Title: Hydrologic modeling to investigate irrigation impacts on the White River stream-aquifer system

Project duration: July 2023 – June 2024

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1. Executive Summary

Motivation

The White River alluvial valley in the region of Meeker, Colorado, is a productive irrigated area for pasture grass and alfalfa, with flood irrigation practiced for over 100 years. Current understanding of the hydrologic system assumes that deep percolation (recharge) from flood irrigation increases groundwater storage and groundwater levels, inducing a hydraulic gradient that drives appreciable volumes of groundwater into the White River and its principal tributaries both during and after the irrigation season, providing important late-season downstream flows for irrigation, drinking water, fish and wildlife habitat, and hydropower.

Objectives

The aim of this project is to elucidate the understanding of the hydrologic system in the White River stream-aquifer near Meeker, Colorado. Specifically, the aims are:

1. Quantify the hydrologic fluxes of major flow pathways: applied irrigation; runoff from rainfall and irrigation; infiltration from rainfall and irrigation; crop evapotranspiration (ET); deep percolation and recharge; exchange between the aquifer and the White River; exchange between the aquifer and tributaries; and exchange between the aquifer and irrigation canals.
2. Perform an initial model calibration, using 1) preliminary groundwater level data from recently installed monitoring wells; and 2) estimates of groundwater-river exchange rates between streamflow gages in the White River.

Main Methods

To accomplish project objectives, we constructed and applied a MODFLOW groundwater model of the region. Due to the intricate water management system of the Meeker region, which includes field runoff being captured by downgradient canals and then reapplied as irrigation, we prepared a new MODFLOW irrigation package to include all major features of the irrigation system: precipitation; canal diversions; irrigation type (sprinkler, drip, flood) and associated efficiencies; seepage from earthen irrigation canals; and a soil water balance for each field, soil unit, and natural area that simulates crop ET and deep percolation (recharge) to the water table. This package can be applied to other irrigated regions in Colorado and the western United States. Aquifer zones and properties were estimated from geologic maps and lithology from a network of 330 boreholes. The MODFLOW model was constructed and run for

the 2019-2023 period, using a daily time step. For each day, canal diversion volumes are applied to the network of fields within each canal command area, leading to runoff, infiltration, crop ET, and deep percolation. Deep percolation is routed to the water table as recharge, which then is used by MODFLOW to simulate groundwater storage, groundwater flow, and exchange between the aquifer and the canals, tributaries, and the White River. Simulated groundwater head and groundwater exchange with the White River were compared to measured field data, in an initial phase of model calibration. The resulting calibrated model is used to quantify hydrologic fluxes throughout the system.

Main Results

- Estimated groundwater return flow rate to the White River is 106 ft^3/sec for the 2013-2022 period based on water balance estimates, 124 ft^3/sec for the 2019-2023 period using the MODFLOW model. These rates are approximately **20% of the average flow in the White River**, as measured by streamflow gages.
- Based on model results, approximately 80% of the canal water diverted from the White River returns via groundwater discharge to the White River and its tributaries.
- Based on model results, **average irrigation efficiency for irrigated fields in the region is 25%**, with 13% runoff fraction and 62% deep percolation fraction. A portion of the runoff is captured by downgradient canals, which can then be reused for irrigation.
- The high deep percolation fraction (62%) indicates that most of the water applied as irrigation is lost to the soil system. However, this "lost" water raises the water table, increasing groundwater flow gradients and associated discharge rates to the White River and its tributaries.
- For an average year, volumes of canal diversion, recharge, and groundwater discharge rates **are equivalent to 20% of aquifer groundwater storage**. Therefore, the aquifer acts as a conveyor system for unused canal water that percolates through the soil profile, recharges the aquifer, and induces gradients that discharge groundwater to the White River and its tributaries. Due to the slow movement of soil water and groundwater, however, increased rates of groundwater return flows occur typically over a 6-month period, from June through November.

Future Work

The first year of the project was focused on establishing a hydrologic model for the study region and providing preliminary hydrologic results. In the second year of the project, our aim is to provide a final calibration and testing of the model, using groundwater head data collected through 2024 and the spring of 2025, and estimated groundwater-river exchange rates along various reaches of the White River and tributaries. The tested model will then be used to quantify the impact of irrigation practices on the White River stream-aquifer system and the impact of converting from flood irrigation to sprinkler irrigation. We will also train local water managers, conservation district employees, and interested stakeholders on model use and analysis, to ensure long-term model application.

2. Study Region and Hydrologic Assessment

2.1 Hydrology and Groundwater Patterns

The White River alluvial valley in the region of Meeker, Colorado (Figure 1), is a productive irrigated area for pasture grass and alfalfa. Irrigation in the valley, typically on the terraces and lands adjacent to the White River, has been practiced for more than 100 years by individual farmers and ranchers, with water diverted from the river via a network of ditches. Figure 1 shows the irrigation and hydrologic features of the Meeker region, including points of ditch diversion, irrigation canals, irrigated fields, the spatial extent of the alluvial aquifer, and the location of three USGS and one CDWR streamflow gages (listed from upstream to downstream):

- 09304115 White River below North Elk Creek
- 09304200 White River above Coal Creek, near Meeker
- 09304500 White River near Meeker
- 09304800 White River below Meeker

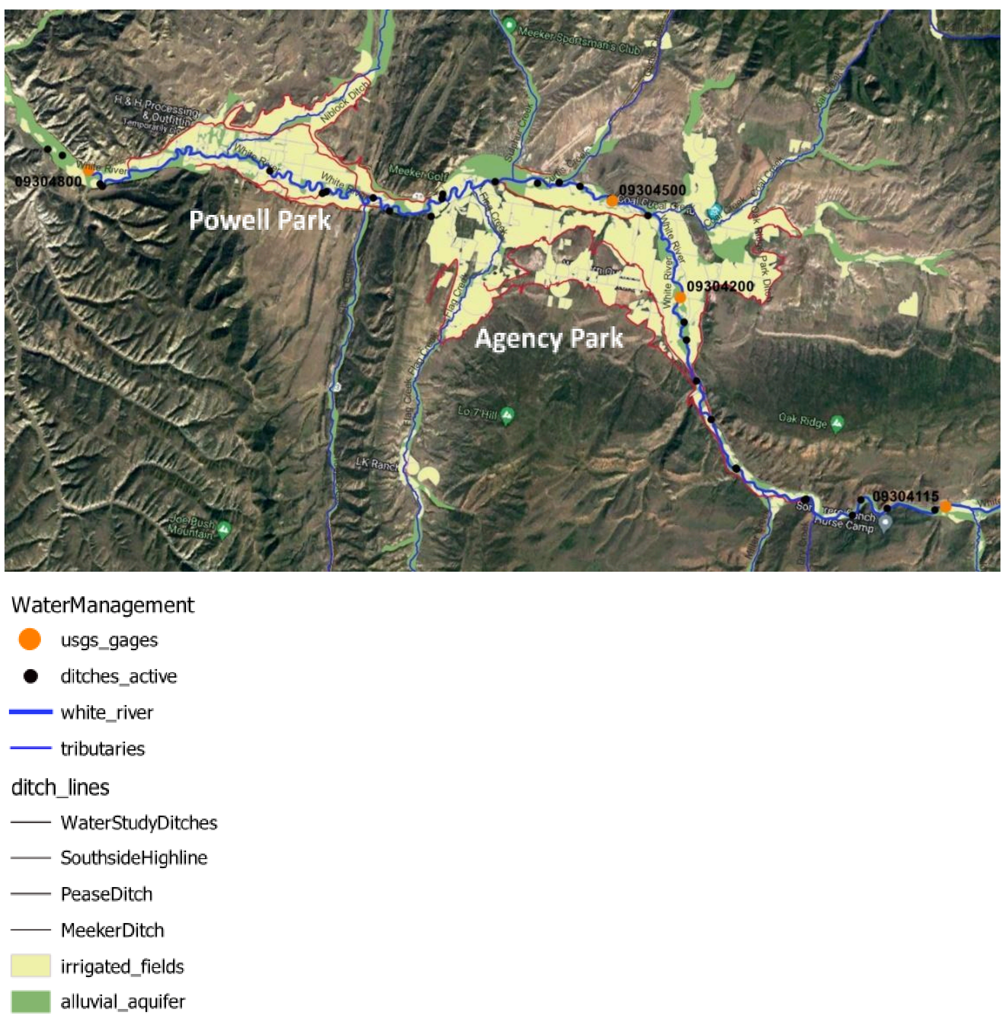


Figure 1. Irrigation and hydrologic features of the Meeker, CO region.

The irrigated region overlies a highly transmissive unconfined alluvial aquifer that is in hydraulic connection with the White River and its tributaries (Van Liew and Gesink, 1985). The irrigated region on the east overlies the Agency Park aquifer, and the irrigation region on the west overlies the Powell Park aquifer (see Figure 1). The aquifer covers an area of approximately 35 mi^2, with widths ranging from 0.1 mile (western part) to about 1.5 miles in the Agency Park aquifer and 0.5 mile in the Powell Park aquifer. Saturated thickness (water table to the bedrock) ranges from zero along the sides of the valley, to more than 100 feet in Agency Park. Average saturated thickness throughout the region is approximately 20 feet. The alluvium consists mainly of coarse sand and gravel, with thin layers of clay, silt, and sand. Based on pumping tests performed by the USGS (Van Liew and Gesink, 1985), hydraulic conductivity of the aquifer material ranges from 70 to 1,550 ft/day, with the highest values occurring in the Agency Park aquifer in the western part of the region. Specific yield of the aquifer material ranges from 0.1 to 0.3, with an average of 0.2, signifying that a change in groundwater levels of 1.0 feet equates to an equivalent water depth of 0.2 feet.

Based on measured groundwater levels and estimated potentiometric surface contours (Van Liew and Gesink, 1985), groundwater flows from the alluvial material into the White River for most of the study area, for most of the year. Figure 2 shows the groundwater head potentiometric surface within the alluvial material near the White River, from Van Liew and Gesink (1985). The red arrows represent approximate direction of groundwater flow, indicating groundwater flow from the aquifer towards the White River.

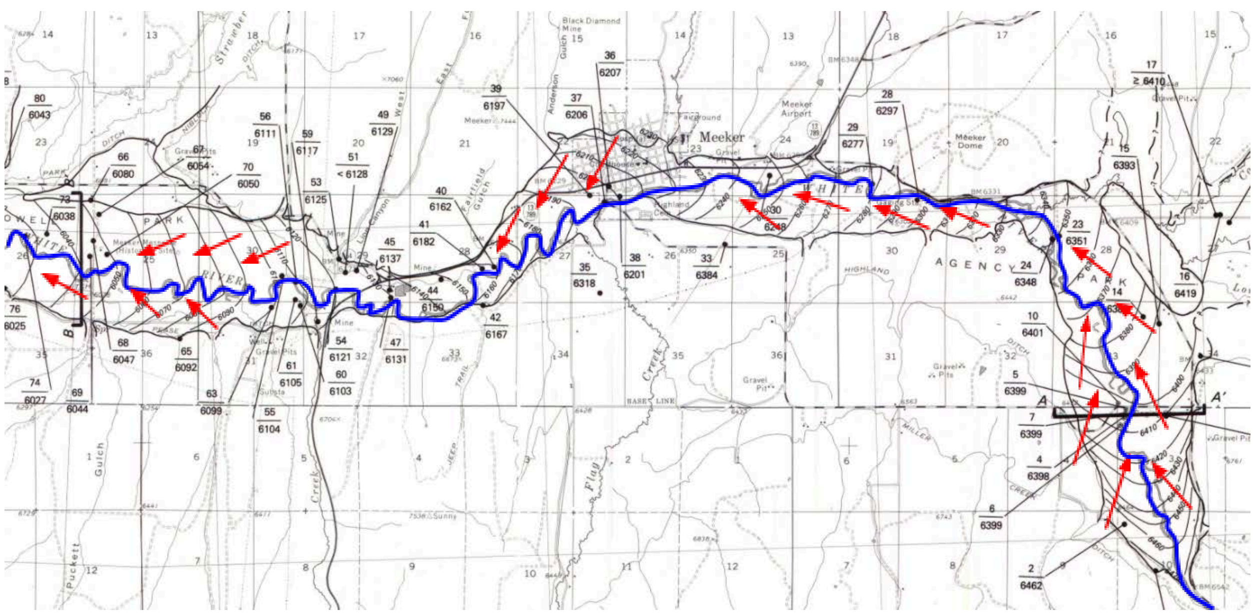


Figure 2. Map of estimated groundwater level (groundwater potentiometric surface), with groundwater flow arrows drawn to show approximate direction of groundwater flow near the White River. The White River is shown in blue.

2.2 Irrigation

Within the White River Basin, approximately 92% of irrigated acreage is flood irrigated. Figure 3 shows the irrigation type for each field, based on the 2020 calendar year (source: Colorado Division of Water Resources). For fields irrigated by flooding, water from the White River is diverted via 30 ditch diversions. Figure 4 shows the average diversion rate (ft^3/sec) for the 2013-2022 period for each ditch. The Highland, Miller Creek, Niblock, and Oak Ridge Park ditches account for 70% of the total diversions. The extensive use of flood irrigation, due to its inherent inefficiencies regarding crop consumptive use, drives the groundwater flow to the White River and its tributaries noted by the USGS study of Van Liew and Gesink (1985). These groundwater flows are termed “return flows”, since originate from the White River via canal diversions for flood irrigation. As stated in the Yampa-White-Green Basin Implementation Plan (YWG BIP) of the Colorado Water Plan, flood irrigation increases the soil moisture and recharge to the water table, increasing groundwater storage and groundwater gradients, generating lagged return flows that come back to the river during fall and winter months. These groundwater “return flows” provide important ecosystem services such as riparian vegetation and downstream flows for irrigation, drinking water, fish and wildlife habitat, and hydropower, similar to many alluvial stream-aquifer systems in the western United States and elsewhere (Venn et al., 2004; Grafton et al., 2018; Gordon et al., 2020; Walker et al., 2020; Donnelly et al., 2024).

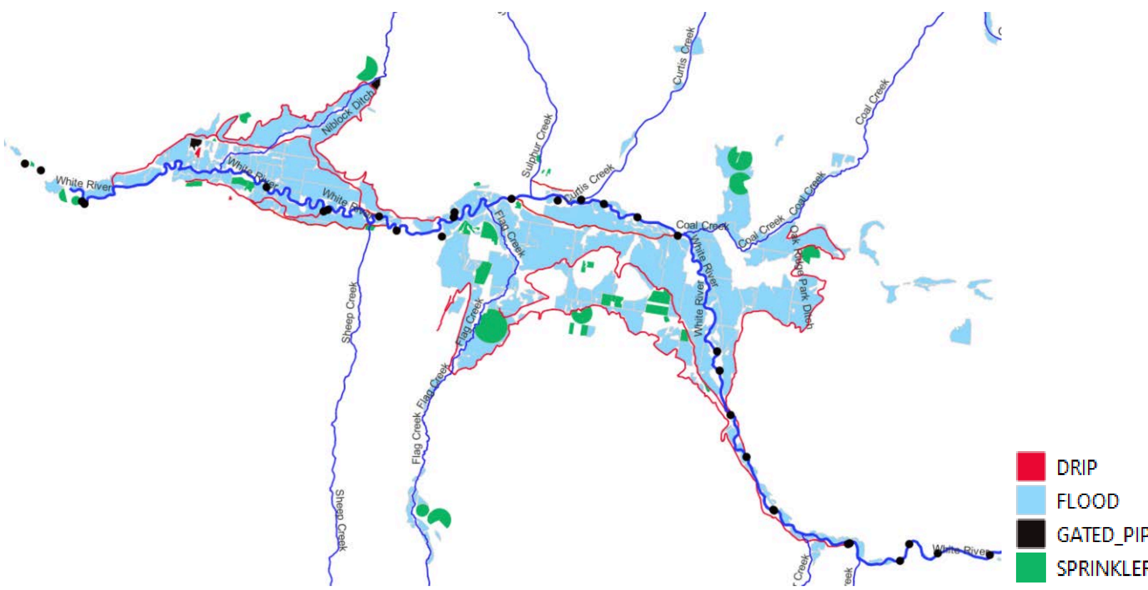


Figure 3. Irrigation type for each irrigated field in the Meeker region.

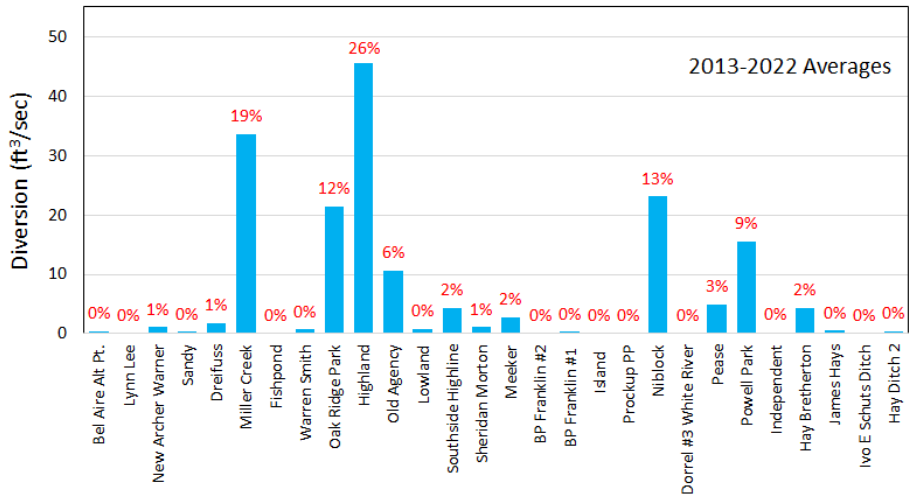


Figure 4. Average flow rate of diversion (ft^3/sec) for each ditch in the Meeker region, averaged over the 2013-2022 period.

2.3 Analysis of Hydrologic Responses

To better understand the general spatial and temporal hydrologic patterns in the Meeker region, two system responses were analyzed: groundwater-river exchange, and groundwater levels.

Groundwater-river exchange

The rate of water volume exchange between the aquifer and the White River was estimated using a water balance approach for river sections (reaches) between adjacent streamflow gage sites (Figure 5). The water balance method applies conservation of mass to the river section between an upstream end and a downstream end, accounting for all inflows and outflows within the section. Inflows consist of river flow at the upstream end, tributary inflows, and groundwater inflow; outflows consist of river flow at the downstream end, canal diversions, and river seepage to the aquifer. The water balance can be written as:

$$\frac{\Delta V}{\Delta t} = inflow + trib - diversions - outflow \pm groundwater \qquad \text{(Equation 1)}$$

where *V* represents the total water storage in the reach. If we assume that, over a given period such as one day, the storage is constant (i.e., steady flow conditions), and assuming that groundwater is a positive term (i.e., groundwater is entering the river), Equation 1 becomes:

$$groundwater = diversions + outflow - inflow - trib \qquad \text{(Equation 2)}$$

Groundwater therefore accounts for the differences between all measured inflows and outflows within the river section.

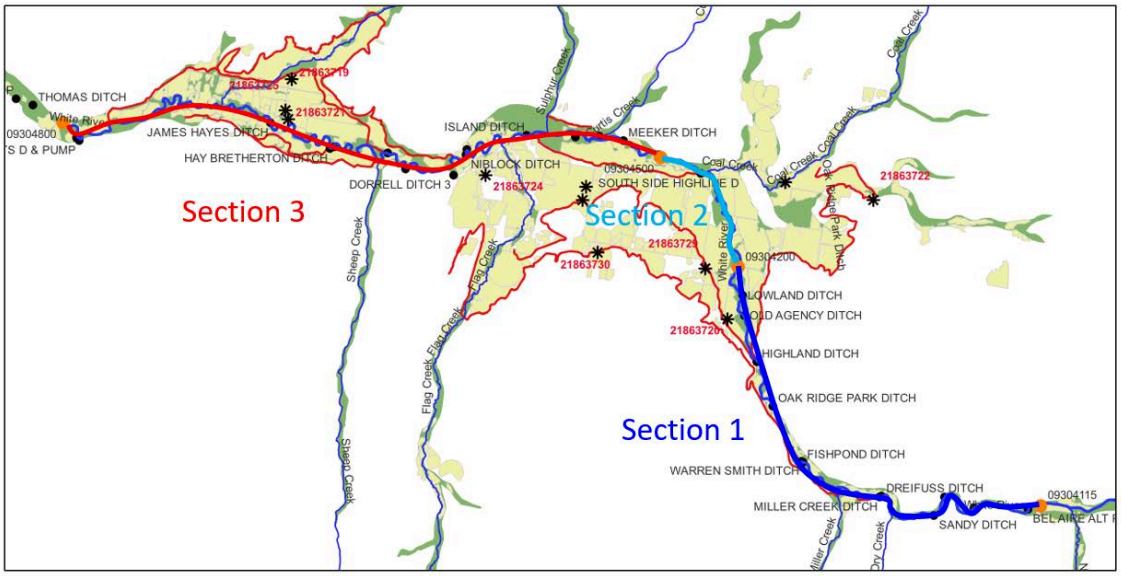


Figure 5. River sections for which a water balance approach was used to estimate groundwater return flow rates.

To populate the terms in Equation 2, and thereby allowing the groundwater term to be quantified, we used daily streamflow data for the gage sites, daily CDWR canal diversion data for the diversion sites, and watershed modeling for the tributary inflows. For watershed modeling, we used the SWAT+ (Soil & Water Assessment Tool) model (Bieger et al., 2017), which uses daily weather, land use, soil type, and topographic slope to simulate rainfall-runoff-infiltration processes in a watershed system. Figure 6 shows the simulated daily flow rate (ft^3/sec) for each of the tributaries in the Meeker region. Due to the lack of flow monitoring gages on the tributaries, these simulated flow rates cannot be corroborated against historical data. However, the overall water balance can be checked for regional accuracy. Of the average annual precipitation of 22 in/yr, 65% is lost to ET, 10% is added to tributary streams via surface runoff, 3% is added to streams via soil lateral flow, and 28% is added to streams via groundwater discharge, for a baseflow fraction of approximately 70%. These values agree with the regional values estimated by Reitz et al. (2017) in their study of recharge, quick-flow runoff, and evapotranspiration for the United States. Although these tributary flow rates cannot be corroborated on a daily or monthly basis, they do not have a significant effect on the estimation of groundwater-river exchange (Equation 2), since flows typically occur during the spring months, before groundwater return flows are expected to be high.

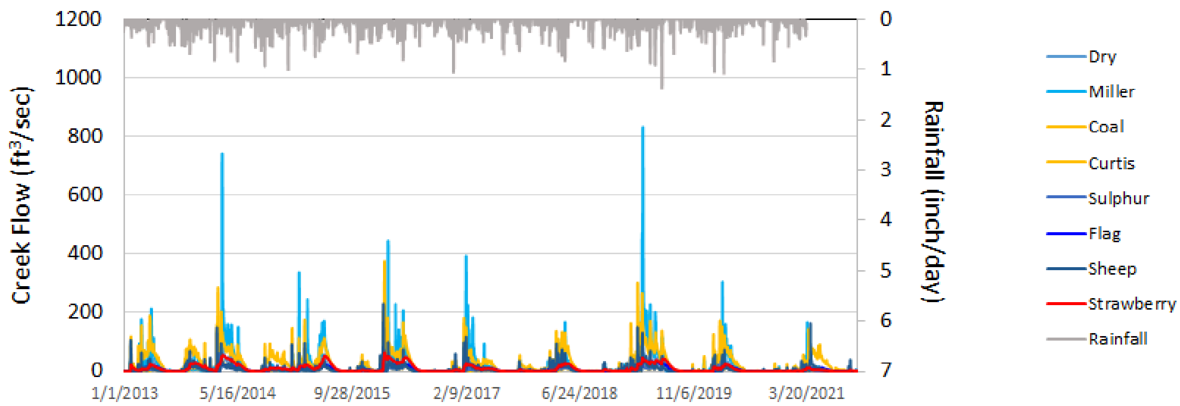


Figure 6. Daily tributary flows as simulated by the SWAT+ model.

Results of the estimated daily groundwater-river exchange rates (ft^3/sec) for Section 1 are shown in Figure 7, indicating periods of groundwater discharge (positive values) and periods of river seepage to the aquifer (negative values). Groundwater discharge typically occurs in the latter half of each year, during and after the growing season (i.e., post-irrigation groundwater return flows). During the 2013-2022 period, the average groundwater-river exchange is 39 ft^3/sec, i.e., a net groundwater inflow to the White River.

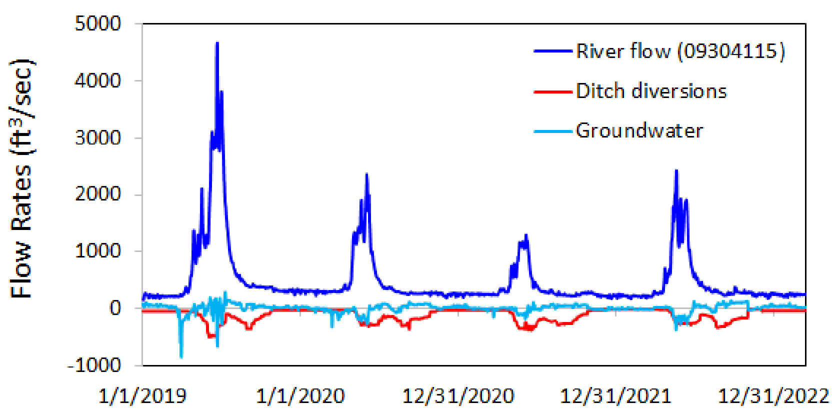


Figure 7. Measured daily flow of the river inflow to Section 1, the aggregated measured canal diversions for Section 1, and the estimated groundwater-river exchange rates for Section 1.

Figure 8 shows the results for the three river sections, with average flow and average flow per mile shown on the right-hand side of each plot. Section 3 has the highest daily groundwater inflow rate (47 ft^3/sec) due to the longest reach length of 16.5 miles, compared to 10.9 miles and 3.4 miles for Sections 1 and 2, respectively. These results corroborate the conclusions from the study of Van Liew and Gesink (1985), that there is a net groundwater inflow into the White River. These flow rates will be used to corroborate the MODFLOW model, as demonstrated in Section 3 of this report.

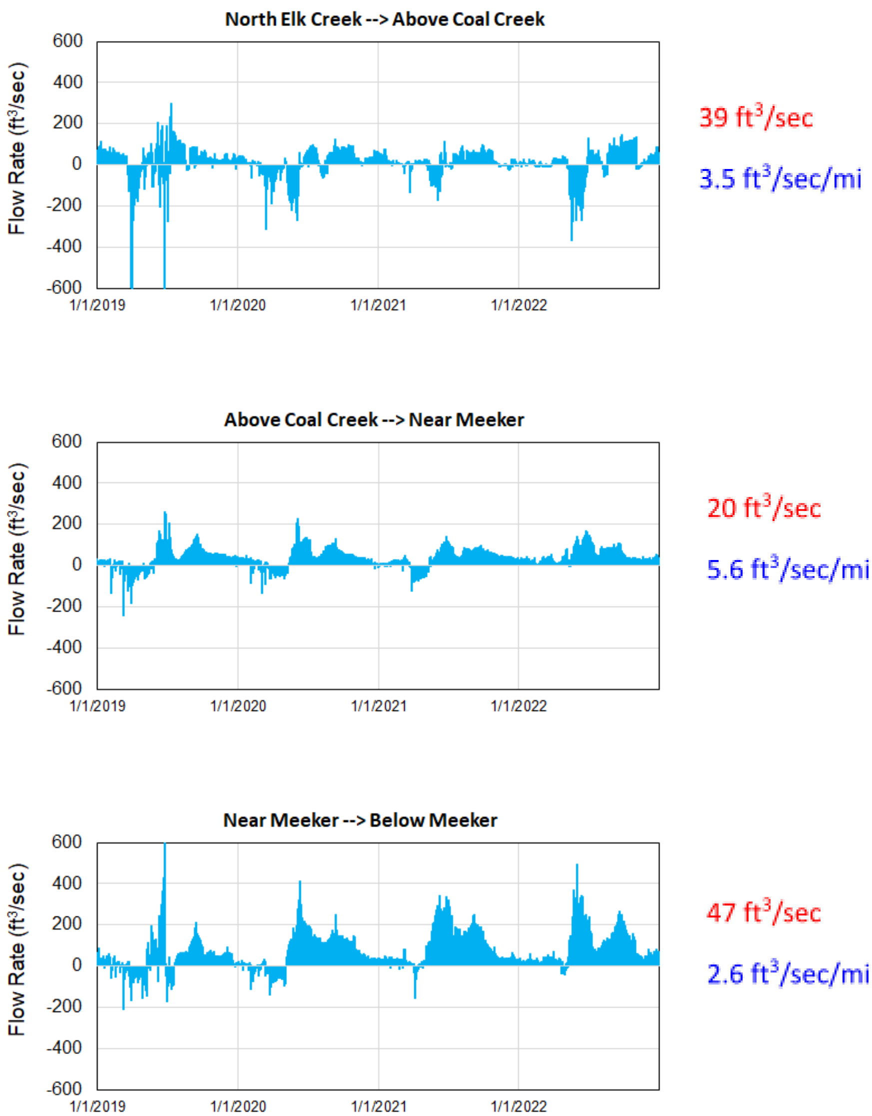


Figure 8. Estimated daily groundwater-river exchange rates, for three sections along the White River in the Meeker region.

To enhance understanding of streamflow rates along the White River in the Meeker region, we used daily average flow rates for the 2013-2022 period (gage sites, tributary inflow, ditch diversions, groundwater-river exchange) to establish a flow-distance plot (Figure 9) between the upstream USGS gage (09304115) and the downstream USGS gage (09304800). For each of the three sections used in the water balance approach, the average groundwater-river exchange rate per mile (see Figure 8) is used to establish changes in river flow between points of inflow (tributary inflow) or outflow (ditch diversions). The ditch diversions produce a negative "jump" on the graph, as water is removed from the White River, whereas tributaries produce a positive "jump" on the graph, as water is added to the White River. Ditch and tributary names and their positions are indicated along the top portion of the graph. The blue dots indicate locations of the four streamflow gages.

For this period of 2013-2022, total ditch diversions are 178 ft^3/sec, total tributary inflows are 68 ft^3/sec, and the change in flow rate between the upstream and downstream points is -3.7 ft^3/sec (518.8 ft3/sec at the upstream end to 515.1 ft^3/sec at the downstream end), a decrease of only 0.7%. To account for this small change even though ditch diversions are higher than tributary inflows by 110 ft^3/sec (178 vs. 68), groundwater enters the White River **at a rate of 106 ft^3/sec**, which is the summation of the daily groundwater flow rates from Sections 1 (39 ft^3/sec), 2 (20 ft^3/sec), and 3 (47 ft^3/sec) (see Figure 8).

By comparing the estimated groundwater inflow rate of 106 ft^3/sec to the total ditch diversions of 178 ft^3/sec, we conclude that, within the Meeker region, approximately <u>60% of ditch diversions returns to the White River via groundwater discharge</u>. These returns can occur either directly from the alluvial aquifer to the White River through the riverbed, or via groundwater discharging to tributaries, which then discharge to the White River. Furthermore, if 60% of diverted water returns to the White River, then approximately 40% of diverted water is used by crops, which equates to a regional value of irrigation efficiency. These results will be used to corroborate the MODFLOW model, as described in Section 3.

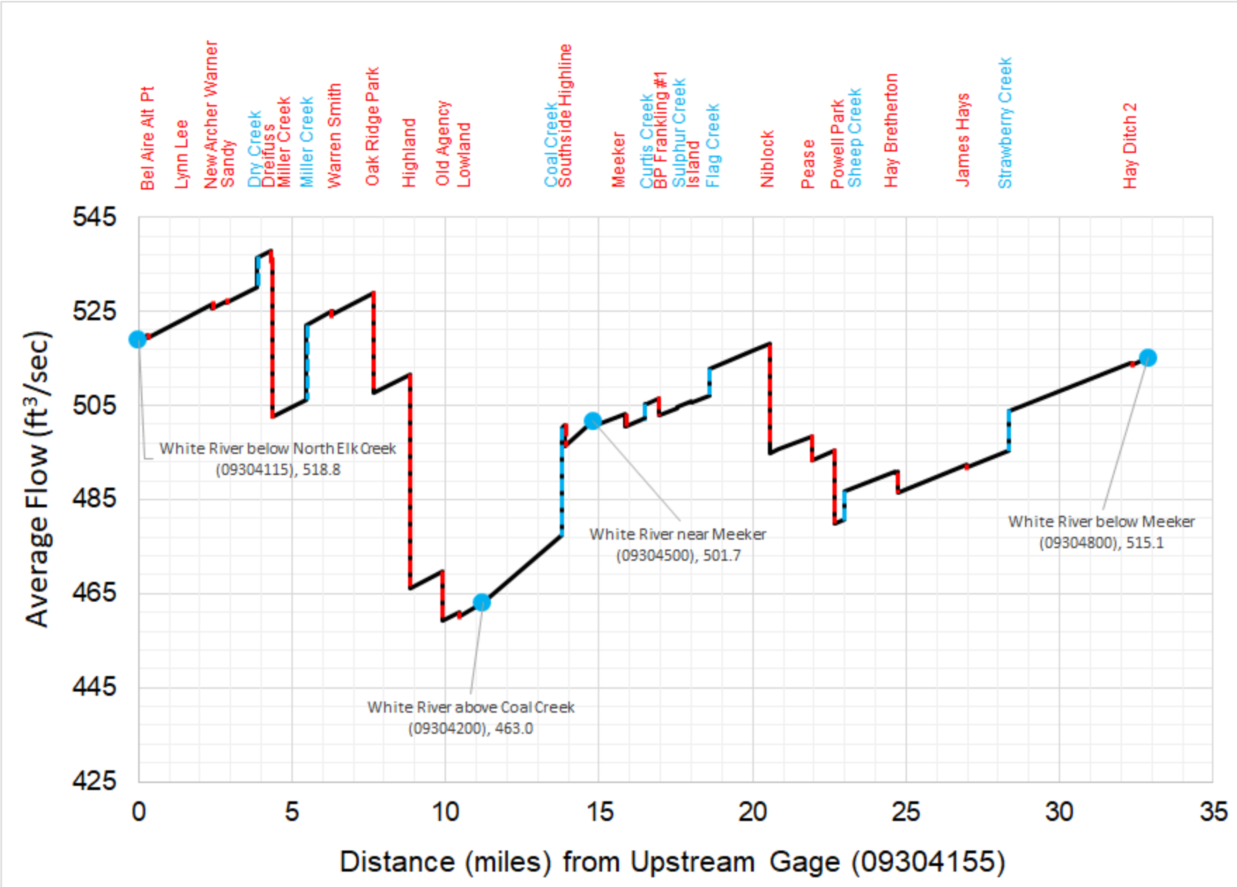
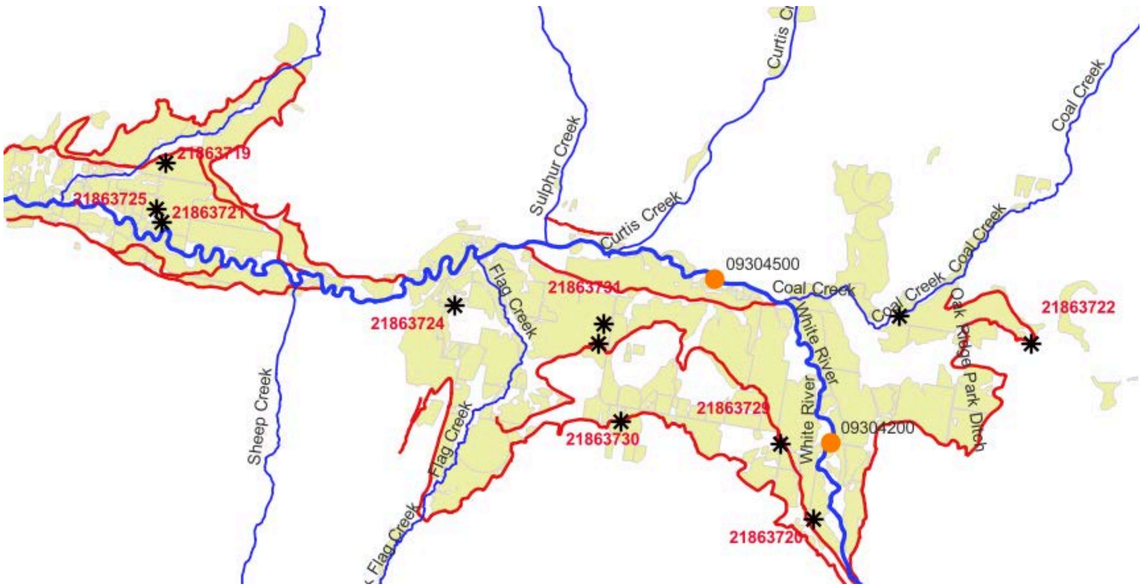
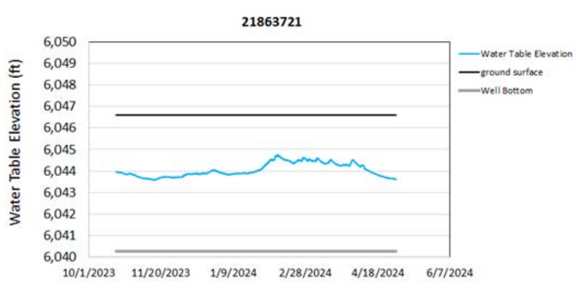


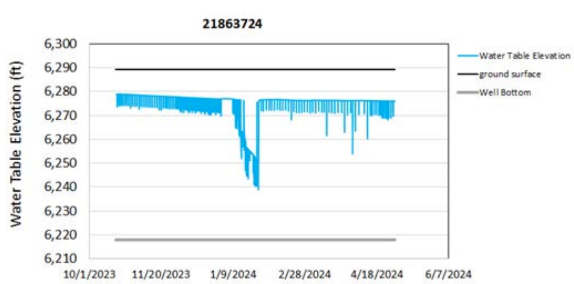
Figure 9. Flow-distance plot of the White River, between the upstream streamflow gage (09304115) and the downstream streamflow gage (09304800). Distance is measured from the upstream streamflow gage site.

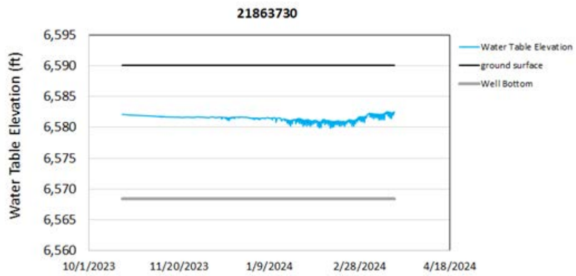
Groundwater levels

A network of 11 groundwater monitoring wells were installed by the White River Conservation District in a companion project, in November 2023. Well locations are shown in Figure 10. Pressure transducers with a data logger were installed in each well, to record groundwater levels every 15 minutes. Figure 10 also shows measured groundwater levels for several of the wells. These initial groundwater level results are used to provide an initial calibration of the MODFLOW model (see Section 3). Groundwater levels will continue to be monitored through 2024 and 2025. We expect to see groundwater levels to increase during the irrigation season, and then slowly decrease during the post-irrigation season, and become stable during the winter and early spring months.









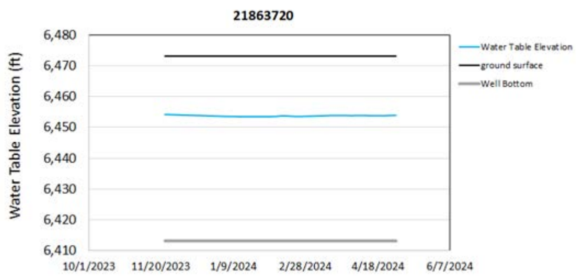


Figure 10. Locations (stars) of groundwater monitoring wells installed in November 2023. Inset plots show time series of measured groundwater level for four selected monitoring wells.

3. MODFLOW Model of the Meeker Region

This section outlines the development, construction, calibration, and testing of the MODFLOW groundwater model of the Meeker region. The MODFLOW modeling code (Niswonger et al., 2011) (Fortran language) simulates the storage and three-dimensional flow of groundwater within an aquifer system. Aquifers can be either unconfined, confined, or convertible, using multiple layers. MODFLOW has a suite of source/sink packages to simulate inflows and outflows, such as soil recharge, pumping, and exchange with streams and rivers. Due to the complex nature of water transfers and movement in the Meeker region, we have prepared a new irrigation package, as outlined in Section 3.2. The MODFLOW model for the Meeker region covers the spatial extent of the aquifer system, including the alluvial material along the tributaries. Figure 11 shows the extent of the model, and the grid cells in relation to the irrigated fields, ditches, the White River, and tributaries.

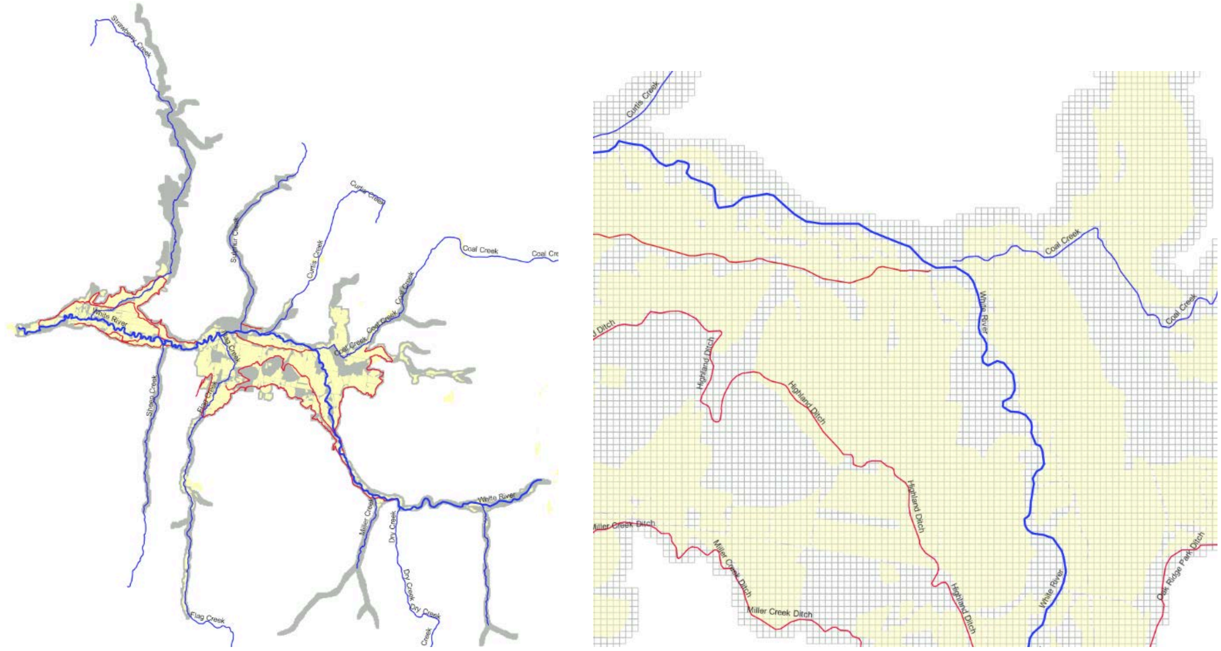


Figure 11. (left) spatial extent of the MODFLOW grid; (right) eastern portion of the Agency Park aquifer area, showing the size of the grid cells in relation to the irrigated fields, ditches, and the White River.

<u>3.1 MODFLOW grid and aquifer properties</u>

The time and length units of the MODFLOW simulation are days and feet, respectively. Each MODFLOW grid cell requires a value for surface area (ft^2), ground surface elevation (ft), bedrock elevation (ft), hydraulic conductivity (ft/day), and specific yield (ft^3/ft^3). Each square cell is given a length of 200 ft on a side, resulting in a surface area of 40,000 ft^2 (0.92 acre). The number of rows and columns in the model is 977 and 836, respectively, with 48,627 cells active (i.e., within the aquifer system). The aquifer is represented by a single layer, with the soil layer simulated by the new irrigation package (see Section 3.2). Ground surface elevation (Figure 12) is provided by a 30-m raster digital elevation model (DEM) of the USGS, with raster pixel values averaged across a MODFLOW grid cell.

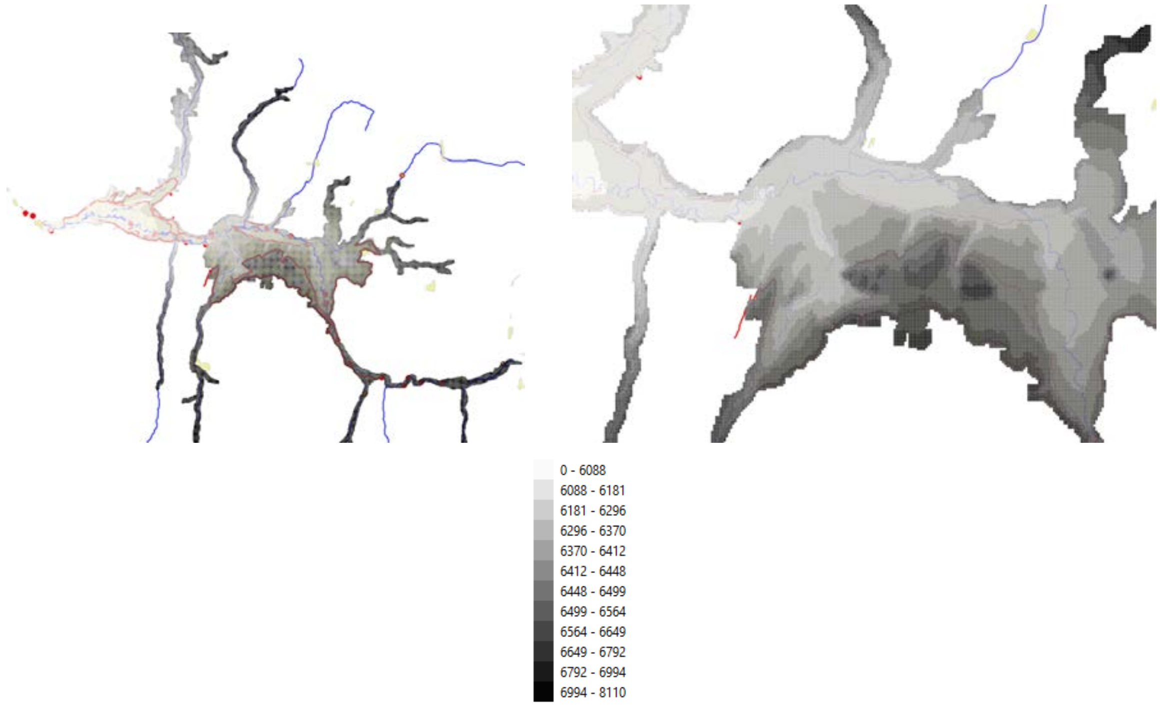


Figure 12. Groundwater surface elevation (ft above sea level) for each MODFLOW grid cell.

Aquifer thickness (ft) and initial (pre-calibrated) values of hydraulic conductivity (K) and specific yield (S_y) were determined using a combination of geologic maps and lithology from 414 boreholes, with the latter available in the CDWR well drilling database. Figure 13 shows the location of the 414 boreholes, and the resulting delineation of the aquifer system into 21 units. Calibrated values of K and Sy for each aquifer unit is presented in a later section. Figure 14 shows the estimated aquifer thickness (ft) for each grid cell, based on the depth to shale (bedrock) as indicated by lithologic logs of the borehole data. Aquifer thickness at borehole locations was spatially interpolated to provide a value for each MODFLOW grid cell. The spatial pattern of these thickness has been corroborated by Travis Day, local well driller in Meeker. Notice the thick aquifer section in the eastern portion of the Agency Park aquifer.

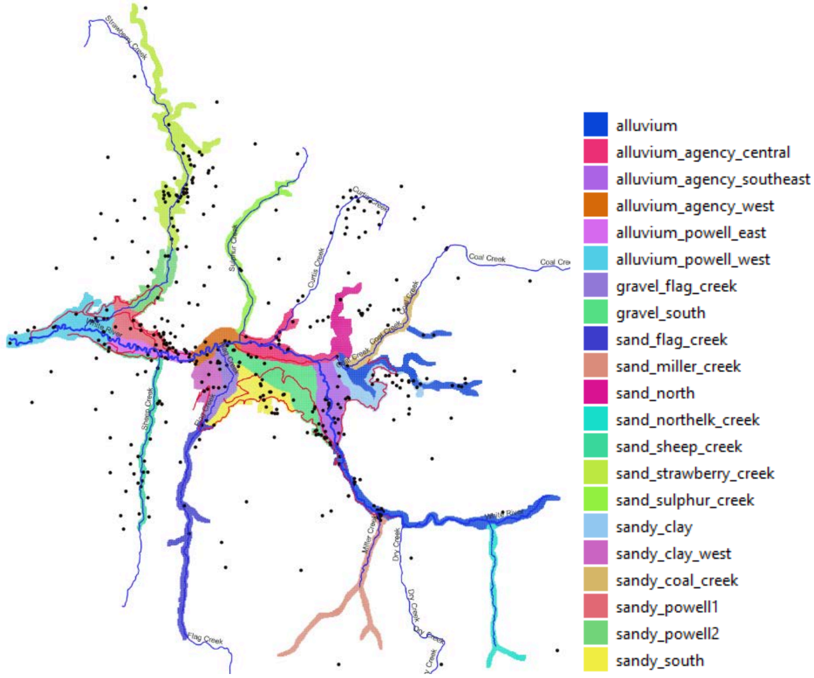


Figure 13. Location of 414 well boreholes; colors indicate 21 delineated aquifer zones.

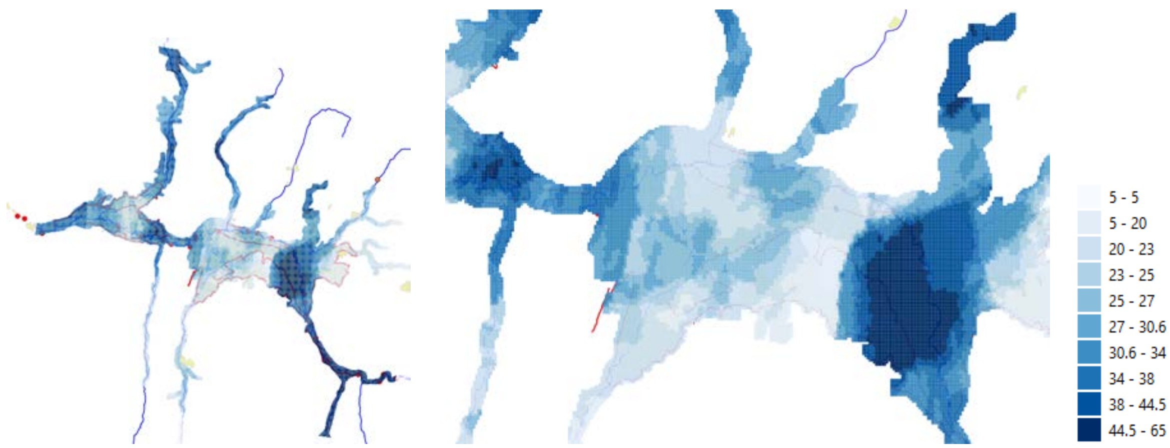


Figure 14. Estimated aquifer thickness (ft) for each MODFLOW grid cell.

3.2 Simulating water exchange between the aquifer and surface water

Water exchange between the aquifer and surface water occurs along the White River, tributaries, and irrigation canals. The exchange of water between surface water and the aquifer is simulated using MODFLOW's River Package. 3,426 grid cells intersect the White River or tributaries, and hence are included in the River Package. Each grid cell requires stream stage (ft), conductance (ft^2/day), and streambed elevation (ft). Stream stage (ft) is based on the DEM value for the grid cell; conductance is calculated using estimated streambed hydraulic conductivity (ft/day), based on the aquifer unit in which the River cell resides (see Figure 13), and the area of contact between the streambed and the aquifer, defined by the width of the river (ft) and the length of the river (ft) in the grid cell. The length of the stream (ft) in the grid cell is found by intersecting the shape file of the stream network (White River and tributaries) with the grid. Lengths range from near 0 ft to 340 ft, with the latter occurring if the stream meanders within the footprint of the grid cell. 2,235 grid cells intersect the network of irrigation canals, and also are included in the River Package. Canal cell properties are determined using the same method as for streambed properties of the White Rive and its tributaries. Figure 15 shows the collection of cells intersecting several of the major canals in the region.

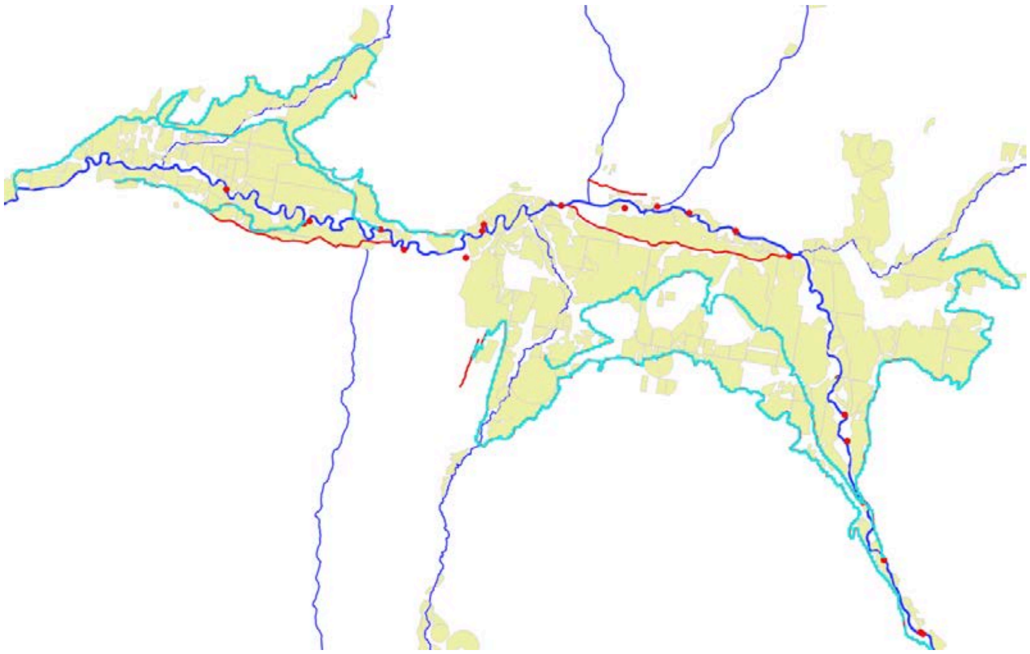


Figure 15. Cells (cyan color) intersecting several of the major canals in the Meeker region. Water exchange between the irrigation canals and the aquifer is simulated for these cells during the MODFLOW simulation.

3.3 Groundwater Pumping

The town of Meeker has 8 pumping wells (Wells B1-B8) for domestic water use. Monthly pumping rates were provided by the town of Meeker, and were applied in the MODFLOW model using the Well Package. As the model runs on a daily time step, the monthly pumping volumes were divided evenly across the days of each month, to provide a daily pumping rate in ft^3/day.

3.4 New Irrigation Package

We created a new irrigation package within the MODFLOW modeling code to handle the unique and complex water management aspects of the Meeker region. Key aspects of the package include:

- **Irrigation volumes** are provided by daily canal diversion data. Each irrigated field is assigned a canal, from which it can receive irrigation water. For each day of the simulation, diverted canal water is applied to each field within its command area, based on the fraction of total command area occupied by the field. The volume of irrigation water for each field is checked against remaining available ditch water, for the current day.
- **Soil water processes** (runoff, infiltration, ET, percolation) are simulated for a collection of "hydrologic response units", with each HRU consisting of a unique combination of soil type, irrigated field boundary, natural vegetation areas, and topographic slope. Figure 16 shows the basic processes of the soil water balance method. Irrigation and rainfall are applied to the ground surface. Runoff is simulated based on runoff fractions for rainfall and irrigation types (flood, sprinkler), with the remaining water infiltrating into the soil profile and made available for crop and vegetation use (ET). Potential ET is compared to available water capacity (soil water storage – wilting point), to determine how much of potential ET can be used for daily crop growth. Water not consumed by ET is added to soil water storage, with deep percolation occurring once soil water storage increases above the soil's field capacity. Deep percolation water is then routed to the water table using a recharge delay term, usually on the order of several days. Recharge from HRUs is mapped to MODFLOW grid cells, based on a geographic intersection within a GIS.

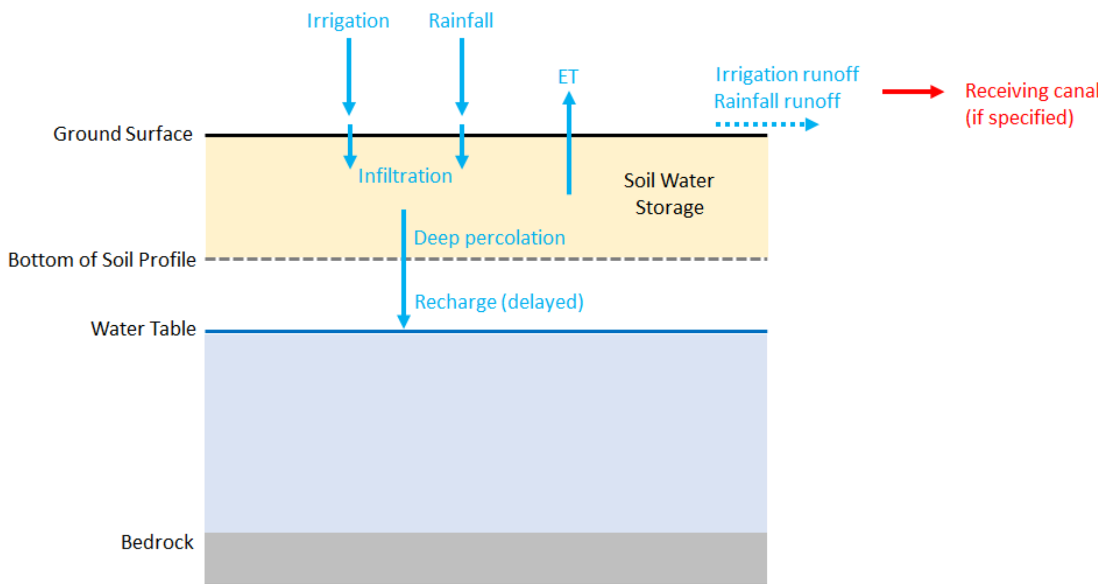


Figure 16. Soil water balance method used in the new irrigation package for MODFLOW.

- **Canal water dynamics.** Canal water available for irrigation is influenced by upgradient field runoff and groundwater exchange. Runoff (rainfall, irrigation) from each HRU can be captured by downgradient canals, and then reused for the irrigated fields of the ditch's command area. For each irrigated field, the canal that can receive runoff water is specified. For example, the Highland Ditch is listed as the canal that can receive runoff from fields in the upgradient Miller Creek Ditch command area. Besides runoff water, canal water can be replenished by groundwater flowing into the canal, based on the head difference between groundwater and the canal stage, in the grid cell that contains a reach of the canal. Similarly, canal water can be removed via seepage to groundwater, if the canal stage is higher than the groundwater head. These additions and removals are performed internally in the code, for each daily time step.

The data required for the irrigation package are provided in a set of input files read in at the beginning of the MODFLOW simulation. These files are:

- *irg.fields_db*: Information for each irrigated field: crop type, irrigation type, canal source for irrigation, and the canal that receives field runoff. For this study, there are 322 fields.
- *irg.soils_db*: Information for each soil type: thickness, wilting point, field capacity (ft of water), starting soil storage, and recharge delay.
- *irg.weather*: Daily weather data: precipitation, ET for each crop type, ET for natural areas, rainfall runoff fraction.
- *irg.irrig*: Information for irrigation: number of irrigation types, runoff fraction for each irrigation type, properties for each canal (depth, width, bed thickness, bed hydraulic conductivity), connection information between canals and grid cells (row and column of grid cell; length of canal in the cell), daily diversions for each canal.

- *irg.hrus*: Information for each HRU: soil type, field, presence of natural vegetation, topographic slope, and surface area.

For these files: all data must be in the same units as specified in other MODFLOW input files. For this simulation: ft and days.

The following datasets are used to populate the required data for the irrigation package:

- Daily rainfall depths (CoAgMet; Meeker station)
- Daily estimated potential crop ET for alfalfa and grass (CoAgMet; Meeker station)
- Daily diversion volumes for each ditch (CDWR)
- HRU delineation (SSURGO soil units; DEM; irrigated field boundaries from CDWR)
- Soil properties (thickness, wilting point, field capacity) (SSURGO)
- Irrigation type (flood, sprinkler) (CDWR)
- Ditch command area for each irrigated field (CDWR)
- Downgradient ditch for selected fields (provided by White River Conservation District personnel)

Figure 17 shows the map of 12,835 HRUs used in the model simulation.

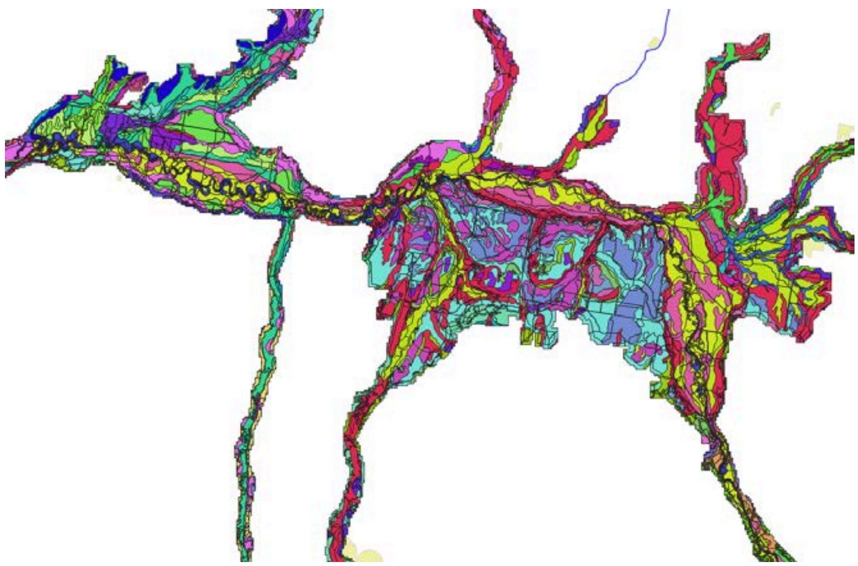


Figure 17. Map showing the delineation of hydrologic response units, which are unique combinations of soil type, irrigated fields, natural vegetation areas, and topographic slope.

3.5 Sensitivity Analysis

The MODFLOW simulation is run for the period 2019-2023, on a daily time step. As a first step towards model calibration, we performed a sensitivity analysis to determine which model parameters have the strongest influence on exchange rates between the aquifer and the White River. The parameters included in the analysis are shown in Table 1, and span aquifer properties, runoff properties, canal properties, weather, and riverbed conductance. Weather properties are not used for calibration, but are included here to determine their relative influence on groundwater-river exchange, as compared to other model parameters. The sensitivity analysis is performed using the Morris method, through the PEST software program. The observation data used to determine sensitivity are annual groundwater return flow volumes for each of the three sections used in the water balance approach (see Section 2.3).

Table 1. Parameters included in the Morris sensitivity analysis.

Parameter	Definition	Unit
K_1	alluvium	ft/day
K_2	alluvium_agency_central	ft/day
K_3	alluvium_agency_southeast	ft/day
K_4	alluvium_agency_west	ft/day
K_5	alluvium_powell_east	ft/day
K_6	alluvium_powell_west	ft/day
K_7	gravel_flag_creek	ft/day
K_8	gravel_south	ft/day
K_9	sand_flag_creek	ft/day
K_10	sand_miller_creek	ft/day
K_11	sand_north	ft/day
K_12	sand_northelk_creek	ft/day
K_13	sand_sheep_creek	ft/day
K_14	sand_strawberry_creek	ft/day
K_15	sand_sulphur_creek	ft/day
K_16	sandy_clay	ft/day
K_17	sandy_clay_west	ft/day
K_18	sandy_coal_creek	ft/day
K_19	sandy_powell1	ft/day
K_20	sandy_powell2	ft/day
K_21	sandy_south	ft/day
ro_slp	Runoff slope	-
ro_fld	Flood runoff fraction	-
ro_spk	Sprinkler runoff fraction	-
ro_drp	Drip runoff fraction	-
ro_gtp	Gated pipe runoff fraction	-
cnl_dep	Canal depth	ft
cnl_wid	Canal width	ft
cnl_thk	Canal bed thickness	ft
cnl_k	Canal bed Conductivity	ft/day
cnl_fr	Fraction of water used	-
delay	Recharge delay	-
prcp_fr	Precipitation fraction	-
et_crop	Crop ET fraction	-
et_nat	Natural ET fraction	-
cond_ft	Riverbed Conductance	ft^2/day

The resulting sensitivity index of each parameter is shown in Figure 18. From these results, we conclude that the following model factors have the strongest influence on groundwater-river exchange, and hence on groundwater return flows to the White River (in order of influence):

1. Riverbed conductance (cond_ft) □ control on how groundwater can discharge to the river.
2. Hydraulic conductivity (K) of the alluvium in the southeast section of the Agency Park aquifer (K_3) □ controls movement of groundwater near the White River.
3. Canal bed hydraulic conductivity (cnl_K): controls canal seepage to the aquifer, which controls groundwater levels and resulting groundwater gradient from the aquifer to the White River.
4. Canal bed thickness (cnl_thk): controls canal seepage to the aquifer, which controls groundwater levels and resulting groundwater gradient from the aquifer to the White River.

5. Crop ET (et_crop): controls recharge to the water table, which controls groundwater levels and resulting groundwater gradient from the aquifer to the White River.

Hence, a combination of aquifer properties, canal properties, riverbed properties, and crop consumptive use controls the volume of groundwater that enters the White River.

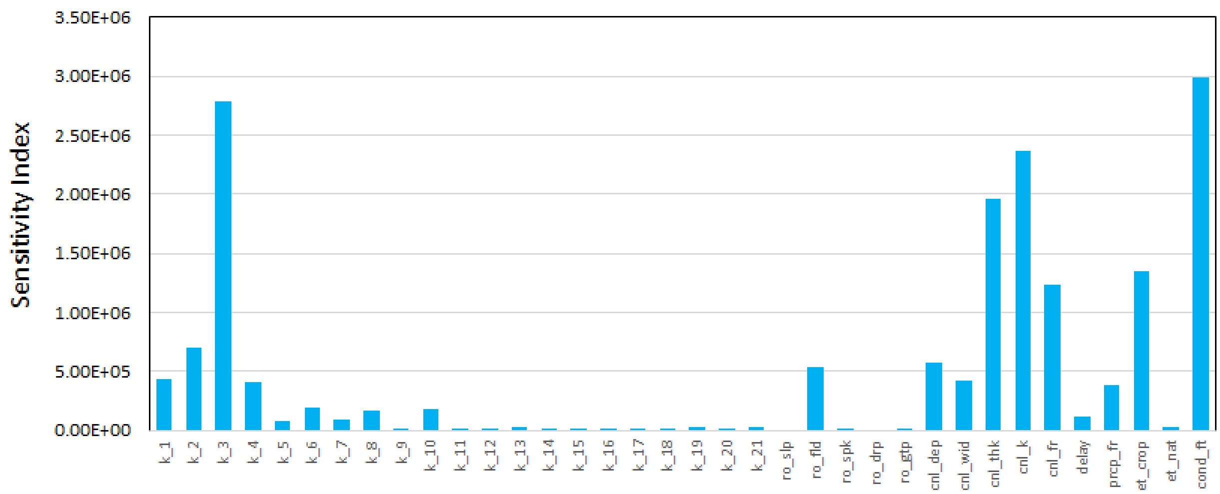


Figure 18. Sensitivity index for each model parameter, based on its influence in controlling groundwater discharge to the White River.

3.6 Calibration and Testing

Model calibration was performed using the list of model parameters in Table 1. The target for calibration was monthly estimates of groundwater-river exchange, for the three sections used in the water balance approach (see Section 2.3). Monthly values for only 2019-2021 were included in the calibration, with monthly values from 2022-2023 used for model testing. Model calibration was performed using the PEST software program.

Groundwater Head

Figure 19 shows the simulated groundwater head (i.e., water table elevation) (ft) at the end of 2023, for each grid cell of the MODFLOW model. The map also shows groundwater head contours (every 20 ft) and associated groundwater flow vectors perpendicular to the head contours. The general groundwater flow direction is from south to north (towards the White River) within the Agency Park aquifer, and from north to south (towards the White River) within the Powell Park aquifer. Notice that within the vicinity of the White River, in the low-elevation floodplain of the valley, the groundwater flow direction is towards the river, similar to the plot from the USGS 1985 study (see Figure 2). These results provide confidence that the model is simulating the spatial distribution of groundwater head correctly.

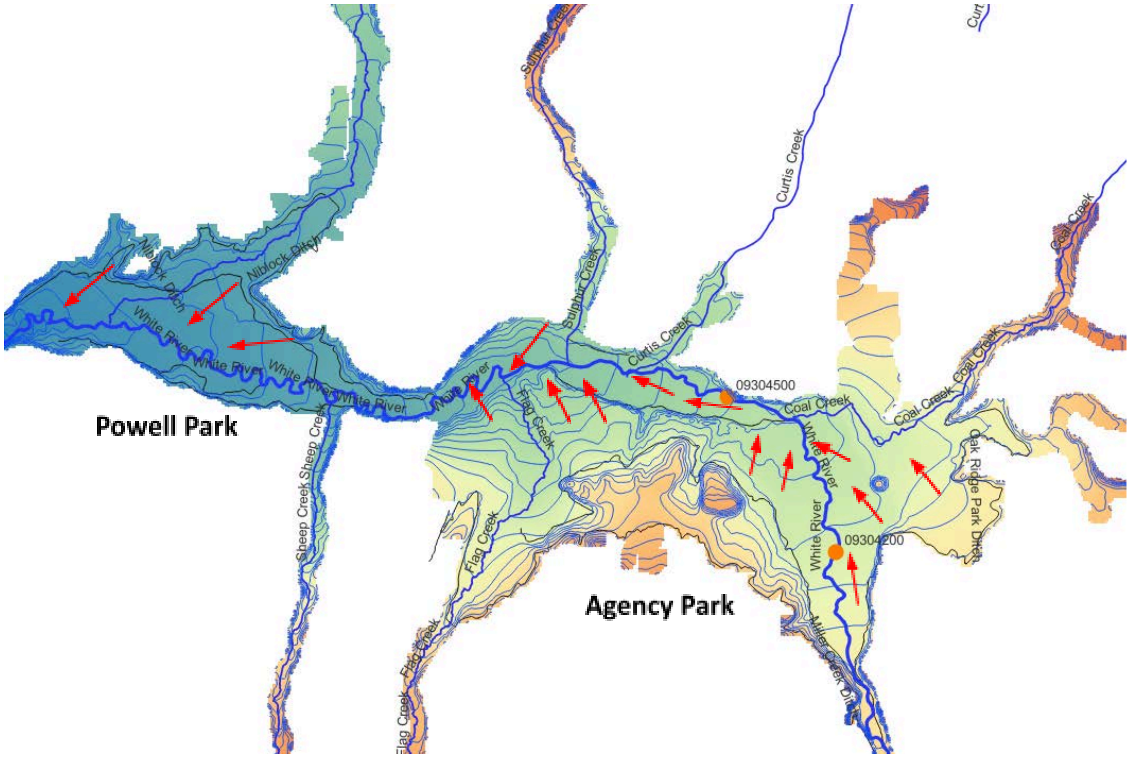


Figure 19. Simulated groundwater head (ft) for each grid cell of the MODFLOW model, for the year 2023.

Figure 20 shows measured and simulated groundwater head (ft) at locations of the groundwater monitoring wells installed in November 2023. The red lines are the measured data, whereas the blue lines are the simulated values from MODFLOW. The black dotted lines represent the ground surface, and the gray line represents the bedrock. Although the model period and the data only overlap by a few months, results indicate that the model is able to capture the local dynamics of water table elevation. However, a much stronger model testing and corroboration will occur when we have groundwater head data through 2024 and the spring of 2025, during which time fluctuations will occur due to recharge from the irrigation season.

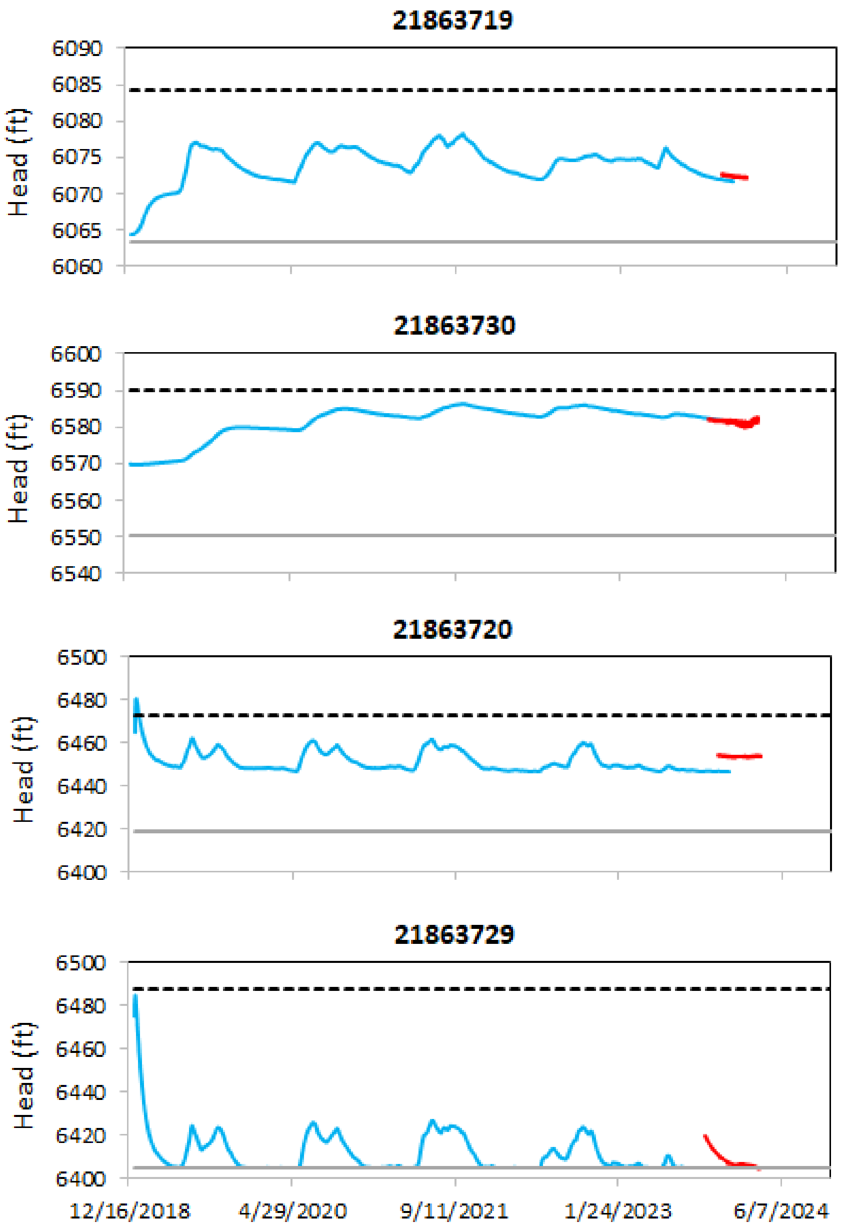


Figure 20. Measured and simulated groundwater head (ft) at four of the groundwater monitoring wells.

Groundwater Return Flows

Figure 21 shows daily measured (using the water balance approach from Section 2.3) and simulated groundwater-river exchange rates for the three sections of the White River, for 2019-2023. Although the model is not able to capture all the temporal variations in daily patterns, it does capture the major temporal, seasonal trends in groundwater return flows., particularly for Sections 2 and 3.

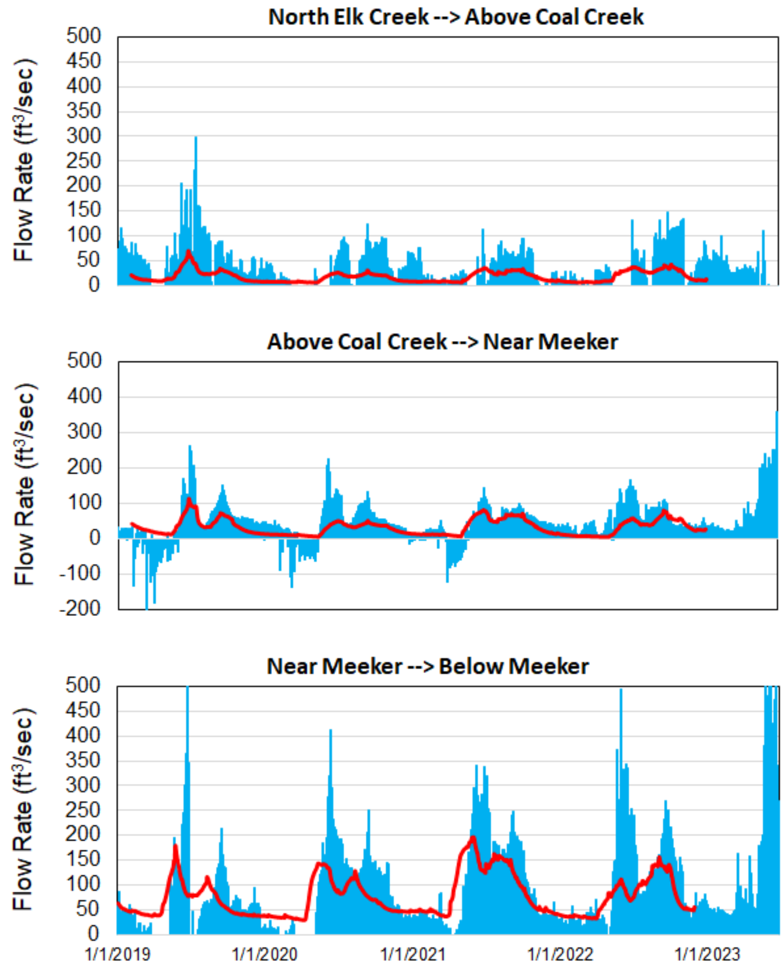


Figure 21. Measured (estimates from water balance method) and simulated daily groundwater-river exchange rates for the three sections of the White River.

Figure 22 shows monthly measured (using the water balance approach from Section 2.3) and simulated groundwater-river exchange rates for the three sections of the White River, for 2019-2023. The Nash-Sutcliffe efficiency value for the three sections is 0.07, 0.42, and 0.55, respectively. Values for Section 1 are low compared to the field-estimated values. Values for Sections 2 and 3, however, are slightly underestimated, but track the seasonal pattern of the field-estimated values. These results demonstrate that the model is able to simulate the temporal pattern and magnitude of groundwater return flows to the White River, based on the seasonal fluctuations of recharge and groundwater level rise. Notice that <u>the majority of return flows are sustained through the end of the irrigation season and into the post-irrigation season (June-November)</u>. This is borne out in both the measured and simulated results. The hydrologic fluxes that control these seasonal patterns are presented and discussed in the next section.

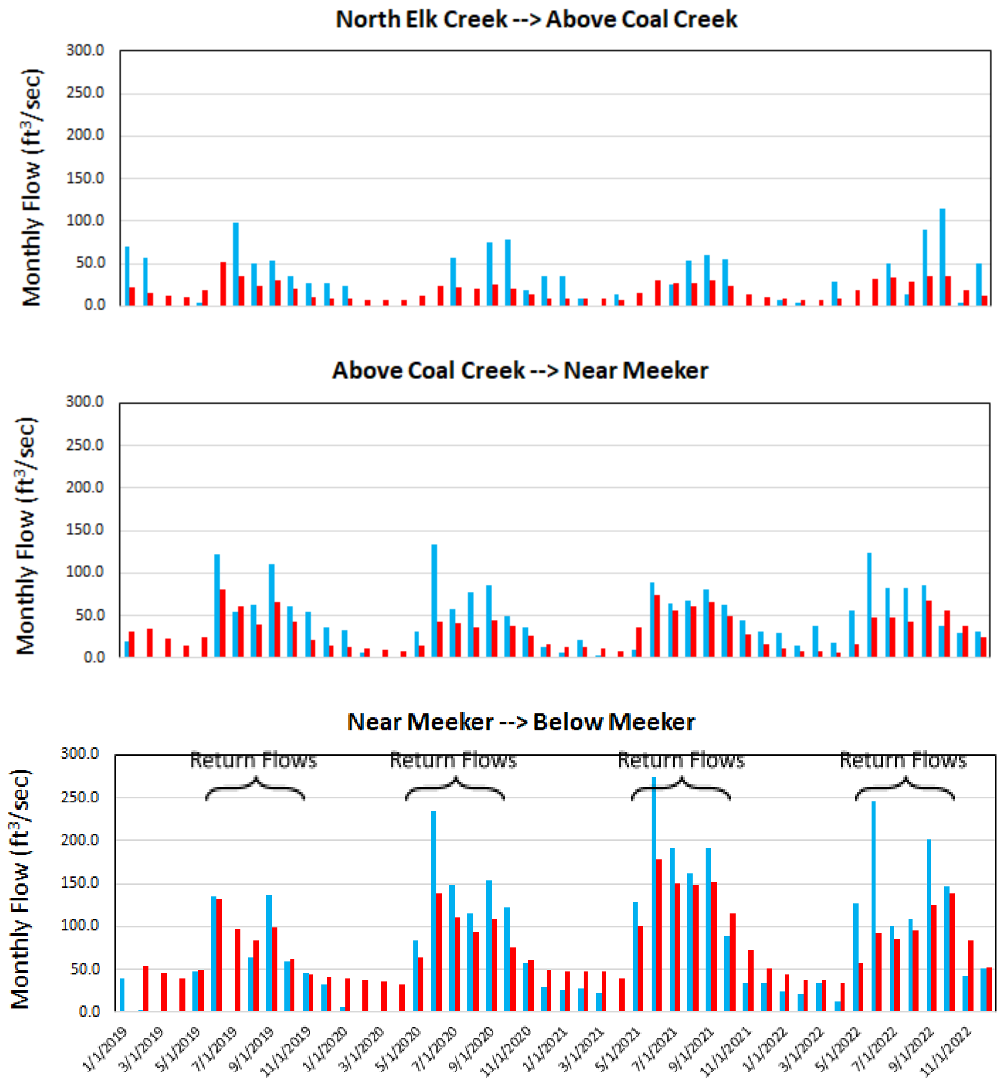


Figure 22. Measured (estimates from water balance method; blue lines) and simulated (red lines) monthly groundwater-river exchange rates for the three sections of the White River.

<u>3.7 Analysis of Hydrologic Fluxes</u>

In this section we analyze the hydrologic fluxes of the system. Figure 23 shows a map of simulated recharge for the year 2019, in total annual depth (ft). Notice that the irrigated fields within the Highland

Ditch command area have the highest recharge depths, due to the large volume of water diverted to the ditch from the White River (see Figure 4).

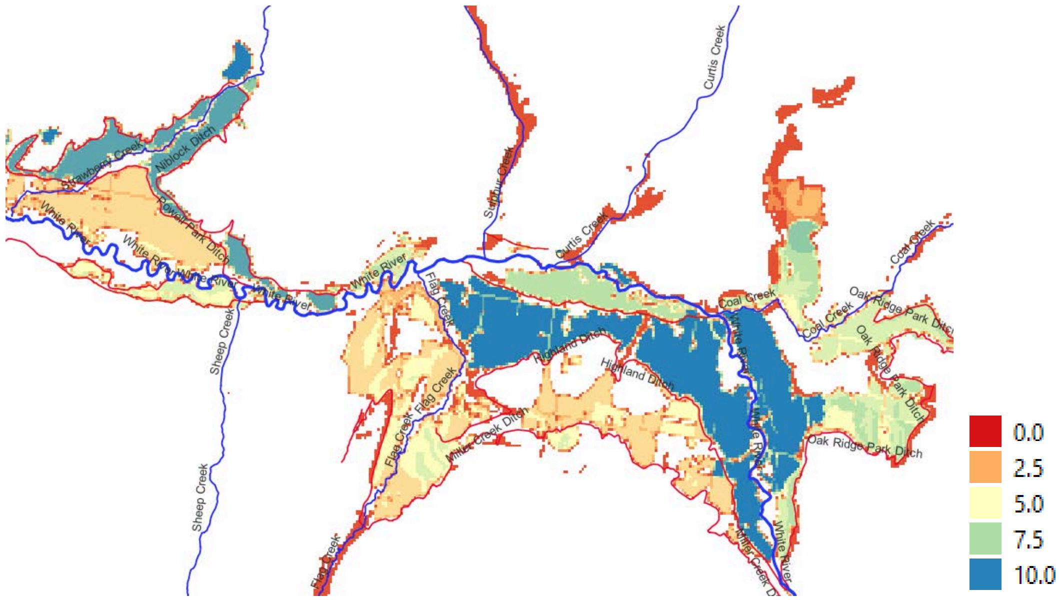


Figure 23. Simulated recharge depths (ft) for the year 2019.

The recharge shown in Figure 23 is a result of the soil water balance method, as described in Section 3.2. Figure 24 shows the daily fluxes for both the soil profile and the aquifer in ac-ft, using the same scale for comparison. For the aquifer plot, notice that groundwater discharge to the river increases during the irrigation and post-irrigation season (June-November) of each year. These patterns are also seen in the groundwater return flow plots in Figures 21 and 22. Figure 25 shows the total daily soil water storage in the region, in ac-ft, with "spikes" occurring on days of heavy recharge, as shown in Figure 24.

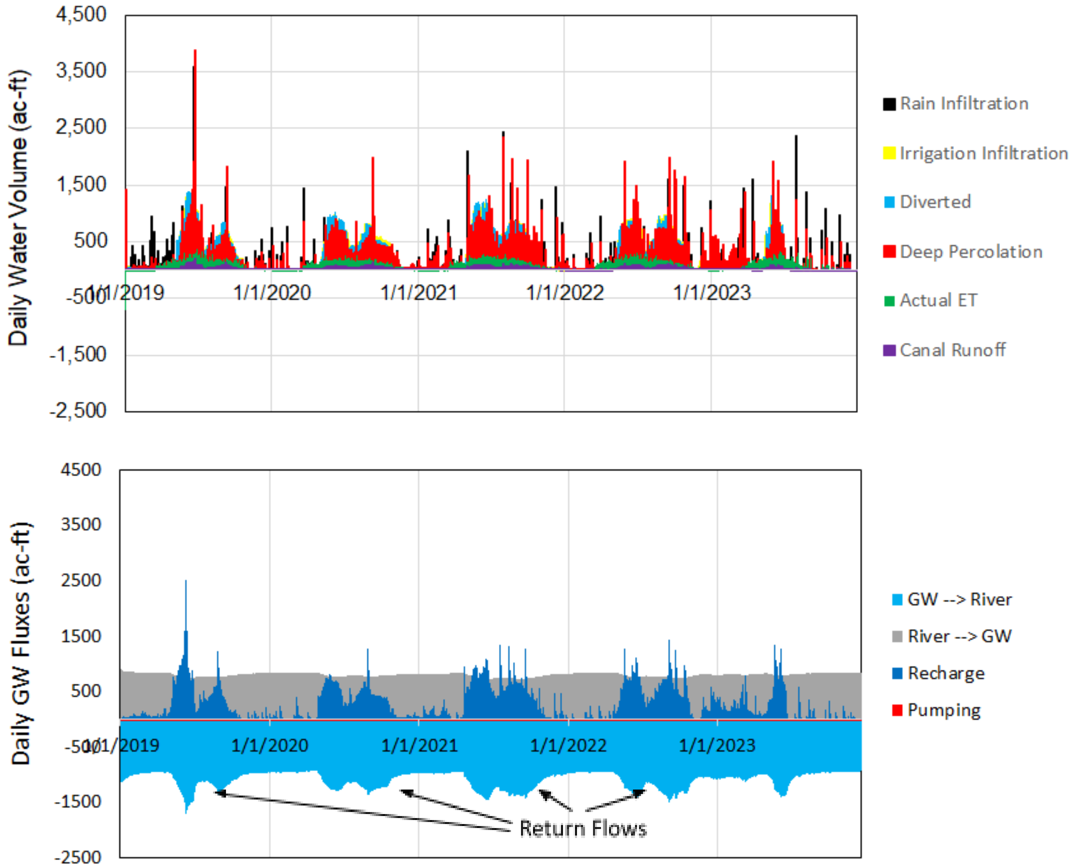


Figure 24. Simulated hydrologic fluxes for the soil profile (top chart) and the aquifer (bottom chart). In the aquifer chart, groundwater-river exchanges include exchanges for the White River, tributaries, and canals.

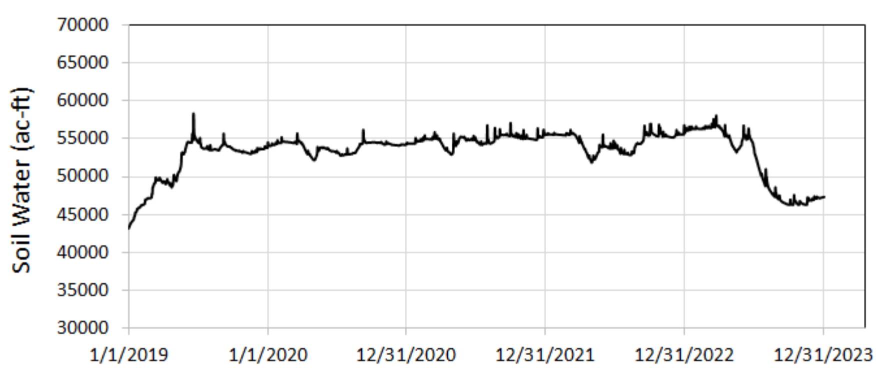


Figure 25. Daily soil water storage (ac-ft) in the Meeker region.

To provide a holistic view of water movement in the Meeker region, the hydrologic flux volumes shown in Figures 23 (soil) and 24 (aquifer) were averaged over the 2019-2023 period. These values, in 1,000 ac-ft per year, are shown in the water balance diagram of Figure 26, with flow arrows scaled according to magnitude. The largest flux is combined infiltration from rainfall and irrigation, totaling 135,000 ac-ft per year, followed by canal diversions (113,000), recharge (101,000), and net groundwater discharge to White River and tributaries (90,000). Notice that a portion (10,000 ac-ft per year) of irrigation runoff is captured by canals, which is then available for irrigation. Canal water volume is also increased by a net groundwater discharge to canals (6,000 ac-ft per year). Key conclusions from this analysis include:

- Irrigation efficiency: The amount of soil water consumed by plants (34,000) divided by the amount of canal water diverted (113,000) is equal to 30%.
- Groundwater fraction: The ratio of groundwater discharge (90,000) to diverted water (113,000) is 80%. From the flow-distance analysis shown in Figure 9, 60% of diverted water returned to the river via groundwater return flow. However, this did not account for groundwater discharge to the tributaries, which is included in the overall water balance shown in Figure 26.
- Discharge fraction: The groundwater discharge (90,000) to recharge (101,000) is 89%. Most of the deep percolation from irrigation returns to the White River and its tributaries.
- Return flows: The volume of groundwater discharge (90,000 ac-ft per year) equates to a flow rate of 124 ft^3/sec. This is similar to the average return flow rate of 106 ft^3/sec estimated from the water balance of the White River sections (see Section 2.3, Figure 8).

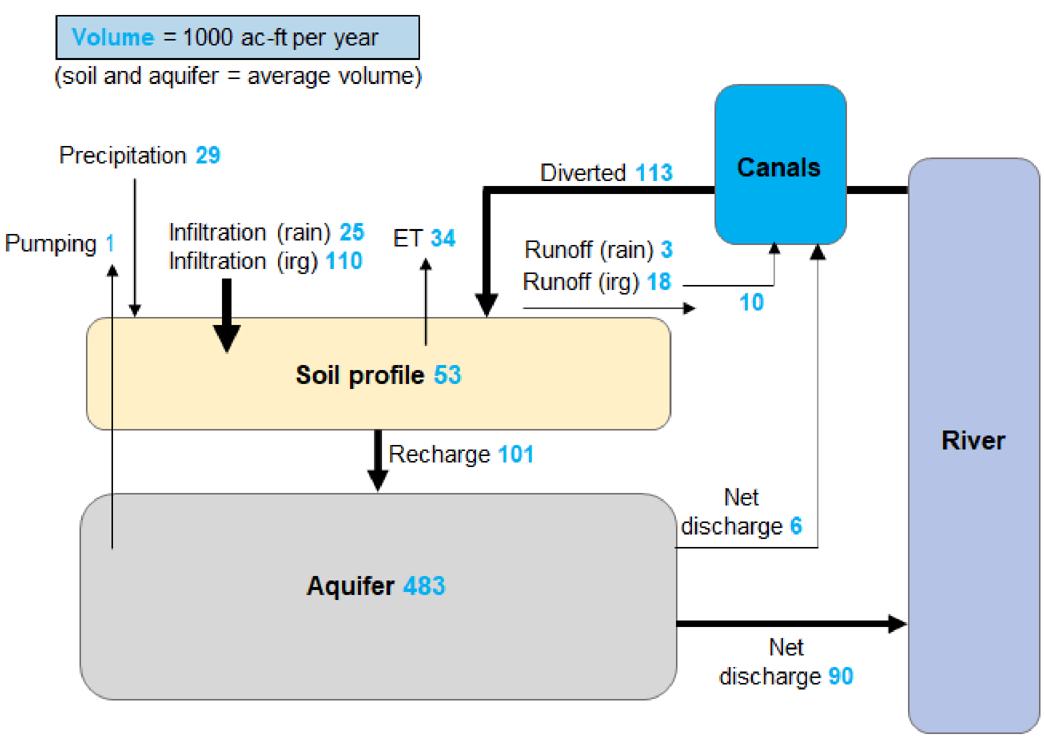


Figure 26. Average annual volumes (x 1000 ac-ft) for hydrologic flux pathways in the Meeker region, as simulated by the MODFLOW model. Flow arrows are scaled according to magnitude.

The aquifer system in the Meeker region has an average volume of 483,000 ac-ft. Approximately one-fifth of the aquifer storage is replenished by recharge (101,000) and diminished by discharge to the river system (90,000).

The volumes in Figure 26 are converted to equivalent water depths (ft) (Figure 27). The average depth of total water in the soil profile is 1.2 ft, and the depth of groundwater in the aquifer is 11.1 ft. With an average aquifer specific yield of 0.2, this equates to an average saturated thickness of approximately 50 ft. The amount of diverted canal water each growing season is equal to approximately one-fifth of the average groundwater storage in the aquifer system. Similarly, recharge and groundwater return flows are equal to approximately one-fifth of the average groundwater storage.

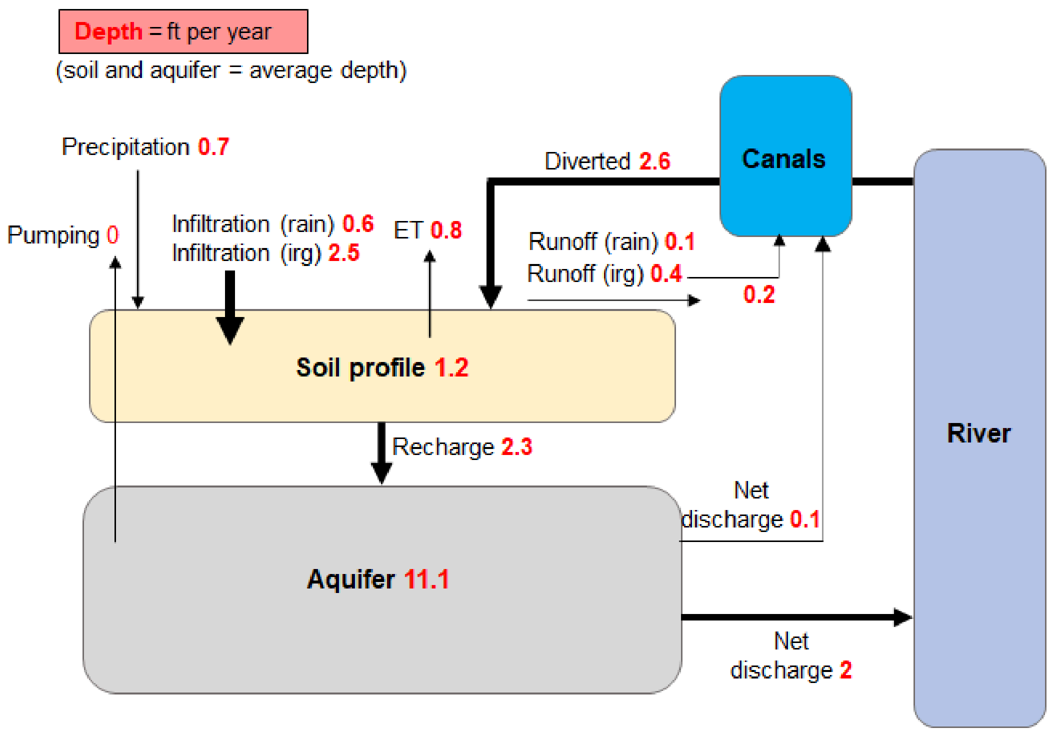


Figure 27. Average annual water equivalent depths (ft) for hydrologic flux pathways in the Meeker region, as simulated by the MODFLOW model. Flow arrows are scaled according to magnitude.

To provide more details regarding field-by-field irrigation efficiency, we assessed the soil water fluxes for each individual HRU in the model. For each HRU that contains an irrigated field, the total (2019-2023) volume of irrigation runoff, crop ET, and deep percolation were summed, and then the crop ET portion of this sum was calculated to provide an estimate of irrigation efficiency. Figure 28 shows the calculated irrigation efficiency for each irrigated HRU, per HRU number and also by a frequency distribution. The average irrigation efficiency is 25%, with an average runoff fraction of 13% and an average deep percolation fraction of 62%.

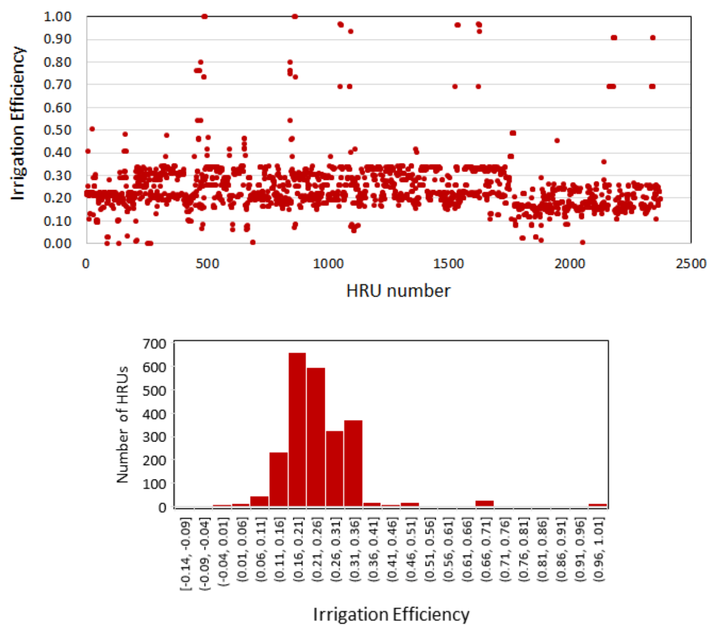


Figure 28. Irrigation efficiency for each irrigated HRU, as computed from simulated irrigation runoff, crop ET, and recharge.

Therefore, for irrigated fields, approximately two-thirds of the applied water is lost to deep percolation, which recharges the aquifer. However, this “lost” water raises the water table, increasing groundwater flow gradients and associated discharge rates to the White River and its tributaries. This results in the 90,000 ac-ft per year of groundwater return flows, as shown in Figure 26.

4. Summary and Conclusions

This project applied a MODFLOW groundwater flow model, modified to include a new irrigation package, to the stream-aquifer White River valley system in the Meeker, Colorado region. The model accounts for canal diversions, canal seepage, rainfall and irrigation infiltration, rainfall and irrigation runoff, canal capture of irrigation runoff, crop ET, soil deep percolation, recharge to the aquifer, groundwater pumping for municipal water supply, and groundwater-river exchange between the aquifer and surface water (White River, tributaries, canals). The model is run on a daily time step for the 2019-2023 period, using 2019-2021 as a calibration period. The model was tested against estimated groundwater-river exchange rates for three sections of the White River, and 6 months of groundwater head measurements from a network of 11 groundwater monitoring wells. Results indicate that the model is able to capture the principal hydrologic features and temporal patterns of the stream-aquifer system, particularly the groundwater return flows that occur during the irrigation and post-irrigation seasons (June-November).

Main findings are:

- Estimated groundwater return flows for the 2013-2022 period are 3.5 ft^3/sec/mi, 5.6 ft^3/sec/mi, and 2.6 ft^3/sec/mi, for the three sections of the White River, between streamflow gages. This equates to a total of 106 ft^3/sec for the White River between the upstream (North Elk Creek; 09304115) and downstream (Below Meeker; 09304800) gages. This is approximately **20% of the average flow in the White River** at the upstream (520 ft^3/sec) and downstream (515 ft^3/sec) gage locations. By applying the MODFLOW model to the 2019-2023 period, an average return flow rate of 124 ft^3/sec was estimated.
- The ratio of groundwater return flows to diverted water to the canals is 0.8. Therefore, of all the canal water diverted from the White River, four-fifths returns to the river via groundwater discharge to the White River and its tributaries.
- The ratio of groundwater return flows to diverted water (0.8) can also be used to represent irrigation efficiency, as only 20% of the diverted water remains in the system, presumably for crop consumptive use. When analyzing individual irrigated fields, average irrigation efficiency is 25%, with 13% runoff fraction and 62% deep percolation fraction. A portion of the runoff is captured by downgradient canals, which can then be reused for irrigation.
- The high deep percolation fraction (62%) indicates that most of the water applied as irrigation is lost to the soil system. However, this "lost" water raises the water table, increasing groundwater flow gradients and associated discharge rates to the White River and its tributaries.
- For an average year, volumes of canal diversion, recharge, and groundwater discharge rates **are equivalent to 20% of aquifer groundwater storage**. Therefore, the aquifer acts as a conveyor system for unused canal water that percolates through the soil profile, recharges the aquifer, and

induces gradients that discharge groundwater to the White River and its tributaries. Due to the slow movement of soil water and groundwater, however, increased rates of groundwater return flows occur typically over a 6-month period, from June through November.

- If recharge to the water table were decreased, water table elevation throughout the region would decrease, resulting in a corresponding decrease in groundwater discharge to the White River. This will be explored in detail in a follow-on study.

Future work includes additional calibration of the model, as new groundwater head data become available from the network of groundwater monitoring wells for 2024 and the spring months of 2025. Estimated groundwater return flow data for the three White River sections for the year 2024 will also be used for additional model testing. In addition, streamflow gaging for the tributaries will be used to check simulated groundwater return flow rates to the tributaries. With the final calibration and testing complete, the model can be used to explore and quantify the impact of system changes on 1) hydrologic fluxes (soil, aquifer); 2) groundwater head; and 3) groundwater-river exchange rates. System changes include potential changes from flood irrigation to sprinkler irrigation, resulting in changes in the timing and magnitude of canal diversions.

Acknowledgements

This work was funded by the Colorado Water Conservation Board (CWCB), contract number 185251. We would also like to acknowledge the White River & Douglas Creek Conservation Districts for providing groundwater head measurements from the network of monitoring wells; to Travis Day for assistance in understanding local hydrogeologic conditions; and to the White River Integrated Water Initiative activity committee for suggestions and guidance during the project.

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