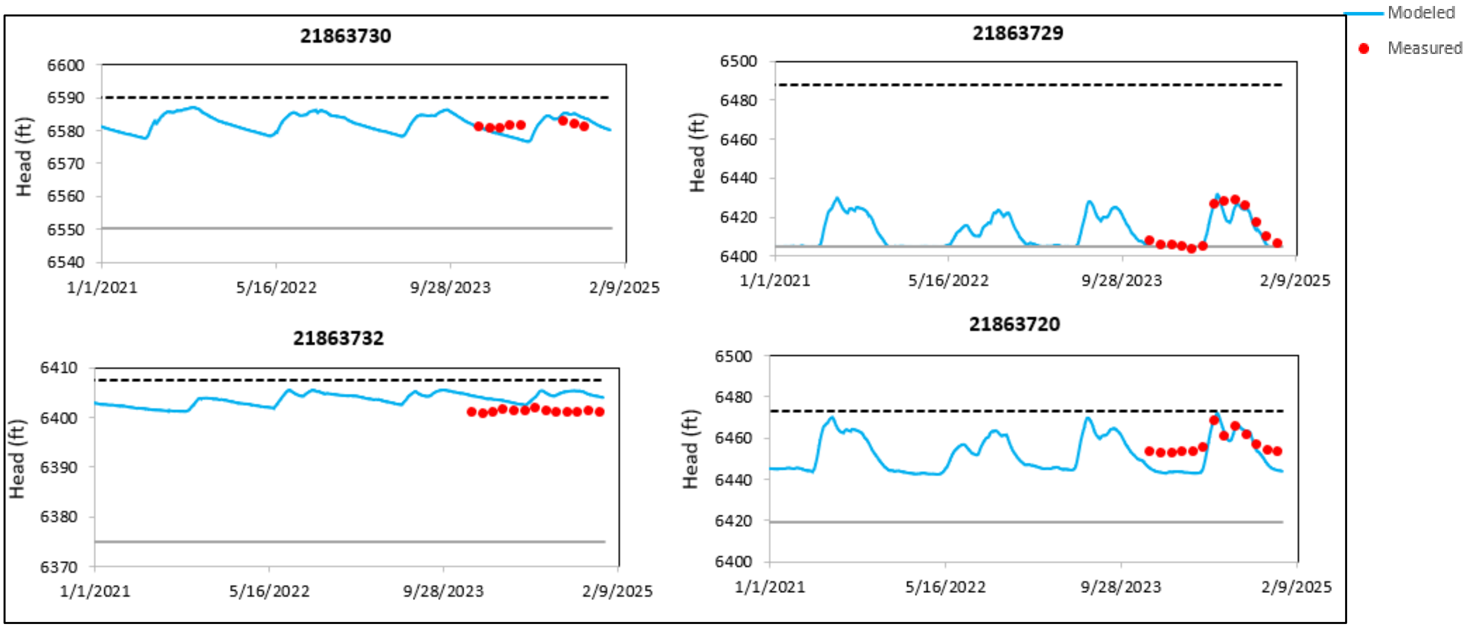


Figure 10: Simulated (blue) vs observed (red) groundwater head results from 4 wells.

Figure 10 displays groundwater-river exchange results after calibration for the White River. The results for this section show a calcualted NSE of approximately 0.65. The model is able to capture the magnitude and seasonal fluctuations of the groundwater-river exchange rates estimated from the river water balance.

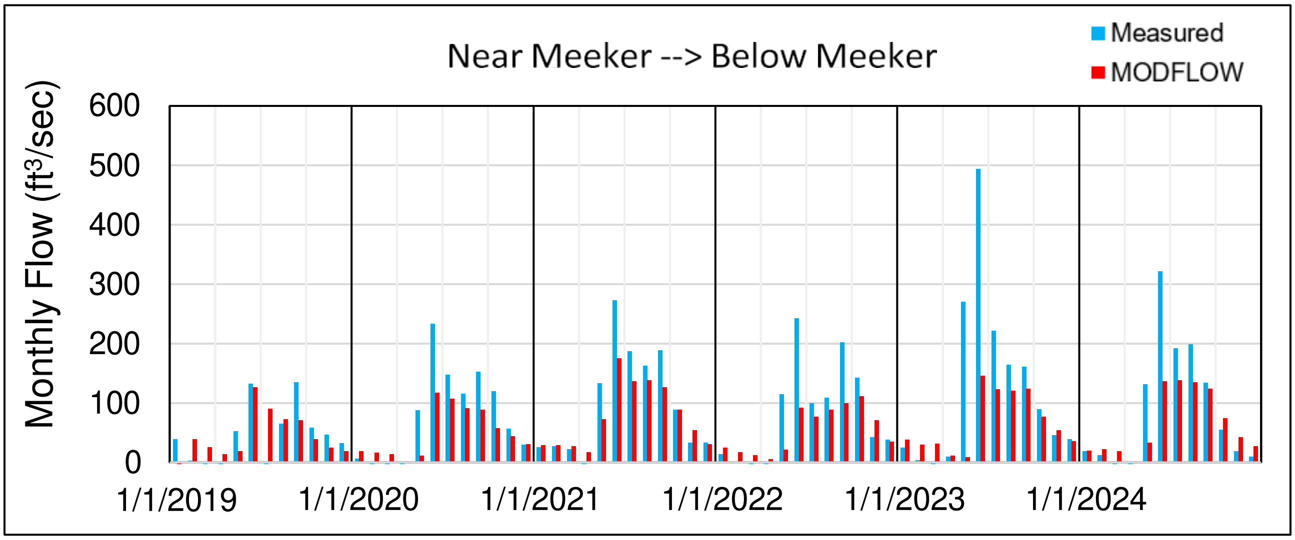


Figure 11: Simulated (red) vs observed (blue) return flows for section three of the study area

Groundwater return flow from irrigated lands are also simulated along tributaries of the White River. During 2023-2024, personnel from the White River Integrated Water Initiative measured flow in the major tributaries, using hand-held flow devices. During fall and winter months these flows are mostly groundwater return flows and hence can be compared to simulated return flows as an additional test of the model. Figure 11 shows the simulated (groundwater return flow; red line) and measured flow for Flag Creek and Strawberry Creek (blue dots), demonstrating that the model can capture the groundwater-driven flows in the creeks. The approximate NSE's of Flag Creek and Strawberry Creek are 0.9 and 0.92, respectively.

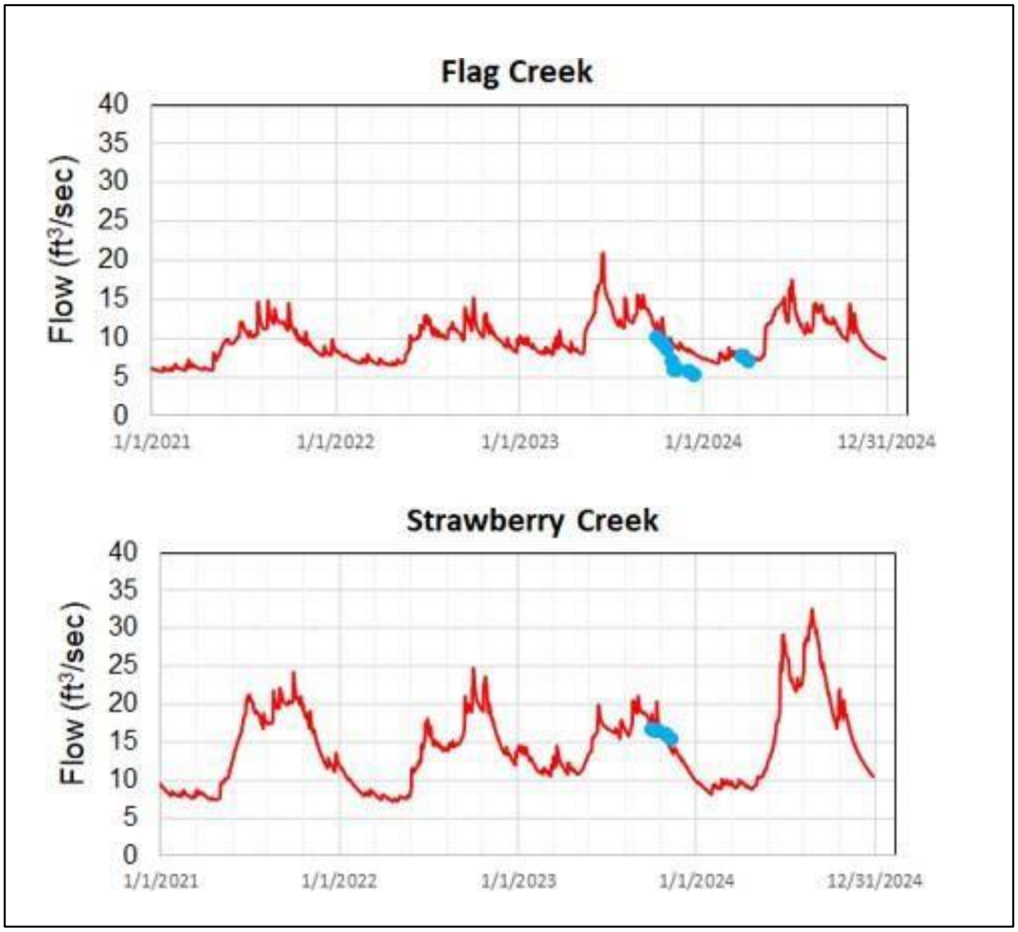
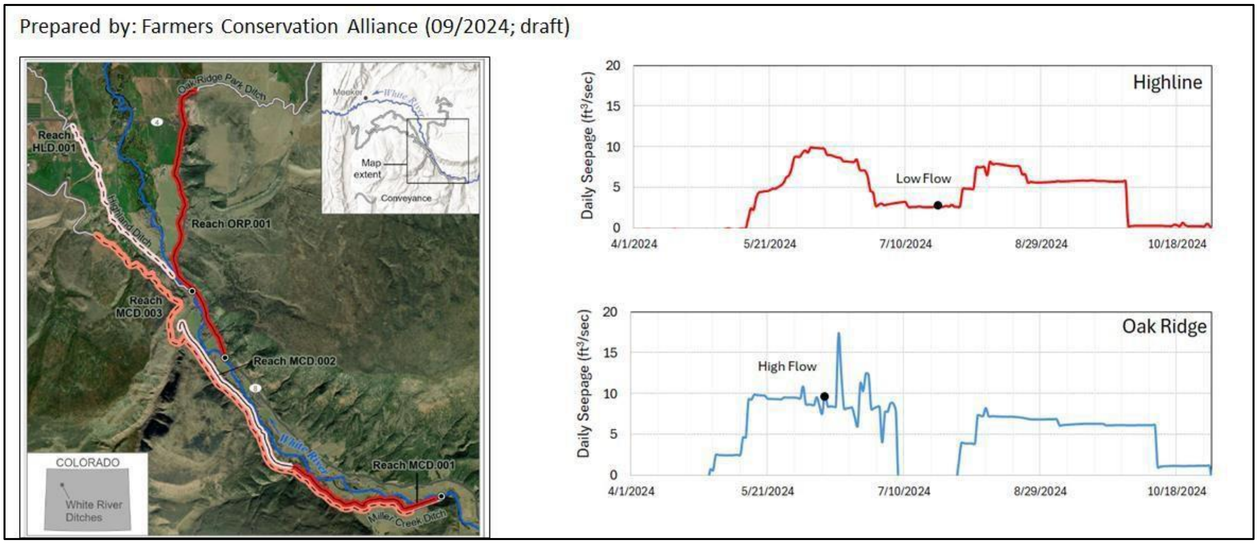


Figure 12. Measured (blue dots) and simulated (red lines) flow rates in two major tributaries: Flag Creek and Strawberry Creek. For most of the year, the flow in these creeks is made up of groundwater return flows from irrigated areas.

Simulated ditch seepage for the Highline and Oak ridge ditches can be seen in Figure 12. Farmer Conservation Alliance, in cooperation with the White River Integrated Water Initiative, performed a ditch seepage study during the summer of 2024. Seepage rates were estimated along the Highline Ditch (at low flows) and the Oak Ridge Ditch (at high flows). Although data are limited to only two estimates, the model tracks the correct seepage rate (2.5 ft^3/sec for Highline; 10 ft^3/sec for Oak Ridge) (Figure 22). To provide the correct seepage rate, the ditch bed conductivities were varied during model calibration. The final conductivity values also provide a general ditch seepage fraction (for the entire study region) of 20%, which is typical of irrigated regions in Colorado.



Prepared by: Farmers Conservation Alliance (09/2024; draft)

Figure 13. (left map) location of ditch seepage study within the Meeker area; (right charts) measured (black dot) and simulated daily seepage rates, for the Highline and Oak Ridge ditches.

By summing up inflows and outflows along the White River from the upstream gage (09304115; below North Elk Creek) and the downstream gage (09304800; below Meeker), we can simulate the river hydrograph at the downstream gage. For this hydrograph construction, groundwater-river exchange between two locations on the river (e.g., between two ditch diversions; between a ditch diversion and a tributary inflow; etc.) is provided by the MODFLOW model. Measured and simulated daily flow at the downstream gage are shown in Figure 13, showing the strong relationships (NSE = 0.95) between the two at all seasons of each year, particularly during the fall and winter months (post-irrigation), during which groundwater-river exchange has the highest impact on river flow. Without correct values of groundwater-river exchange (i.e., "return flows"), river flow would go to 0 during these months.

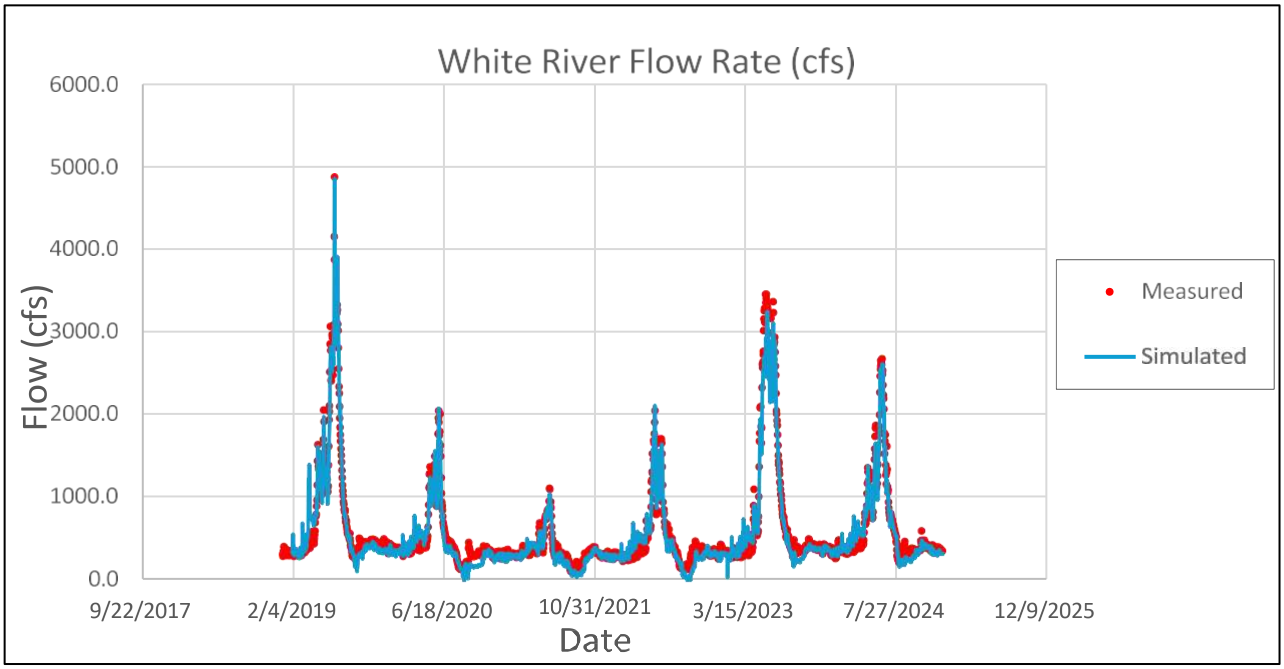


Figure 14: Simulated (blue line) vs observed (red dots) results of average White River flow

3.2 Scenario Results

The scenarios being analyzed were both set at all sprinkler irrigation across the study region, with diversions being set at 40% and 70% of the baseline diversions. Section 3 was the primary region of analysis. The study assumes that sprinkler irrigation systems operate at a high level of efficiency and thus may be able to operate across a large range of diversion reductions. The study also assumes that crop evapotranspiration remains maintained at each diversion scenario.

3.2.1 General water balance

Figure 14 compares flux totals from water balances conducted for the 40% (target diversion amount for sprinkler irrigation), 70%, and baseline scenarios. This water balance encompasses the entire 2019-2024 testing period. Evapotranspiration shows little variation between each scenario. Irrigation runoff shows a sharp increase between the sprinkler irrigation scenarios and the baseline flood scenario due to the change in efficiency between the systems. The 40% scenario declines 87% from the baseline while the 70% scenario observes a 77% drop. Trends observed among irrigation infiltration and deep percolation show steeper declines among the 40% diversion scenario. Total water volume drops 60% and 67% for irrigation infiltration and deep percolation, respectively. From these results we see that “lost water” due to irrigation runoff and deep percolation remain at their highest quantities during baseline conditions. From the previously conducted water balance, we know that this water is returned to the river, indicating that the baseline conditions see the largest percentage of water from the system water balance returned to the White River. Cumulative irrigation runoff and deep percolation for the baseline conditions remain 60% higher than the 40% scenario and 30% higher for the 70% scenario.

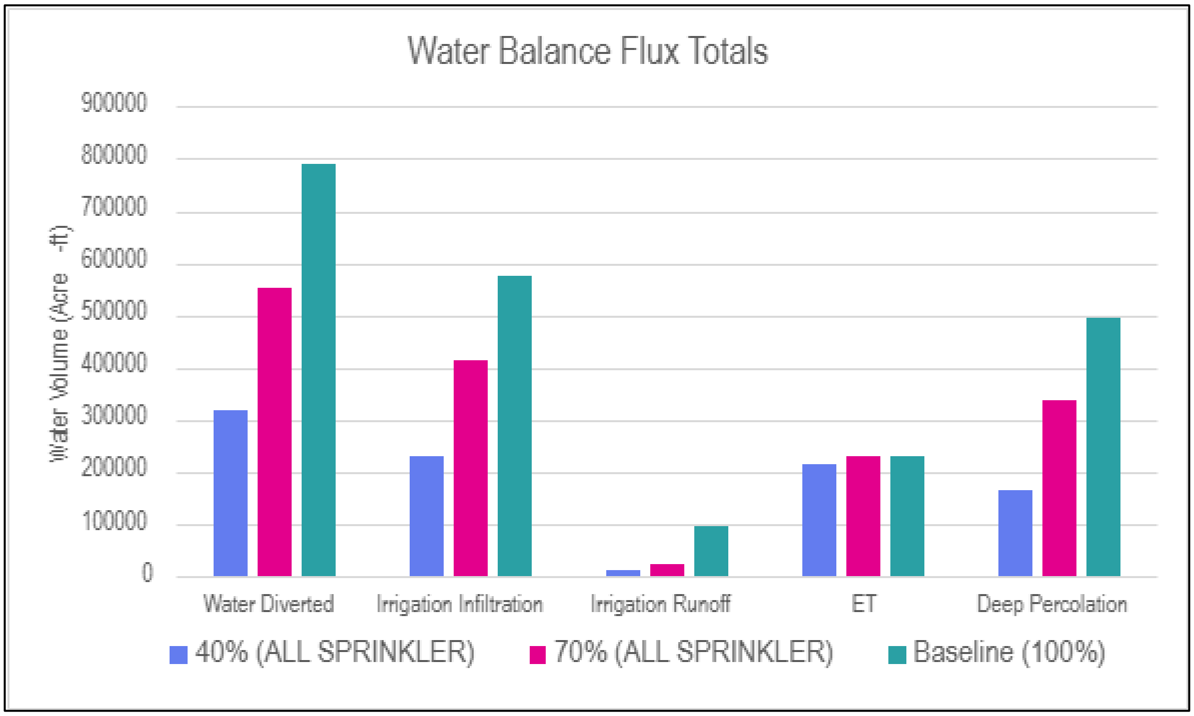


Figure 15: Water balance flux totals across baseline, 40% and 70% (all sprinkler)

3.2.2 Groundwater-River Exchange

Baseline groundwater return flows in 2024 were analyzed at section 3 of the White River study area alongside scenarios run at 40% and 70% of the baseline at an all-sprinkler setting (Figure 15). Section three was chosen because it contains the largest number of diversions and is dependent on upstream results. Positive return flows indicate groundwater return to the river, and negative return flows indicate river to aquifer exchange. Trends in the data show highest return flows during summer months, with return flows still mostly remining positive throughout the remainder of each year. In this 2024, simulated baseline return flows during June, July, and August, and September all flow at above an average of 100 cubic feet/second. Return flows see steady decline going into the winter. All flows except for April remain positive. Average Summer, Fall, and Winter flow rates are 132.6, 48.2, and 20.2 cfs, respectively. Average Fall flow rates see a 64% drop from average summer rates. Winter rates see a subsequent 58% drop in average flow rate from the average Fall rates. When comparing the baseline to the 40% and 70% scenarios, average monthly return flows at 70% (all sprinkler) show a 32% reduction in magnitude from the baseline flood sprinkler scenario. For the 40% (all sprinkler) scenario, return flows are reduced by 69%. All three scenarios still show peak return flow levels during July. For all positive return flows, the baseline scenario results remain the highest, followed by 70% and 40%, respectively. However, for the negative return flow values in April, the trends in magnitude are reversed, with the 40% scenario showing the largest flux of flow from the river to the aquifer. All of these trends indicate that irrigation operating under baseline conditions sees the greatest amount of water delivered from the river to the aquifer.

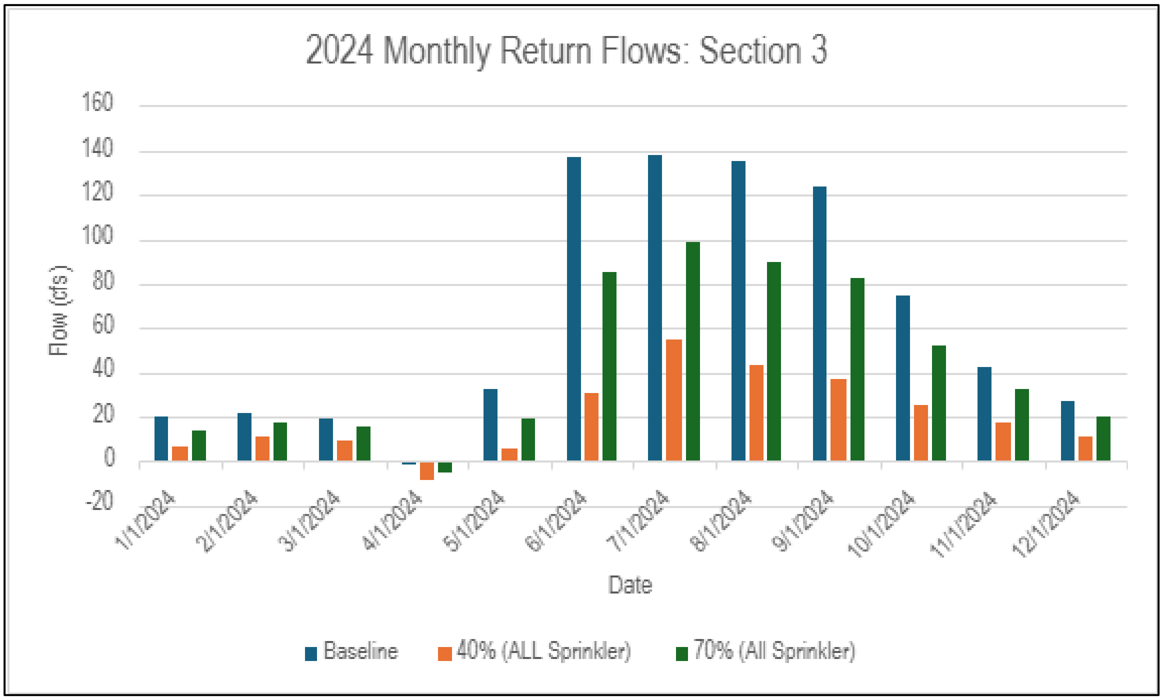


Figure 16: Simulated monthly return flows in 2024 for baseline, 40% and 70% (all sprinkler)

Seasonal trends from 2024 are shown in Figure 16. Winter return flow rates see a 56% and 22% decline from baseline results for the 40% and 70% scenarios, respectively. Summer flow drop 66% and 32% for the same respective scenarios. Fall months have similar drops at 63% and 28%. Across all seasons and months, the general observed trend is that the 40% diversion scenario at all sprinkler irrigation results in averages of over a 50% reduction in return flows. The 70% diversion scenario sees more moderate declines, staying under 40% annually.

Results from Figures 15 and 16 show the sharp decline in levels of return flows during typical "low flow" months. When peak river flow is greatly reduced during winter months, groundwater return flows become increasingly more important contributors to cumulative flow along the White River. Because of this, the reductions in late season return flows significantly impact flow along the white river as snowmelt becomes less dominant during the year.

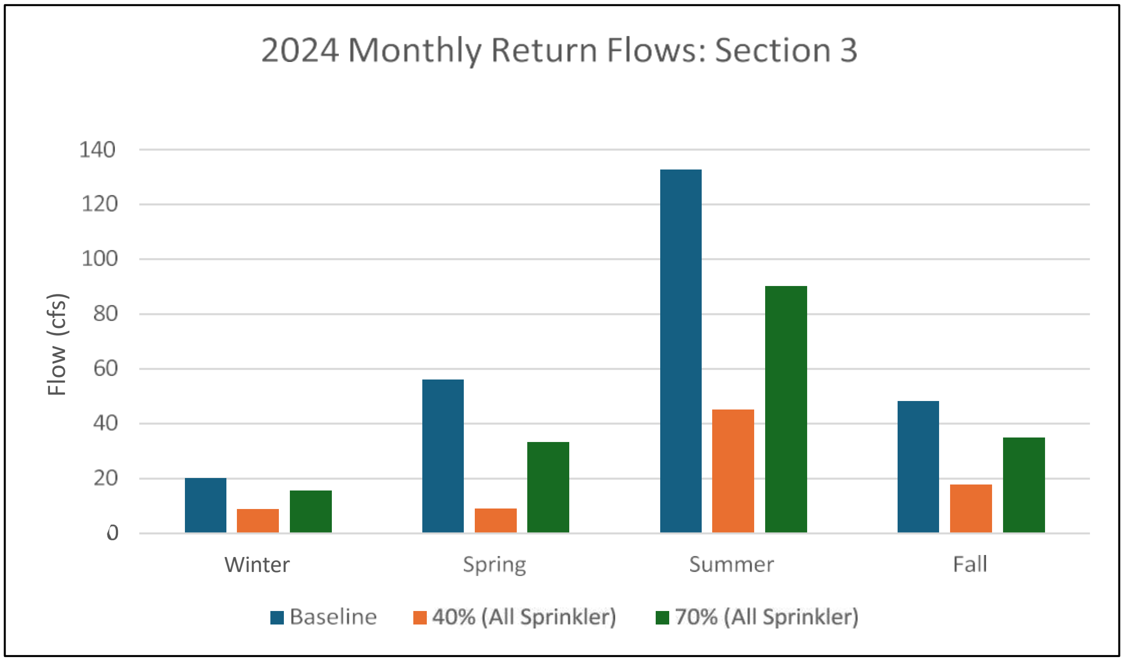


Figure 17: Simulated seasonal return flows in 2024 for baseline, 40% and 70% (all sprinkler)

A daily time series of return flows across Section 3 of the White River for 40%, 70% and baseline can be seen in Figure 17. This hydrograph visualizes trends in return flows for the entire testing period. Again, all three scenarios show similar seasonal trends of peak and low flows. One notable observation is that the magnitude of the differences in return flows grows larger durng peak season, and get smaller during low flow season. This is due to the overall reduction in magnitudes among return flows during low flow seasons. The reduction in magnitude for each scenario from the baseline align closely with the average reduction actross each year.

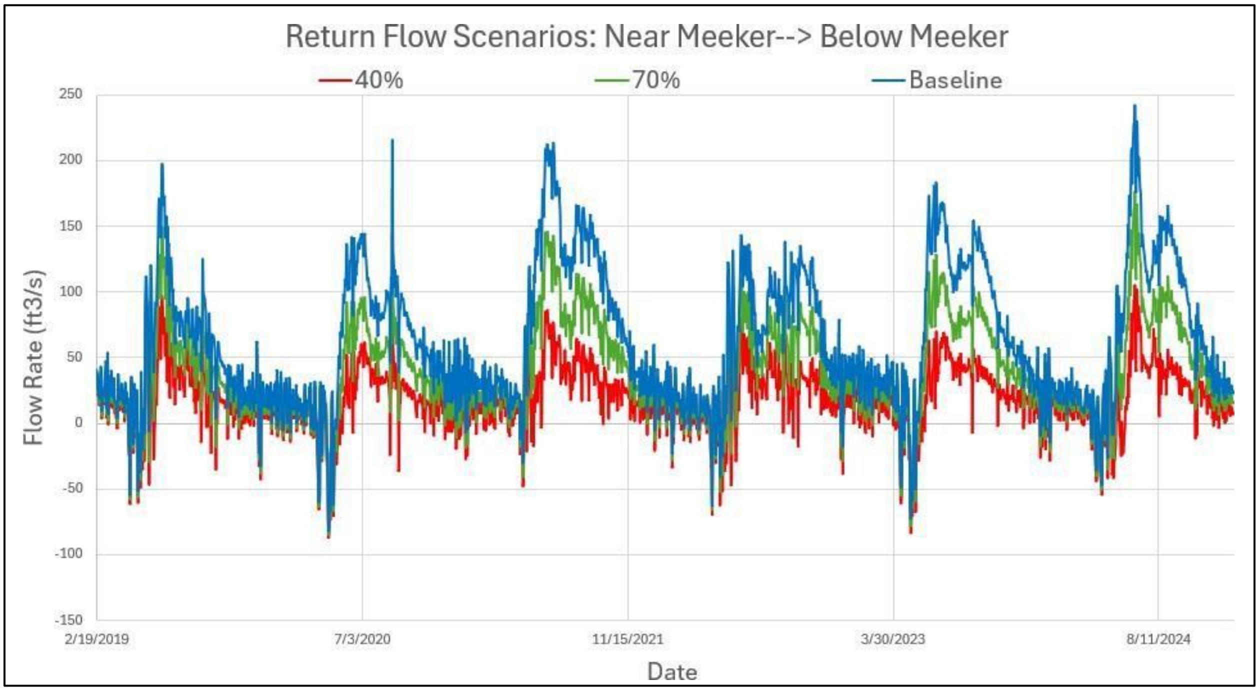


Figure 18: Hydrograph return flows in 2024 for baseline, 40% and 70% (all sprinkler)

3.2.3 River Flow

A hydrograph of average modeled river flow at the end of Section 3 (i.e., downstream end of study region) is shown in Figure 18. Trends in river flow closely align with seasonal trends in groundwater return flows, with a few noted differences. Annual peaks in streamflow occur during early spring and summer months, with the flow rate seeing significant decline in late summer and early fall months. This is due to the Study Region seeing snowmelt earlier in the year due to its vicinity to the Rocky Mountains. The delay between return flow rates and peak streamflow rates also aligns with common irrigation practices. During peak streamflow dates, irrigation operates at its highest level, lost water from this irrigation will likely see some delays as it makes its way through the aquifer and back to the river as return flow.

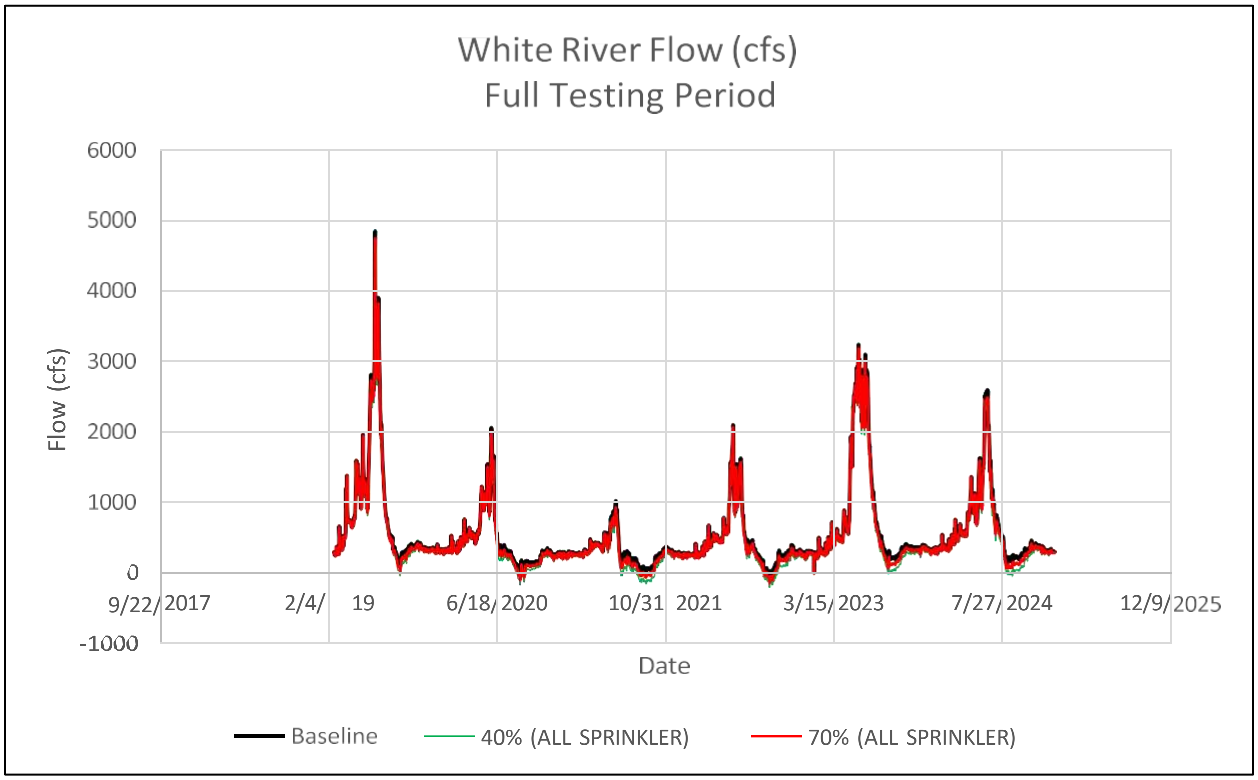


Figure 19: Hydrograph of White River flow at the end of Section 3 for entire testing period (2019-2024)

From Figure 18, we see that peak flow rates along the river are much higher than peak groundwater return rates during the same months, with these peak rates reaching over 1000 cfs each year. In 2024, the peak streamflow rate was 2597 cfs in June. When comparing this value to the average groundwater return flow rate of 137 cfs from June 2024, we see that groundwater return flow makes up approximately 5% of flow during peak, snowmelt-controlled months. However, when comparing the minimum river flow value in 2024, we get a value of 149 in August. This value, compared to the average monthly return flow value of 135 cfs, suggests that groundwater return flows could make up 90% of streamflow at given points in time.

Hydrographs displaying temporal variation of flow along the studied portion of the White River for scenarios at 40% and 70% can be seen in Figure 19. General noted trends across these results see high flows across all scenarios with lower diversion percentages. However, these results also show much lower flow during later months of the year, due to less groundwater recharge in the fields and less subsequent return flows back to the river. These results imply that a switch to sprinkler irrigation, due to less diversion from the river, results in less ditch seepage and irrigation recharge, leading to less groundwater storage throughout the year and subsequent reduced flows in late season months. Conversely, less diversion in the growing season increases river flow during these months. Because groundwater return flows make up a larger portion of streamflow as snowmelt declines, it can be implied that a reduction in return flows contributes to the change in streamflow between scenarios.

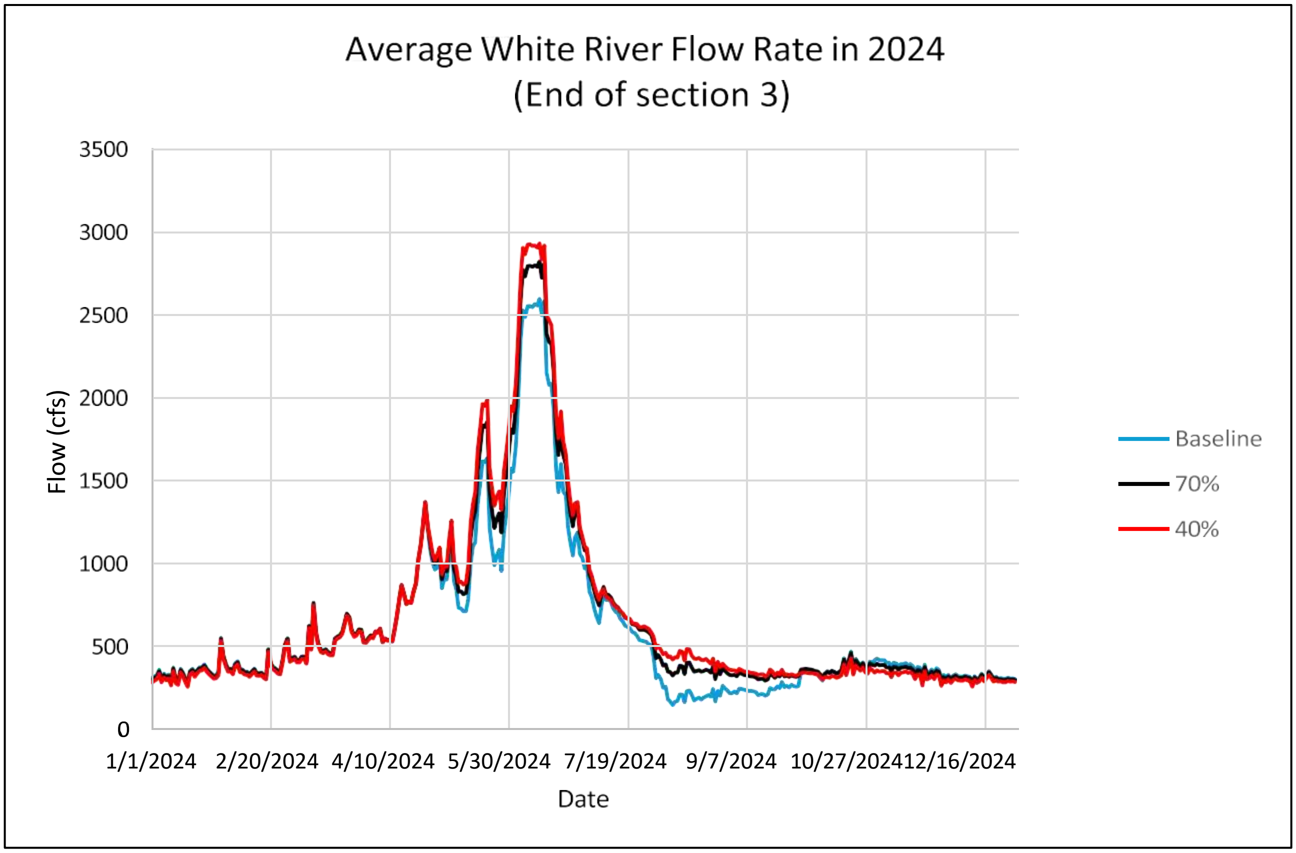


Figure 20: Hydrograph of White River flow in 2024 for baseline, 40% and 70% (all sprinkler)

3.4 Groundwater Levels and Wetlands Analysis

Groundwater levels were investigated for all sprinkler irrigation at 40% and 70% diversion levels, with its decline being investigated in surrounding wetlands. All results shown are taken from the final day of the testing period (12/31/2024). Shown in Figure 20 is a map of groundwater head across the MODFLOW grid for the baseline scenario on the last day of the testing period. The maximum groundwater head observed was 8,105 ft, with the minimum elevation observed at 5,907 ft. General trends see a steady decline in groundwater head from east to west and from south to north in the eastern aquifer (gradient towards the river) and north to south in the western aquifer (gradient towards the river) The declining elevation as groundwater nears the river indicates a direction of flow from the surrounding aquifer to the White River.

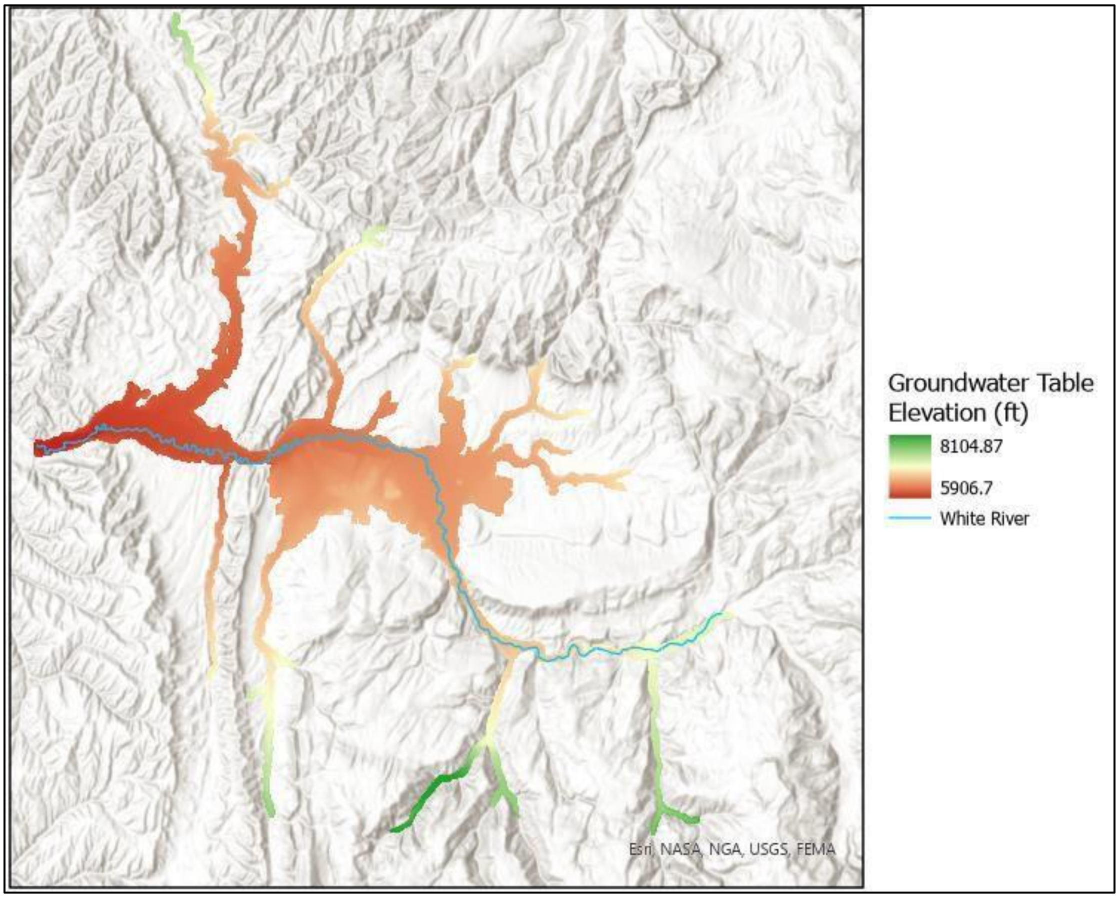


Figure 21: Groundwater elevation above sea level in study area at baseline conditions

Figure 21 shows the location of wetlands in the region, using the National Wetland Inventory database (https://www.fws.gov/program/national-wetlands-inventory) of the US Fish and Wildlife Service. The map shows four wetland types: freshwater emergent (3,480 ac), freshwater forested/shrub (208 ac), freshwater pond (83 ac), and riverine (2,567 ac). Notice that the freshwater emergent (light blue) wetlands are located within irrigated areas, indicating the influence of flood irrigation on creating and maintaining wetlands.

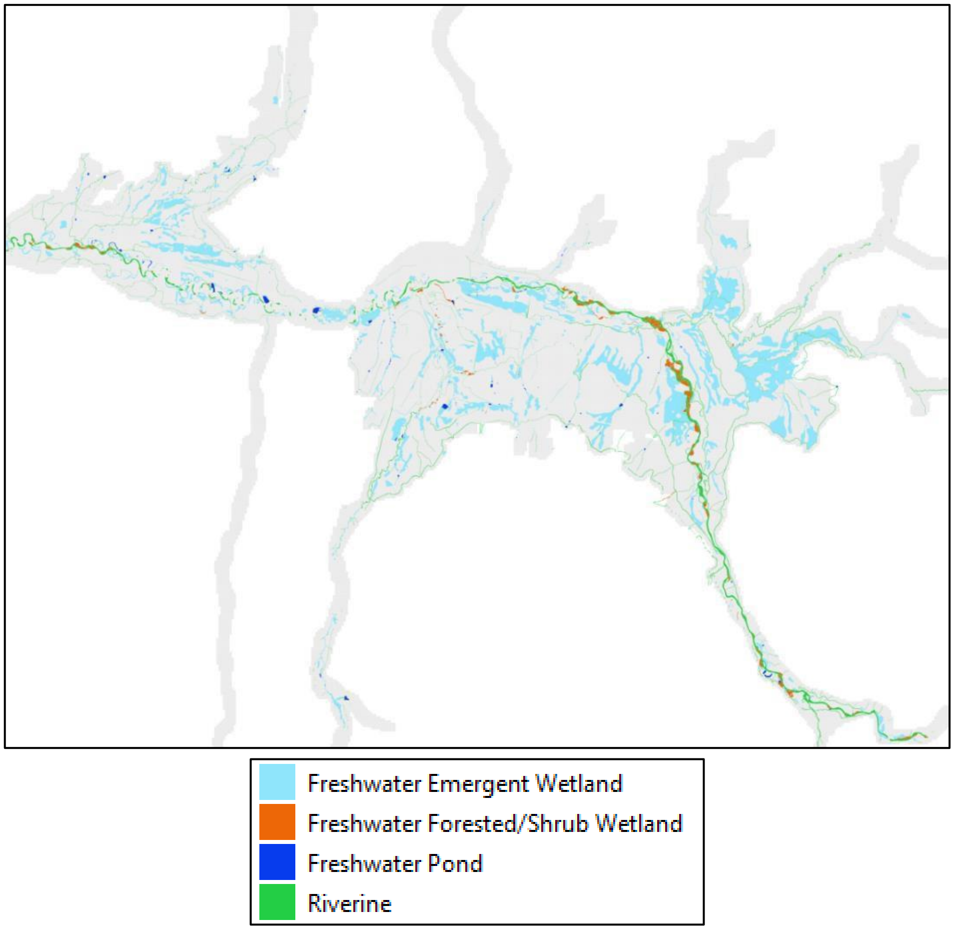


Figure 22. Map of wetlands, provided by the National Wetlands Inventory database of the US Fish and Wildlife Service.

A map of groundwater head change in wetlands within the MODFLOW grid is presented in Figure 21, between the baseline scenario and the 40% diversion scenario. Each wetland polygon is an average of rasterized pixels located within each polygon boundary.

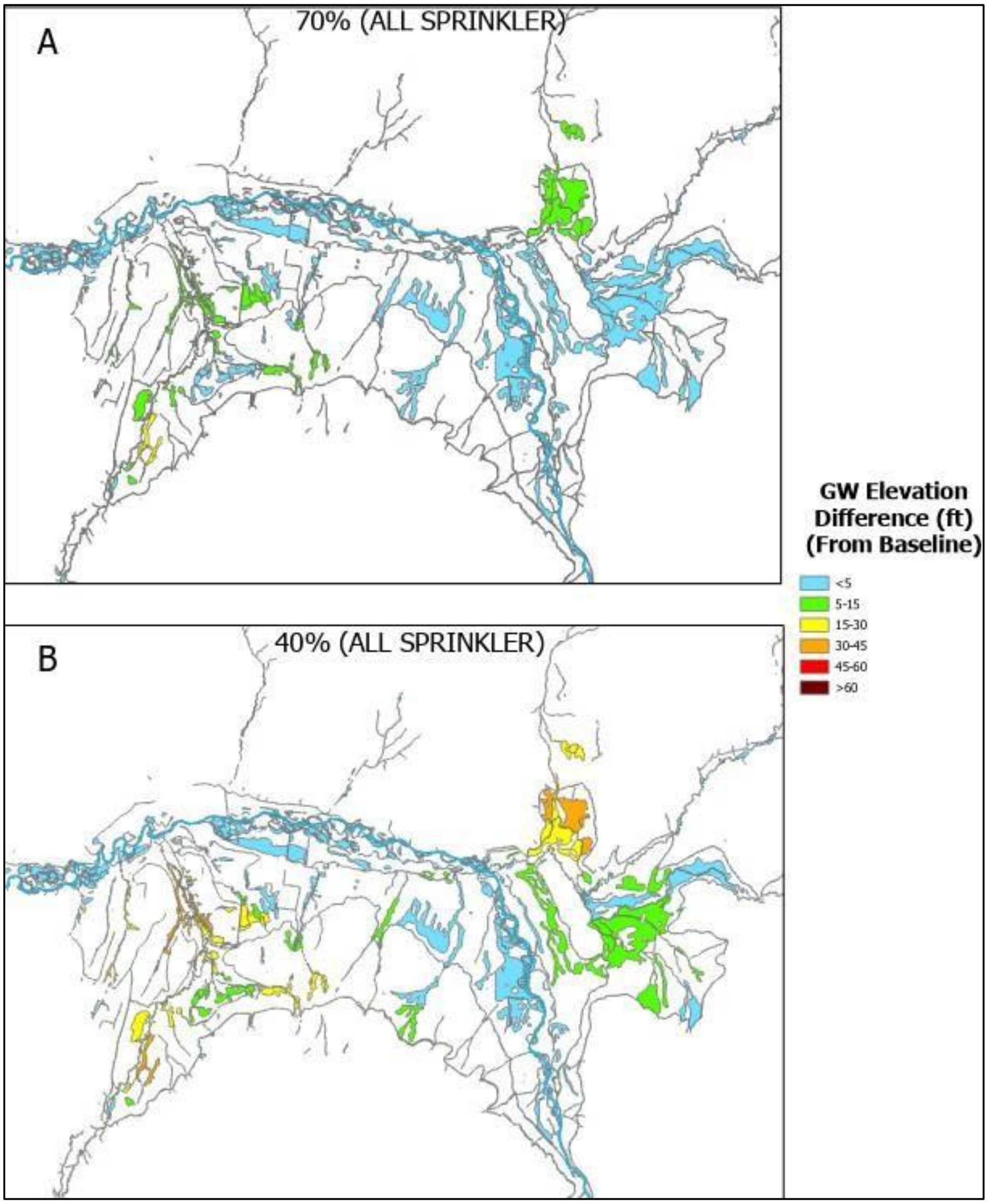


Figure 23: Difference in groundwater elevation from baseline at the end of the testing period. For 70% (A) and 40% (B)

Trends were also identified within specific wetland types. Figure 23 shows the mean difference from the baseline scenario for each wetland type for the 40% and 70% scenarios. Freshwater emergent wetlands and freshwater ponds both have the highest mean difference from baseline water table elevation at both 40% and 70% diversions. At the 40% scenario, the difference from the baseline reaches 6 ft. Differences across the 70% scenario show less deviation from the baseline across all wetlands. Lakes show no notable changes in water table elevation across any scenarios. Excluding lakes, on the total mean groundwater elevation difference for the 40% scenario was 60% lower than the 70% scenario.

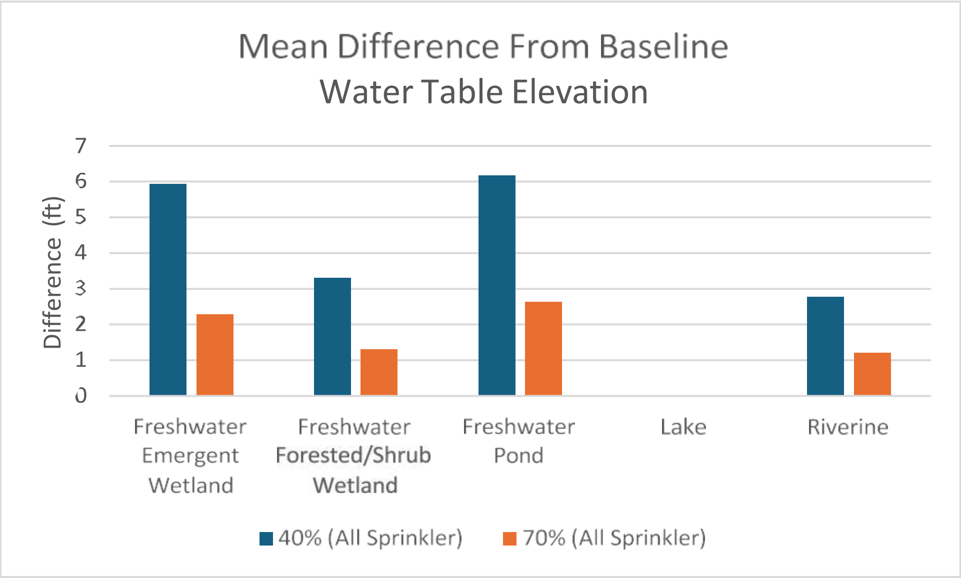


Figure 24: Difference in wetland elevation for 70% and 40% scenarios across different wetland types

Presented in Figure 24 is a chart of total area coverage within each wetland-difference elevation group. Overwhelmingly, most of the wetlands in the study area deviate less than 5 feet from the original baseline conditions. However, the 40% scenario does cover significantly more area across the elevation difference groups greater than 5 ft. Compared to the 70% scenario, the 40% scenario covers 33% more land in the 5-15 ft range and 90% more land in the 15-30 ft range. Moreover, the 40% contains 210 acres of wetland that deviate between 30-45 ft in water table elevation. Overall, under a 40% diversion scenario, 1429 acres of land will see a decline in water table elevation over 5 ft (approximately 5.5% of total wetland area). This could imply significant ecological impacts within these wetland regions, especially when the water table begins to drop greater than 10 ft. Potential impacts include lower stages in surface water areas, lowered levels of wildlife population, and complete loss of water availability in specific areas.

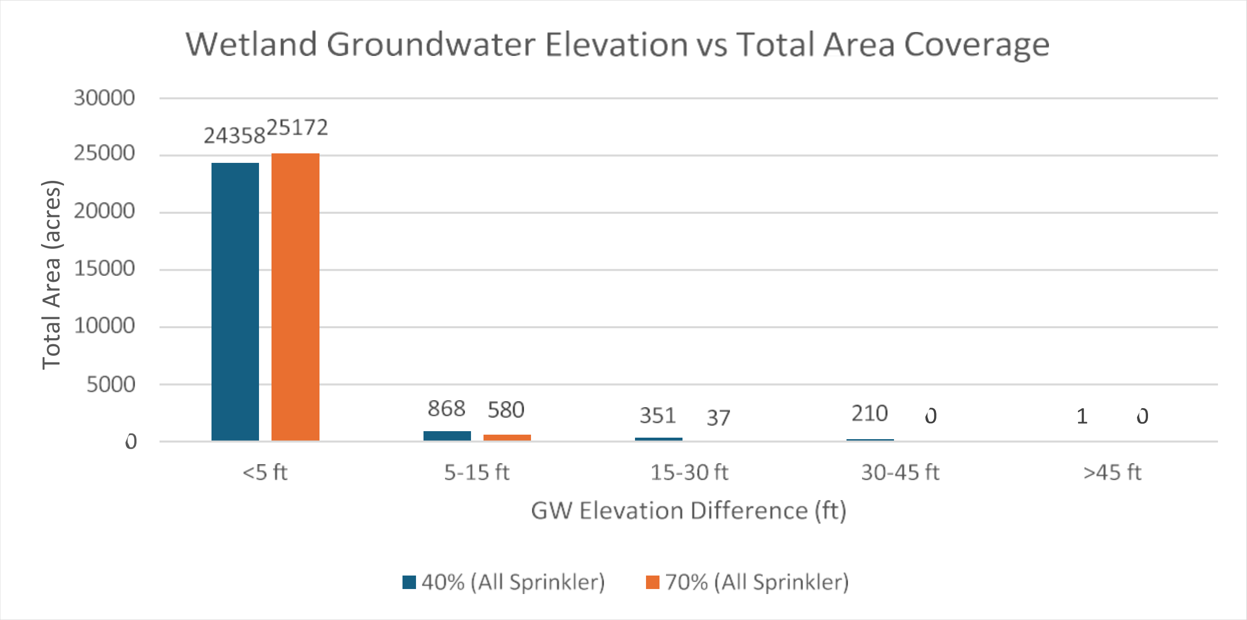


Figure 25: Total areal coverage for groundwater elevation changes for 40% and 70%

4. Conclusions

In this thesis we use field data and a modified MODFLOW model to investigate hydrologic fluxes (ditch diversions, ditch seepage, irrigation runoff, recharge, groundwater-river exchange) in the Meeker region of the White River Valley and quantify the impact of conversion to sprinkler irrigation. The MODFLOW model is calibrated and tested against monthly estimates of groundwater return flows between river gaging stations, and monthly measured water table elevations from a network of 11 monitoring wells. The study period is 2019-2024. Major Findings of the study included:

Historical Fluxes

- *Groundwater fraction*: The ratio of net groundwater discharge (**142**) to diverted water (**158**) is 90%. This shows that for the entirety of the model, 90% of water diverted from the river for irrigation will return via return flows.
- *Irrigation*: Recharge from irrigation **(95)** implies that 60% of diverted water for irrigation returns to the aquifer via deep percolation. If irrigation runoff is factored in (**19)**, then 72% of diverted flows return to either a ditch canal, or the White River.
- *Ditch seepage:* approximately 28% (**44/158**) of ditch water seeps to the aquifer.
- *Region-wide irrigation efficiency*: (**46**/(**158**-**44**)) = 40%. Although very low compared to other irrigated valleys, the majority of "lost" water recharges the aquifer, **returning to the river slowly** via groundwater return flows.

Water Balance

- Irrigation runoff declines 87% from the baseline at 40% diversions and 77% at 70% diversion.
- Irrigation infiltration and deep percolation show 60% and 67% respective declines in total volume over the 40% testing period.
- Cumulative irrigation runoff and deep percolation for the baseline conditions remain 60% higher than the 40% scenario and 30% higher than the 70% scenario.

Groundwater River Exchange

- Compared to baseline return flows, average annual return flows drop 32% in the 70% scenario and 69% in the 40% scenario.
- Winter return flow rates see a 56% and 22% decline from baseline results for the 40% and 70% scenarios, respectively. Summer flows drop 66% and 32% for the same respective scenarios. Fall months have similar drops at 63% and 28%.

Groundwater Levels and Wetlands Analysis

- Under the 40% diversion scenario, 5.5% of total wetland area underwent a drop in water table over 5 ft. 39% of this land experienced water table declines of over 15 ft throughout the testing period.
- Freshwater ponds and freshwater emergent wetlands saw the highest average water table drop at approximately 6 ft for each.

Common assumptions about irrigation systems imply an increase in irrigation efficiency may be universally beneficial, as less water is “lost”. However, in some alluvial aquifer-river systems, water lost in irrigation may be recycled back into the river system via return flows. The lost water often percolated back into the aquifer, and that stored groundwater provides significant contributions to late season reiver flow. In other snowmelt dominated river systems, groundwater could serve a similar purpose in sustaining river flow during low-flow seasons.

Implementation of more efficient sprinkler irrigation systems in place of flood irrigation would see both increases and decreases in specific seasonal flow. Sprinkler irrigation implies a reduction of water diverted from the river, which in turn keeps flows higher during peak flow months. However, when snowmelt no longer dominates flow in lower flow seasons, river flow significantly decreases due to the decreased groundwater storage. This suggests that water lost in flood irrigation still remains part of the system but is returned to the river later in time. Downstream irrigated fields may rely on these later season contributions.

Modeled results of the study indicate that implementation of sprinkler systems will likely decrease groundwater storage, and subsequently, groundwater elevation. This loss in groundwater elevation is seen not just along the river, but in surrounding wetlands within the study area as well. This reduction in groundwater elevation may present consequences for the ecology in these areas, as many are dependent on the presence of substantial water to continue to exist.

Future areas of research should aim to target economic implications of an irrigation system switch. Additionally, there is a need to investigate scenarios involving combinations of both food and sprinkler irrigation systems. Another potential area of focus could be investigating hydrologic consequences of changing crop types under different irrigation types.

This research highlights the importance of specificity when it comes to selecting irrigation systems in different communities. While some systems may benefit from the increased efficiency of sprinkler-based systems, others may see unforeseen hydrological effects. Understanding the unique hydrology of a given area if important when it comes to making decisions about water use in the area

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