Development of the Diversion Runoff Calculator to Estimate Agricultural Water Consumption and Irrigation Diversions at the Field- to Basin-Scale in Northeastern Utah

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Abstract: With the western United States experiencing aridification and prolonged drought, there is a need for improved water management to understand irrigation water requirements and to forecast how drought mitigation efforts may affect irrigation operations at the field-, canal-, and basin-scale. This paper presents the Diversion Runoff Calculator (DRC), which uses geospatial and field-scale data sets (monthly evapotranspiration estimates from OpenET and effective precipitation estimates from the ET Demands model) to estimate irrigation requirements, field runoff, and canal seepage at the field-, canal-, and basin-scale. Because the geospatial data sets characterize field-scale attributes (irrigation method, canal lining, etc.), changes to these attributes can be made to reflect potential drought mitigation strategies and processed using the DRC. The effects of drought mitigation strategies are realized through changes in irrigation demands. The DRC is tested on irrigated lands along the Duchesne River in northeast Utah. At the field scale, the study finds that the consumptive use values calculated using OpenET data and the ET Demands model match well with the irrigation requirement tables typically used by water managers. The field-scale consumptive use data are aggregated to the canal-scale and a transit loss within the canal is calculated, resulting in an estimated diversion flow requirement at the headgate of each canal, which is subsequently aggregated to the basin scale. The canal- and basin-scale diversion estimates reasonably replicate observed diverted flows, with basin-scale Nash–Sutcliffe Efficiency of 0.74. Two test cases are presented that demonstrate how the DRC can be used to evaluate drought mitigation strategies. The first considers lining all the earthen canals, which results in a 5.0% reduction in diverted flows. The second considers converting all flood-irrigated fields to sprinkler-irrigated fields, which results in a 4.4% reduction in diverted flows. Although the geospatial data sets used are Utah-specific, avenues for applying the DRC in other western states are discussed. **DOI: 10.1061/JIDEDH.IRENG-10452.**

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Introduction

Water is often referred to as the lifeblood of the American West. In the Upper Colorado River Basin (Colorado, New Mexico, Utah, and Wyoming), early American settlers realized the need for irrigation to grow crops and sustain life and began building irrigation networks (Arrington and May 1975). Today, agriculture remains the largest consumer of water in the Upper Basin (Dieter et al. 2018) and is central to rural economies and communities. However, prolonged drought and climate change in the Colorado River Basin have strained water supplies (Udall and Overpeck 2017) and require an emphasis on prudent water management and drought mitigation planning. In the Upper Colorado River Basin in particular, there is a need for strategies to maintain interstate commitments while ensuring that agricultural communities and water users continue to prosper.

Established by the Utah State Legislature in 2021, the Colorado River Authority of Utah (Authority) has a mission to protect, conserve, use, and develop Utah's waters of the Colorado River system [Colorado River Authority of Utah Act (2021)]. As drought mitigation is a priority in the Authority's 5-year Colorado River Management Plan (Colorado River Authority of Utah 2022a), the Authority commissioned the development of water management

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and planning tools to analyze, plan, and develop successful drought mitigation programs (Colorado River Authority of Utah 2022b). In short, these tools were commissioned to plan and assess how drought mitigation strategies (e.g., fallowing fields, crop switching, etc.) will affect the water budget and water rights within a basin before the strategies are implemented. These programs also aim to support partnerships with the agricultural sector, to increase resiliency for agricultural producers, and to leverage the saved water as an additional asset. The Diversion Runoff Calculator (DRC) is one component of the larger Utah Colorado River Accounting and Forecasting–Decision Support Tool (UCRAF-DST) (Colorado River Authority of Utah 2022b; Follum et al. 2023) commissioned by the Authority to support its mission. The DRC incorporates the latest scientific advancements in consumptive use calculations and geospatial data sets to estimate irrigation water use at the field-, canal-, and basin-scale within the Colorado River Basin in Utah. Prior to implementing drought mitigation measures (such as fallowing fields or lining canals), the DRC enables the Authority to understand the potential impacts of drought mitigation measures on the water budget and water rights (via the RiverWare components of the UCRAF-DST). In this work, we primarily discuss the development and testing of the DRC.

Consumptive use of irrigation water is generally defined as the amount of water beneficially used in the production of crops. Although consumptive use includes crop evapotranspiration, frost protection, canal evaporation, and spray evaporation, here we focus on crop evapotranspiration as the primary use of irrigation water. Utah water management officials currently use net irrigation water requirement (NIWR) estimates derived from Hill (1998) as one method to determine irrigation requirements (referred to henceforth as the Utah Tables). Using weather station data throughout the State of Utah from 1961 through 1990, Hill (1998) calculated monthly NIWR values for each of the dominant crop types near each weather station. Hill (1998) used the Soil Conservation Service Blaney–Criddle equation with calibrated crop coefficients to calculate crop evapotranspiration and approximated effective precipitation (EP), the amount of precipitation (P) that is beneficially used in crop production as 80% of P.

Recently, more advanced methods of calculating consumptive use have become available in Utah. Methods like GridET (Lewis and Allen 2017) build upon the work by Hill (1998) by spatially filling in areas that the Utah Tables do not cover. Use of remotely sensed and satellite-based technologies (often in conjunction with energy-balance models) to estimate water consumption in crops has also become common practice (Abatzoglou 2013; Allen et al. 2011, 2007; Bastiaanssen et al. 1998). Assembling six of these methods/models together, OpenET was developed to facilitate continuous data production and ease of access to field-scale (30-m) remotely sensed evapotranspiration (ET) data across the western United States at daily, monthly, and annual timescales (Melton et al. 2022). OpenET currently provides data on total actual evapotranspiration (ET_a, cm) and computes an ensemble mean ET value from the six models after using the median absolute deviation approach (Mauder et al. 2013) to flag and remove outliers from the ensemble for each timestep and pixel. One of the models implemented within the OpenET framework is the Google Earth Engine implementation of the Mapping Evapotranspiration at High Resolution with Internalized Calibration model (eeMETRIC), based on the work by Allen et al. (2011, 2007), which was selected by the U.S. Bureau of Reclamation and the Upper Colorado River Commission as a unified approach for measuring agricultural water use in the Upper Colorado River Basin (Mefford and Prairie 2022). Recently, the Bureau of Reclamation collaborated with the Desert Research Institute to develop historical estimates of irrigated consumptive use for the Upper Basin using ET_a estimates from eeMETRIC and effective precipitation (EP, cm) estimates from the daily crop ET and soil–water balance model, ET Demands (Pearson et al. 2024). The ET Demands model applies a daily soil water balance and soil moisture carryover from month-to-month to estimate EP and is described elsewhere (Allen and Robinson 2009; Huntington and Allen 2010).

While other studies have used OpenET data to evaluate water consumption at the point-scale (Eddy-Covariance systems and weighing lysimeters) (Mefford and Prairie 2022; Melton et al. 2022; Volk et al. 2024) or field-scale (Christiansen 2022; Deb et al. 2022; Djaman et al. 2022; Ferreira et al. 2022; Filippelli et al. 2022; Kustas et al. 2022), there is an additional need to evaluate how remote sensing products (such as OpenET) can be used to estimate diversion requirements at the canal and basin scales. Evaluation at the canal scale is important for applications such as UCRAF-DST and for evaluating how drought mitigation programs may affect local water use. Evaluation at the basin scale is important for larger-scale assessments, such as basinwide water balance studies.

The focus of this paper is the development and testing of the DRC to calculate canal- and basin-scale diversions for irrigation. First, we compare irrigation requirements and consumptive use data at the field scale using data from both the Utah Tables and eeMETRIC/ET Demands. Using the DRC, we then estimate canal-scale (Q_c) and basin-scale (Q_b) diversion requirements using eeMETRIC/ET Demands data, runoff calculations, and seepage calculations. We then modify the geospatial data sets and use DRC simulations to test how drought mitigation efforts at the field scale and canal scale might alter the water budget within the test basin. Last, we discuss irrigation efficiencies and DRC data requirements and provide insight for application of the DRC in evaluating drought mitigation efforts in Utah and potentially other western states.

Methods

Test Basin

The irrigated lands adjacent to the Duchesne River in northeastern Utah serve as the test case for this study (Fig. 1). The Duchesne River is fed by water from the Uinta Mountains and Wasatch Range [peak elevation of 4,114.8 m (13,500 ft)] before flowing from west to east where it flows into the Green River [elevation of 1,417.3 m (4,650 ft)] and ultimately into the Colorado River. Annual precipitation in the basin ranges from less than 12.7 cm (5 in.) near the Duchesne River–Green River confluence to 177.8+ cm (70+ in.) in the Uinta Mountains (Uinta Basin Watershed Council 2015). The irrigation season within the Duchesne River Basin varies, but typically runs from April through mid-October.

The lands surrounding the Duchesne River were some of the first to be irrigated in Utah, and many of the canals developed in the 19th and 20th centuries by the Bureau of Indian Affairs and settlers are still in operation today (Historic American Engineering Record et al. 1989). The Uinta Basin, including the Duchesne River, continues to be a highly productive agricultural region within Utah's Colorado River Basin. The Duchesne River (mainstem) was chosen for this study because it is well-regulated by the Utah Division of Water Rights (DWRi) and has available flow data for multiple canals. Daily observed flow (Q_{obs}, m^3 s^{-1}) at 17 of the main canals (a canal that diverts water from a natural source) were obtained from the DWRi website (Utah Division of Water Rights 2023a). For several canals, DWRi collects canal flow data at both the headgates and at the return, where excess water within the canal

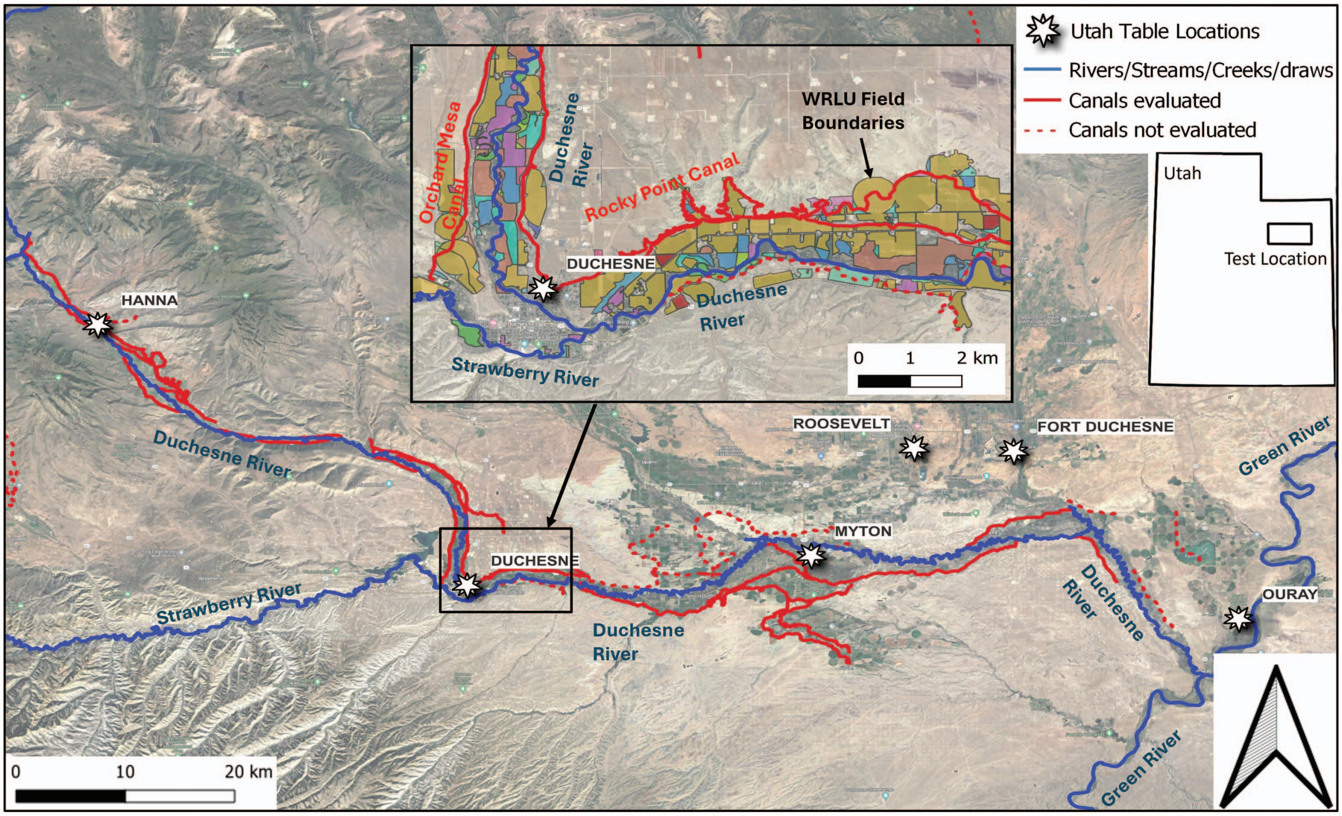

Fig. 1. (Color) Duchesne River in northeastern Utah. Rivers, canals, and weather stations are shown. Canals evaluated within this study are depicted by a solid red line and other canals in the region that are not evaluated are shown as dashed red lines. (Map data © 2024 Google.)

flows back to the river. When possible, the amount of water within the canal that flows back to the river is accounted for within the Q_{obs} values. There are approximately 261.7 km (162.6 mi) of main canal in the test area.

Geographic Information System (GIS) Data

The DRC uses geospatial layers to identify the locations and attributes associated with irrigated fields, canals, and rivers. The Utah Division of Water Resources (DWRe) produces a water-related land use (WRLU) data set each year that includes crop type and irrigation method at the field scale for the entire state of Utah. The WRLU data set pertaining to 2022 was used in this study, and was collected in shapefile format from DWRe (Department of Natural Resources 2022). Although more recent data sets are available, the 2022 data set was used to be consistent with field-scale eeMETRIC/ET Demands data used in this study. In total, there are 76 different combinations of land use classifications available within the State of Utah, and 30 are present within the study area. Agricultural land use classifications are denoted by the crop type and irrigation method (e.g., alfalfa irrigated by flood irrigation and alfalfa irrigated by sprinkler are two different land use classifications). Although there are slight differences, the spatial component of the eeMETRIC/ET Demands data aligns closely with the polygon boundaries of the WRLU data set, meaning that the timeseries of the eeMETRIC/ET Demands data are available for each irrigated field identified within the WRLU data set.

The DWRi is currently creating a polyline (canals and streams) and polygon (irrigated fields) geospatial data set for Utah (Utah Water Right Distribution Network; UDN). The UDN provides tables that link each main canal to the irrigated lands that the canal serves both directly and via secondary canals (Utah Division of Water Rights 2023b). Additionally, the UDN provides information on river names, canal names, canal length (L_c, km), and whether the canal is lined, piped, or earthen. Some canals in the UDN were incorrectly listed as unlined and were changed to lined. Although the data set was not complete for the entire state of Utah at the time of data collection (June 12, 2024), it includes the majority of fields surrounding the Duchesne River.

Runoff from adjacent fields (R_f) and seepage from canals that can benefit a field (S_f) can provide water for the growth of crops. It is anticipated that a drought mitigation strategy may affect R_f and S_f, and therefore have unintended consequences on adjacent fields. For instance, fallowing a flood-irrigated field will reduce runoff from that field. The runoff from that field may have provided water to an adjacent field, thus requiring the adjacent field to pull additional water from the canal to satisfy crop demands. Similarly, seepage from earthen canals can provide water to adjacent fields (Lancaster 1952). If a canal is lined, the seepage will be reduced and adjacent fields may no longer benefit from the seepage, thus requiring additional water be diverted from the canal to supply the irrigation demands.

As previously discussed, changes to R_f and S_f from a drought mitigation effort may affect the irrigation demand of adjacent fields, and therefore need to be accounted for within the DRC. The methods to calculate R_f and S_f are discussed below; however, here we focus on the GIS information that will be used to calculate R_f and S_f for each field (Fig. 2). Elevation data (1/3 arc-s) was collected from the National Elevation Data set (Gesch et al. 2002), and flow direction was computed for the entire domain using the hydrology toolset within ESRI ArcPro. Using the flow direction, elevation, WRLU data (converted from polygon to raster), and

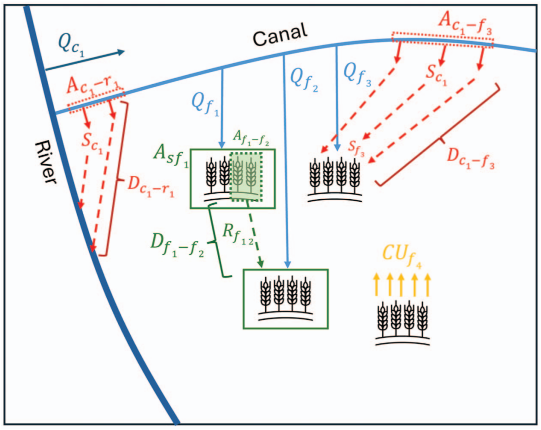

Fig. 2. (Color) Conceptual diagram of the water balance within the DRC: Q_c is water diverted to the canal, Q_f is water supplied to the field boundaries, CU_f is water consumptively used by the field, S_c is seepage water from the canal, S_f is seepage water that can be used by adjacent fields, and R_f is irrigation runoff that can be used by adjacent fields.

UDN data (converted from polyline to raster), a program was written that determined the area from each field that drains to adjacent fields: recording the area of the source field (A_{f-f}, m^2) that drains to the adjacent field; distance from the source field to the adjacent field (D_{f-f}, m); and elevation change between the source field and the adjacent field (H_{f-f}, m). The script also determined which canals would seep to adjacent fields: recording the area of the canal that would seep to the field (A_{c-f}, m^2); the distance from the canal to the adjacent field (D_{c-f}, m); and the elevation change between the canal and the field (H_{c-f}, m). The script also determined which canals would seep to nearby rivers: recording the area of the canal that would seep to a river (A_{c-r}, m^2); the distance from the canal to the adjacent river (D_{c-r}, m); and the elevation change between the canal and the river (H_{c-r}, m).

Within the Duchesne River Basin, Cruff and Hood (1976) concluded that approximately 20% of canal seepage (S_c, m^3 s^{-1}) from the Rocky Point Canal and the Grey Mountain Canal systems (two of the largest earthen canals within the test basin) returns to the Duchesne River. This is used to calculate a proxy hydraulic conductivity. In accordance with Darcy's Law, water moves through a porous medium based on hydraulic conductivity, hydraulic gradient, and flow area. It is assumed that the amounts of seepage that flow to the river are also related to these same drivers. Using the structure of Darcy's Law, we calculate a proxy hydraulic conductivity between a canal and the river (K_{c-r}, m^{-2}) as

$$K_{c-r}A_{c-r}\frac{H_{c-r}}{D_{c-r}}f(D_{c-r}, D_{\text{full}}, D_{\max}) = 20\% \tag{1}$$

where 20% = canal seepage (S_c, m^3 s^{-1}) from the Rocky Point Canal and the Grey Mountain Canal systems that returns to the Duchesne River; H_{c-r}/D_{c-r} = hydraulic gradient; A_{c-r} = surrogate for flow area; and $f(D_{c-r}, D_{\text{full}}, D_{\max})$ = weighting function designed to provide more impact for canal sections that are closer to the river (D_{full} and $D_{\max}$ are both distances with units of m). If $D_{c-r} \leq D_{\text{full}}$, then $f(D_{c-r}, D_{\text{full}}, D_{\max})$ returns 1. If $D_{c-r} > D_{\max}$, then $f(D_{c-r}, D_{\text{full}}, D_{\max})$ returns 0. If D_{c-r} is between D_{full} and $D_{\max}$, then $f(D_{c-r}, D_{\text{full}}, D_{\max})$ returns a value linearly interpolated between 0 and 1. Higher values of D_{full} and $D_{\max}$ indicate that a portion of seepage can travel farther distances. D_{full} and $D_{\max}$ are calibration parameters within the DRC and will be tested, with D_{full} initially set to 15 m and $D_{\max}$ set to 100 m. Using Eq. (1), K_{c-r} for the Rocky Point Canal system was calculated as 75.1 m^{-2}, and 92.8 m^{-2} for the Grey Mountain Canal system.

Consumptive Use

The DRC also requires water consumption data for each irrigated field within the domain. For each field in the WRLU data set, monthly consumptive use (CU_f, m^3 month^{-1}) is calculated by subtracting EP from ET_a, then multiplying by the area of the field (A_f, m^2). Monthly ET_a and EP data for each field within the WRLU data set are from the Upper Colorado River Basin eeMETRIC/ET Demands data set between 1991 and 2023 (Pearson et al. 2024), which were made available for this study by the Bureau of Reclamation and Desert Research Institute. ET_a is calculated as a spatial average of the OpenET eeMETRIC monthly actual ET data set. Within a field, if EP is greater than ET_a for a given month, the excess effective precipitation ($ET_a - EP$) is carried over into the next month. This carryover of excess effective precipitation provides a method to account for antecedent soil moisture (ET Demands 2019).

Because the CU_f data sets are relatively new, we will compare the CU_f data to more readily used NIWR data. NIWR estimates from Hill (1998) are based on the crop type of the field and were collected for the Hanna, Duchesne, and Myton weather station locations because they are closest to the study area (see Fig. 1) (Utah Division of Water Rights 2001). Because the crop type information from the WRLU data is at the field scale, it is possible to estimate the monthly NIWR at the field-scale (NIWR$_f$, m^3 month^{-1}) by assigning the appropriate value from the Utah Tables based on weather station proximity and crop type, then multiplying by A_f.

Field-, Canal-, and Basin-Scale Diversion Requirements

By grouping the fields by the canals that serve them, the consumptive use at the canal scale (CU_c, m^3 month^{-1}) is simply calculated as

$$CU_c = \sum (CU_f) \tag{2}$$

where CU_f = consumptive use of all the fields that receive irrigation from a given canal. Fields that are subirrigated (irrigated by high groundwater tables), dry-cropped, or fallowed have a CU_f value of 0 because they are assumed to receive minimal to no irrigation water, and therefore do not contribute significantly to CU_c.

CU_f represents the amount of water the crops within a field consume; however, the amount of water required at the field boundary (Q_f, m^3 s^{-1}) is typically higher to account for inefficiencies in the irrigation system. Different water application methods (sprinkler or flood irrigation) have varying degrees of efficiency in delivering water to the crops. Water application efficiency, e_a, is the water used by the crop (i.e., CU_f) divided by Q_f (Heermann and Solomon 2007, p. 112). Irrigation system efficiency, e_i, is a lumped term that encompasses many characteristics including soil conditions, management decisions, wind-drift, etc. Here, e_i is also related to the total demand of water by the crops (i.e., CU_f). R_f and S_f can also provide water for the growth of crops (Lancaster 1952) that are not accounted for within Q_f (Fig. 2). Accounting for the efficiencies of the irrigation system as well as additional water from runoff and seepage, the required Q_f for a given field can be approximated as

$$Q_f = CU_f/(e_a e_i) - R_f - S_f \tag{3}$$

S_f and R_f are difficult to measure due to differences in irrigation methods, groundwater table, gradients, soil types, etc. We assume S_f is also related to S_c of earthen canals, where higher values of S_c will likely correlate to higher S_f values. K_{c-r} was calculated for the Grey Mountain Canal and the Rocky Point Canal using Eq. (1). Similarly, a surrogate hydraulic conductivity between the canal and adjacent fields is defined as K_{c-f} (m^{-2}). For the Grey Mountain Canal and the Rocky Point Canal, the K_{c-f} values are set equal to the computed K_{c-r} value of that canal. For all other canals, K_{c-f} is set to 83.95 m^{-2} (the average of K_{c-r} for the Grey Mountain Canal and the Rocky Point Canal). Like Eq. (1), S_f for a field receiving seepage from an unlined canal can be approximated as

$$S_f = S_c K_{c-f} A_{c-f} \frac{H_{c-f}}{D_{c-f}} f(D_{c-f}, D_{\mathrm{full}}, D_{\mathrm{max}}) \tag{4}$$

R_f represents water gained by a field when an upgradient field [i.e., the source field (subscript sf in Fig. 2)] has sufficient runoff. It is assumed that only flood-irrigated fields result in runoff, and that the maximum amount of runoff possible from the source field can be approximated as $(1 - e_{a,sf})(CU_{sf}(A_{f-f}/A_{sf}))$, where only the fractional area of the source field that drains to the adjacent field (A_{f-f}, m^2) is considered. However, not all of the excess water encapsulated within the e_a term will runoff, therefore a runoff coefficient (C_r, $\mathrm{m}^3\ \mathrm{m}^{-3}$) and the distance ($D_{f-f}$) between the receiving field and the source field needs to be considered. R_f for a given field is calculated as

$$R_f = (1 - e_{a,sf})\left(CU_{sf}\frac{A_{f-f}}{A_{sf}}\right)C_r f(D_{f-f}, D_{\mathrm{full}}, D_{\mathrm{max}}) \tag{5}$$

where C_r = calibration parameter with a range from 0 to 1. Higher values of C_r will result in larger amounts of runoff being available to flow from a field to an adjacent field. The C_r parameter is tested in a later section and is initially set to 0.2.

Eq. (3) provides a means to calculate Q_f, but rarely is flow measured at the field scale. By aggregating all fields serviced by a given canal and accounting for seepage along the canal system, the required flow at the diversion of a canal Q_c ($\mathrm{m}^3\ \mathrm{s}^{-1}$) can be approximated as

$$Q_c = \sum Q_f + S_c \tag{6}$$

where S_c can be positive or negative depending on the section of a canal (Cruff and Hood 1976); S_c is related to the length and shape of canal, soil properties, siltation, sediment sealing, and Q_c (Alam and Bhutta 2004). As Q_c values increase, the wetted perimeter within a canal also increases, resulting in higher S_c values (Naranjo et al. 2023). For all lined or piped canals, S_c is set to 0. Cruff and Hood (1976) calculated seepage losses for the Grey Mountain Canal system [$L_c = 48.86$ km (30.36 mi)] as 8% of flow capacity, and 6% of flow capacity for the Rocky Point Canal system [$L_c = 29.5$ km (18.33 mi)]. Calculating a seepage loss (as function of flow rate) per length of canal (X_c, km^{-1}), the X_c for the Grey Mountain Canal system is 0.001637 km^{-1}, and 0.002034 km^{-1} for the Rocky Point Canal system. For all other canals, $X_c =$ 0.0018355 km^{-1} (average of X_c for the Rocky Point Canal and Grey Mountain Canal systems). For a given canal, S_c is calculated as

$$S_c = L_c X_c Q_c \tag{7}$$

To this point, we have not calculated Q_c, therefore we use $\sum CU_f/(e_a e_i)$ as an approximation for Q_c, as follows:

$$S_c = L_c X_c \sum CU_f/(e_a e_i) \tag{8}$$

Combining Eqs. (3), (6), and (8), Q_c is calculated as

$$Q_c = \sum(CU_f/(e_a e_i) - R_f - S_f) + L_c X_c \sum(CU_f/(e_a e_i)) \tag{9}$$

Here, e_a and e_i are applied to each field serviced by the canal, and the canal loss is applied to the entire canal system [S_f is calculated using Eqs. (4) and (8)]; and e_i will be evaluated in the results section and is initially set to 0.80.

Estimates of e_a vary greatly based on irrigation method, soil type, and grading of the field being irrigated. Utah State University has compiled e_a values for different irrigation systems within their Irrigation Conversion Water Savings Destination Calculator (https://extension.usu.edu/crops/tools/conversion-calculator; accessed June 15, 2024). Based on a wide variety of publications, $e_{a,\mathrm{flood}}$ values range from 0.5 (wild flood) to 0.80 (basin), with an average of 0.717. $e_{a,\mathrm{sprinkler}}$ values range from 0.57 (top-of-pipe pivot/linear and big gun) to 0.90 (pivot/linear with low-elevation spray application), with an average of 0.727. Although e_a values will be further tested in the following sections, initially we use the average e_a value for each irrigation method, where $e_{a,\mathrm{flood}}$ is set to 0.717 and $e_{a,\mathrm{sprinkler}}$ is set to 0.727.

The consumptive use at the basin scale (CU_b, $\mathrm{m}^3\ \mathrm{month}^{-1}$) is simply calculated by summing all CU_c values within the basin. Similarly, the total amount of water diverted for irrigation within a basin (Q_b) is calculated by summing all Q_c values within the basin. This calculation does not account for fields in the basin that receive water from sources other than canals (e.g., pumping water directly from the river or from ponds, lakes, or groundwater). Because this analysis does not consider all canals within the basin, values of CU_b and Q_b are informed only by canals included within this study (Fig. 1).

Results

Twenty-two canals were analyzed ranging in service area from 42.1 ha (104.1 acres) (Knight Canal) to 4,069.1 ha (10,055.0 acres) (Pleasant Valley Canal). Some canals interconnect, making it difficult to isolate the specific areas served by each diversion from the river. For example, the Grey Mountain Canal supplies water to the Pleasant Valley Canal and supplements the Myton Townsite Canal. In the following analysis, where multiple main canals supply water to the same fields, the canals were considered as a whole. For instance, the Grey Mountain Canal, Pleasant Valley Canal, and the Myton Townsite Canal (Grey Mountain and Myton Townsite Canals divert water from the Duchesne River) are considered combined and therefore the Q_{obs}, Q_{canal}, and the irrigated area are combined for analysis as the GM-MT-PV Canal. Another example is the Rocky Point A Canal supplying water to the Rocky Point B and Rocky Point C Canals. All three of these canals are combined and considered the Rocky Point Canal. Because of the interconnected complexities and canal grouping, 15 main canals were analyzed in this study. Table 1 lists the crop type, irrigation method, and area of the fields serviced by each of the 15 main canals used within this study.

Table 1. Crop type, irrigation method, and total hectares (ha) of the fields serviced by each of the main canals used within this study

	Pasture		Grass/Hay		Alfalfa		Corn				
Main canal/basin	Sprinkler	Flood	Sprinkler	Flood	Sprinkler	Flood	Sprinkler	Flood	Other crops or irrigation methods	Fallow	Total
Rhoades Canal	80.0	12.9	384.5	1.7	5.6	0.0	0.0	0.0	19.6	26.4	532.2
Turnbow Ditch	0.0	4.6	9.7	44.8	0.7	6.7	0.0	0.0	0.0	0.0	66.7
Farm Creek Canal	117.8	16.9	301.2	24.2	147.9	3.6	0.0	0.0	0.2	7.3	620.6
Jasper Pike Canal	72.3	63.6	104.7	143.6	13.4	1.5	0.0	0.0	1.4	8.1	409.0
New Tabby Canal	80.0	16.3	298.6	6.9	60.2	0.0	0.0	0.0	11.8	34.1	508.4
Hicken Ditch	0.0	3.8	16.1	97.9	16.8	11.8	0.0	0.0	8.8	0.0	155.8
WPPBB Pipeline	3.6	0.0	167.6	44.8	0.0	0.0	0.0	0.0	6.2	1.9	225.1
Jones Ditch	0.0	0.4	72.4	51.4	0.0	0.0	0.0	0.0	0.0	2.9	127.4
Shanks Pipe	0.0	12.5	66.6	0.3	58.2	0.0	0.0	0.0	0.3	0.0	138.4
Pioneer Canal	88.1	120.9	20.0	30.3	124.0	52.8	0.0	0.0	1.8	13.8	452.6
Orchard Mesa Canal	61.0	84.2	32.5	0.0	239.9	12.9	0.0	0.0	1.1	5.6	438.1
Rocky Point Canal	71.5	176.1	129.6	19.9	1,030.8	56.7	25.3	0.0	22.0	13.6	1,549.8
GM-MT-PV Canal	267.9	1,042.8	491.8	153.2	2,697.7	273.7	1,507.4	53.4	739.9	181.7	7,420.6
Ouray School Canal	1.9	41.7	24.9	5.3	106.9	35.6	0.0	0.0	426.4	94.7	738.8
Leland Canal	0.0	0.0	0.0	12.0	53.1	11.0	0.0	0.0	48.0	35.2	159.3
Duchesne River Basin	844.1	1,596.6	2,120.1	636.2	4,555.3	466.5	1,532.7	53.4	1,287.4	425.1	13,543.0

Field Scale (CU_f and NIWR$_f$*)*

Remotely sensed data (i.e., OpenET) are becoming more commonly used by water managers to estimate agricultural consumptive use; however, standard approaches of evaluating crop water consumption using crop- and location-specific tables (e.g., Utah Tables) are still common practice. Conceptually, consumptive use (i.e., CU_f) and NIWR$_f$ values will be similar in healthy fields with no water stress, meaning the crops have ample water to support plant growth. Due to a well-established irrigation network with a mix of senior water rights and reservoir supplementation, the crops within the Duchesne River Basin often have sufficient water. Thus, it is expected in the Duchesne River Basin that the CU_f values from eeMETRIC/ET Demands will align well with the NIWR$_f$ values from the Utah Tables.

Fig. 3 compares depth values of CU_f and NIWR$_f$ associated with the Rhoades Canal and GM-MT-PV Canal, respectively. Each light green line within Fig. 3 represents a different field irrigated by the associated canal. Rhoades Canal is in the upper portion of the basin, while the GM-MT-PV Canal is toward the lower portion of the basin. Each section within the graph shows a different crop type and irrigation method associated with the fields. The NIWR$_f$ value is taken from the Utah Table that is closest to the irrigation canal. The Utah Table associated with the Hanna Weather Station is closest to the fields irrigated by the Rhoades Canal, and the Utah Table associated with the Myton Weather Station is closest to the majority of fields irrigated by the GM-MT-PV Canal. The median CU_f value ($CU_{f,\text{med}}$) is also depicted in Fig. 3. Because the Utah Tables are based on historic averaged data, the NIWR$_f$ values vary by month but are consistent (rise, fall, and peak) from year to year; they are also constant for each crop type regardless of irrigation method (the NIWR$_f$ values are the same for all the Rhoades Canal fields shown in Fig. 3). Alternatively, Fig. 3 shows the CU_f values vary throughout the entire timeframe. The rise, fall, and peak of the $CU_{f,\text{med}}$ values are variable between years, which likely represent differences in antecedent (e.g., soil moisture) and weather conditions between years. Variability of $CU_{f,\text{med}}$ within a year is also shown, with 2016 having a late season $CU_{f,\text{med}}$ increase in all sections shown in Fig. 3.

Despite the large variability in the individual CU_f values, the NIWR$_f$ and $CU_{f,\text{med}}$ values are similar for the GM-MT-PV Canal, with the annual peak values typically within approximately 2.54 cm (1 in.) of each other. The Rhoades Canal, which irrigates far less area than the GM-MT-PV Canal, shows annual peak CU_f values 31% (Grass/Hay-Sprinkler) to 54% (Pasture-Sprinkler) higher than the NIWR$_f$ values. Compared to the GM-MT-PV Canal, the Rhoades Canal is higher in elevation, has more topographic shading, and has less irrigated areas that are mainly near the Duchesne River. Edge-effects on smaller fields surrounded by arid, nonirrigated lands may introduce a bias in the OpenET data. These edge-effects on smaller fields are a result of the 60- to 100-m resolution thermal data from Landsat images being resampled to a 30-m pixel size in OpenET (Mefford and Prairie 2022). Edge-effects and not properly accounting for subirrigation (specifically near the river) are two possible reasons for the large differences between CU_f and NIWR$_f$ for the Rhoades Canal.

Canal Scale (CU_c and Q_c)

For all 15 canals, CU_c values were calculated for each canal by aggregating field-based values (i.e., CU_f) according to the canal that services the fields [Eq. (2)]. Q_c values for each canal were calculated using Eq. (9). Fig. 4 shows CU_c, Q_c, and Q_{obs} values for all 15 canals, descending in order (upstream to downstream) in the basin.

Although both CU_c and Q_c are presented, we focus on the comparison between Q_c (calculated canal flow) and Q_{obs} (observed canal flow). Table 2 and Fig. 4 show the Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970), the annual peak flow ratio (PFR), and the volumetric ratio (VR) between Q_{obs} and Q_c. Only monthly flow values from April through September are used in the calculation of NSE, PFR, and VR. NSE is calculated as

$$\text{NSE} = 1 - \frac{\sum(Q_{\text{obs}} - Q_c)}{\sum(Q_{\text{obs}} - \overline{Q_{\text{obs}}})} \tag{10}$$

where $\overline{Q_{\text{obs}}}$ = mean of the observed flow rates. A NSE value of 1.0 indicates Q_{obs} and Q_c match perfectly. In numerical modeling, a NSE value of 0.0 indicates that the $\overline{Q_{\text{obs}}}$ and Q_c have equal skill in predicting Q_{obs}, and a negative NSE value indicates $\overline{Q_{\text{obs}}}$ has a greater skill than Q_c in predicting Q_{obs}. For our purposes, NSE values greater than 0.5 indicate satisfactory agreement of Q_c and Q_{obs} at the canal-scale. PFR is calculated as

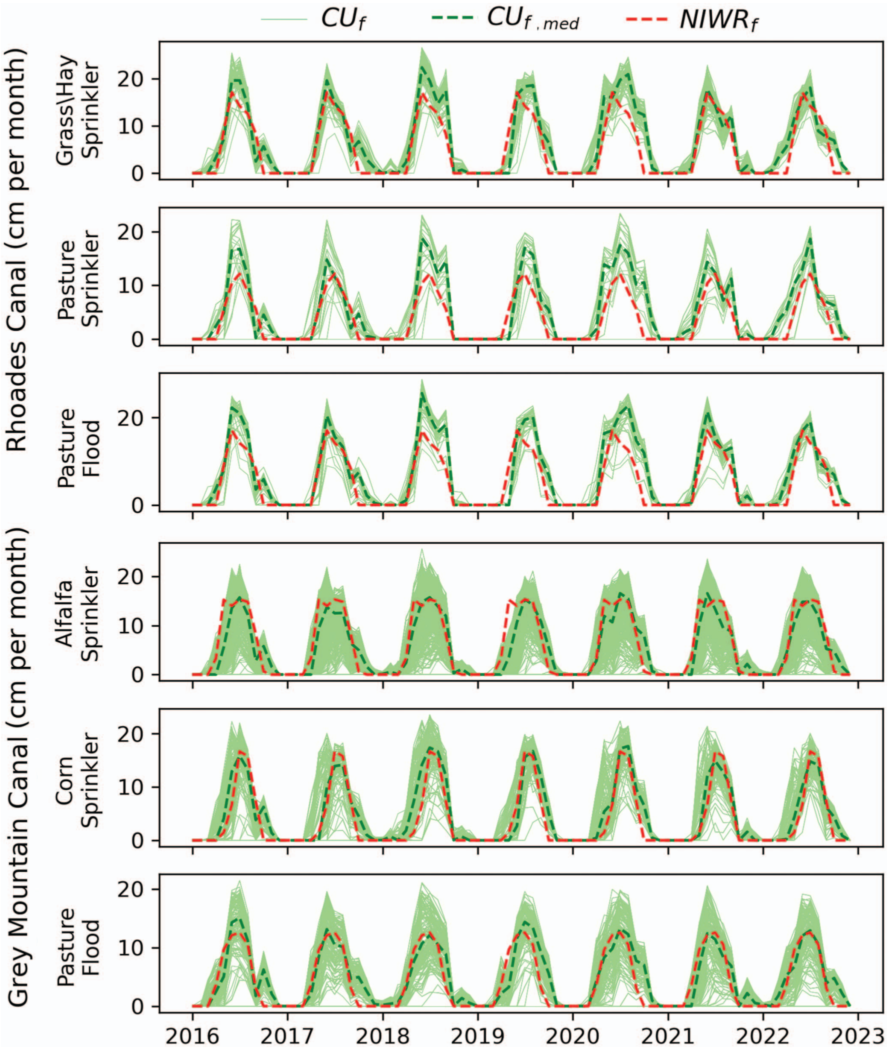

Fig. 3. (Color) CU_f and NIWR$_f$ values for Rhoades Canal and GM-MT-PV Canal. Each green line represents a separate field (CU_f).

$$\mathrm{PFR} = \frac{\sum Q_{c,\text{annual peak}}}{\sum Q_{\text{obs,annual peak}}} \tag{11}$$

where $Q_{c,\text{annual peak}}$ is the annual peak of Q_c and $Q_{\text{obs,annual peak}}$ is the annual peak of Q_{obs}. A PFR value of 1.0 indicates that the average annual peak flows between Q_c and Q_{obs} are nearly identical. PFR values less than 1.0 indicate that Q_c, on average, underpredicts the annual peak flow, and PFR values greater than 1.0 indicate that Q_c, on average, overpredicts the annual peak flow. VR is calculated as

$$\mathrm{VR} = \frac{\sum Q_c}{\sum Q_{\text{obs}}} \tag{12}$$

where a VR equal to 1.0 indicates the calculated and observed diversion volumes for the time period (7 years, 2016–2022) are equal, a VR less than 1.0 indicates underestimation in total volume, and a VR greater than 1.0 indicates overestimation of the observed diversion volumes. Due to limitations in Q_{obs} data, all statistics are calculated between May and September between 2016 and 2022.

Only Rhoades Canal, Farm Creek Canal, Orchard Mesa Canal, Rocky Point Canal, and GM-MT-PV Canal have NSE values greater than 0.5, indicating satisfactory agreement in only 5 of the 15 main canals evaluated. However, the peak flows (based on PFR) and the volumes of flow (based on VR) are more accurate, with exception of New Tabby Canal, Jones Ditch, Ouray School Canal, and Leland Canal.

Jones Ditch and New Tabby Canal have CU_c values that more closely match Q_{obs} (Fig. 4), indicating a potential discrepancy in calculating CU_c rather than the calculation of Q_c. Jones Ditch and New Tabby Canal are near the river, and many of their fields likely receive water from subirrigation. There is no category within the WRLU data set to represent fields that are partially irrigated by subirrigation (fields are dry, subirrigated, sprinkler-irrigated, or flood-irrigated). Therefore, a field can be labeled as sprinkler-irrigated and thus receive 100% of its required irrigation from the canal within the DRC, but in actuality, it may receive some of its water from subirrigation.

Based on Fig. 4 and Table 2, the Q_c values drastically underpredict the observed flows at Ouray School Canal and the Leland Canal. The Leland Canal has the highest underprediction in specific years (namely 2019 and 2022), while the Ouray School Canal is underpredicted in all years. Ouray School Canal and Leland Canal only have gaged flow measurements at the headgates, meaning any water that may return to the river is not captured within Q_{obs}. The Ouray School Canal diverts water from the Duchesne River and returns the water to the Uinta River, often diverting outside the

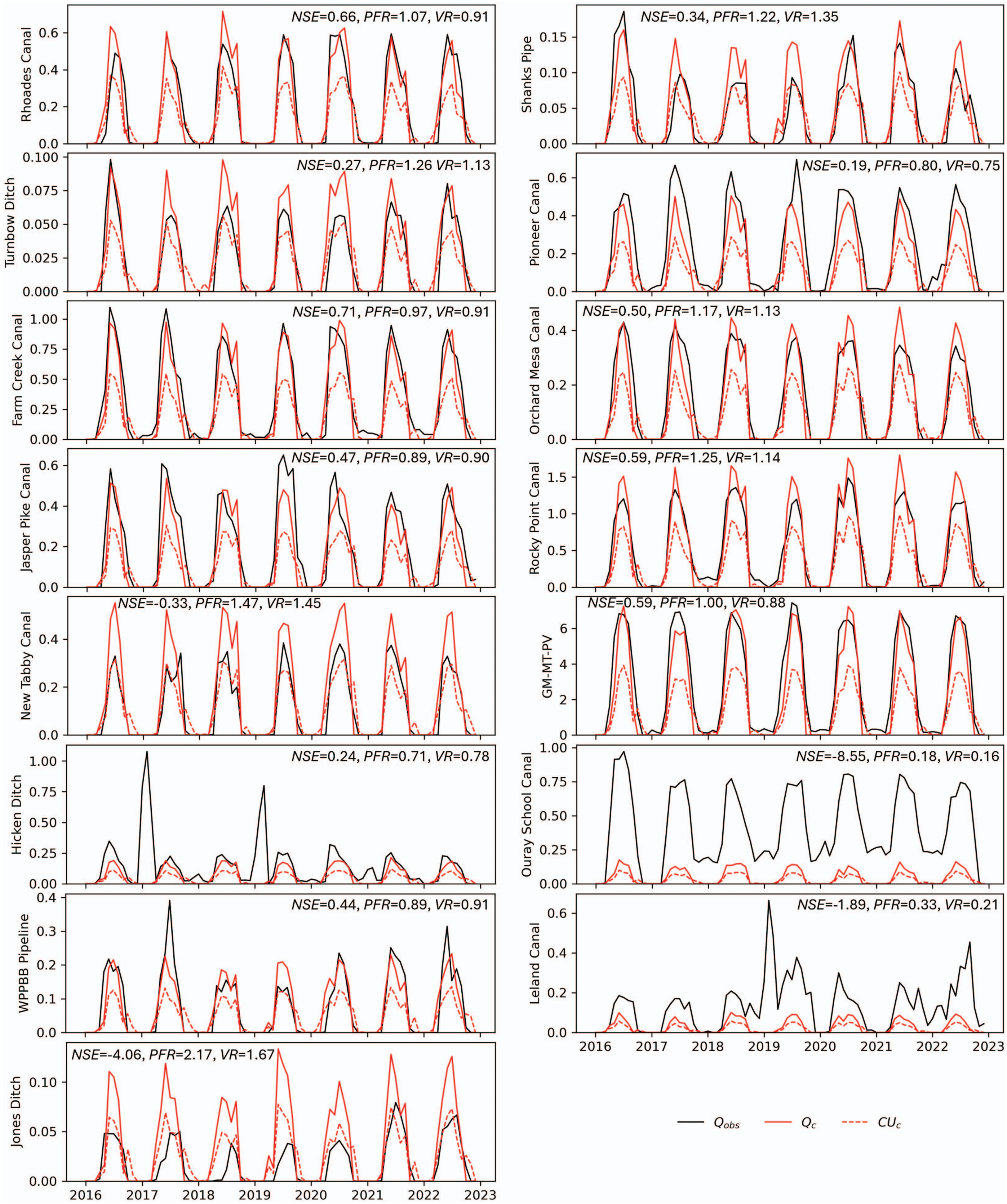

Fig. 4. (Color) Monthly CU_c and Q_c data for all 15 canals within the Duchesne River Basin. Monthly CU_c data are the dashed lines (data was converted from $\mathrm{m}^3\ \mathrm{month}^{-1}$ to $\mathrm{m}^3\ \mathrm{s}^{-1}$). Q_c data are solid red lines, with the observed flow data (Q_{obs}) in black. Although 1991–2023 is simulated by the DRC, only results from 2016 to 2022 are shown due to availability of Q_{obs} data.

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Table 2. Canal-scale NSE, PFR, and VR values between simulated flows (Q_c) and Q_{obs}. Also shown are the annual average flow volumes (ha-m) for each canal

	Q_c and Q_{obs}			Annual average flow volumes (ha-m)			
Main canal/basin	NSE	PFR	VR	Q_c	Q_f	R_f	S_f
Rhoades Canal	0.66	1.08	0.92	541.0	541.0	0.0	0.0
Turnbow Ditch	0.27	1.26	1.13	76.6	75.9	0.4	0.1
Farm Creek Canal	0.71	0.97	0.92	858.8	824.6	0.5	2.6
Jasper Pike Canal	0.47	0.89	0.91	454.4	446.6	0.3	0.4
New Tabby Canal	−0.34	1.47	1.46	484.1	476.8	0.0	0.5
Hicken Ditch	0.24	0.72	0.78	176.6	174.3	0.4	0.2
WPPBB Pipeline	0.44	0.90	0.91	218.6	218.6	0.1	0.0
Jones Ditch	−4.11	2.18	1.68	127.7	127.7	0.2	0.0
Shanks Pipe	0.34	1.22	1.35	150.3	150.3	0.0	0.0
Pioneer Canal	0.19	0.80	0.75	474.3	466.1	0.5	0.8
Orchard Mesa Canal	0.50	1.17	1.14	397.9	392.0	0.2	0.6
Rocky Point Canal	0.58	1.25	1.14	1,525.6	1,431.5	0.5	6.9
GM-MT-PV Canal	0.59	1.00	0.88	6,478.8	5,983.9	2.1	35.8
Ouray School Canal	−8.55	0.18	0.16	134.4	131.8	0.0	0.1
Leland Canal	−1.89	0.33	0.21	72.4	71.5	0.1	0.0
Duchesne River Basin	0.74	1.06	0.94	12,171.4	11,512.5	5.3	48.0

irrigation season (Fig. 4). This indicates that some of the diverted flows to the Ouray School Canal are not intended for irrigation. Therefore, the Ouray School Canal is not considered in any further analysis in this study.

Table 2 also displays the average annual flow volumes (ha-m) for Q_c, Q_f, R_f, and S_f. Although a relatively small volume, the Turnbow Ditch has the highest R_f value as a percentage (0.6%) of overall flow that contributes to the field. This relatively high percentage of R_f correlates to the Turnbow Ditch having the highest percentage (84.4%) of irrigated land using flood-irrigation. As expected, all piped or lined canals have Q_c equal to Q_f (due to no seepage from the canal), and therefore also have S_f values equal to 0.

Basin Scale (CU_b and Q_b)

Fig. 5 shows CU_b, Q_b, and Q_{obs} data for the entire Duchesne River Basin. The bottom of Table 2 shows the NSE, PFR, and VR values between Q_b and Q_{obs}. As expected, accuracy in NSE, PFR, and VR increases as data sets are aggregated and errors within individual canals are negated (e.g., overestimation in one canal offsets the underestimation in another canal). When aggregated, the basin-scale statistics are much improved over the canal-scale statistics, with NSE of 0.74 and near-perfect PFR and VR values.

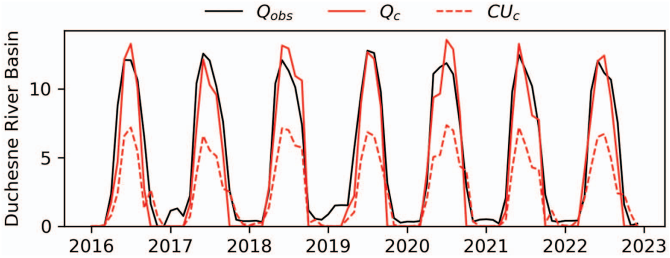

Fig. 5. (Color) Monthly CU_b, Q_b, and Q_{obs} data for the Duchesne River Basin. Monthly CU_b data are the dashed lines (data were converted from $\text{m}^3\ \text{month}^{-1}$ to $\text{m}^3\ \text{s}^{-1}$). Q_b data are solid red lines, with the observed flow data (Q_{obs}) in black.

Evaluation of Irrigation Efficiency

The irrigation efficiency term (e_i), which encompasses system efficiency characteristics (e.g., soil conditions, wind-drift, etc.), is difficult to approximate and was set to 0.80 for model results thus far. However, e_i must be optimized to represent each unique irrigation system before it is used in a planning or operational model to estimate the amount of water that must be diverted under current management and environmental (e.g., soil water) conditions. Although e_i could be optimized based on each individual canal using Q_c values, here we set e_i for the entire Duchesne River Basin based on Q_b values. e_i values between 0.01 and 1.00 were tested until two e_i values were optimized—one e_i value to create the highest NSE values between Q_{obs} and Q_b, and one e_i value to create VR values close to 1.0. Table 3 shows the optimized e_i values with associated statistics. The results show that the e_i values are within 0.05 and 0.02 of the initial 0.8 value, and therefore only minimal changes are observed in the Q_b data shown in Fig. 5. From a water management standpoint and based on the goals of UCRAF-DST, the volume of diverted water is paramount, therefore optimizing e_i based on VR is more advantageous than optimizing e_i based on NSE.

Total efficiency of the irrigation system includes e_i, e_a, and X_c, and can be calculated by dividing the total water used directly by the crops (i.e., CU_c or CU_b) by the total water diverted (Q_c or Q_b). When e_i is optimized to VR, the total efficiency of the Duchesne River Basin is 52%, with the efficiencies of the canals varying between 51% and 55%. These values indicate that approximately 50% of the water that is diverted is directly used by the crops.

Table 3. Basin-scale NSE, PFR, and VR values between simulated flows (Q_b) and Q_{obs} for the entire Duchesne River Basin. The first row of the table shows results using the default e_i of 0.80. The second and third rows of the table show results using adjusted e_i values that were optimized based on NSE and VR, respectively

	Q_b and Q_{obs}			
Test case	e_i	NSE	PFR	VR
Default $e_i = 0.80$	0.80	0.74	1.06	0.94
Optimize e_i based on NSE	0.78	0.75	1.09	0.97
Optimize e_i based on VR	0.75	0.73	1.13	1.00

Table 4. Percentage of water supplied to the crops from irrigation (Q_f), runoff from adjacent fields (R_f), and seepage from the canal (S_f). Two sets of calibration parameters were used. The first used initial values of C_r, D_{full}, and $D_{\max}$, with results shown on the left side of the table. The second used maximum values of C_r, D_{full}, and $D_{\max}$, with results shown on the right side of the table. (Note that any instances where the individual percentage values do not sum to 100% is due to rounding)

	$C_r = 0.2$, $D_{\mathrm{full}} = 15$ m, $D_{\max} = 100$ m			$C_r = 1.0$, $D_{\mathrm{full}} = 1{,}000$ m, $D_{\max} = 1{,}000$ m		
Main canal	Q_f (%)	R_f (%)	S_f (%)	Q_f (%)	R_f (%)	S_f (%)
Rhoades Canal	100.0	0.0	0.0	100.0	0.1	0.0
Turnbow Ditch	99.4	0.5	0.1	96.7	3.2	0.1
Farm Creek Canal	99.6	0.1	0.3	99.1	0.5	0.5
Jasper Pike Canal	99.9	0.1	0.1	98.7	1.2	0.1
New Tabby Canal	99.9	0.0	0.1	99.8	0.0	0.2
Hicken Ditch	99.6	0.2	0.1	98.4	1.4	0.2
WPPBB Pipeline	100.0	0.0	0.0	99.7	0.3	0.0
Jones Ditch	99.9	0.1	0.0	99.5	0.5	0.0
Shanks Pipe	100.0	0.0	0.0	99.9	0.1	0.0
Pioneer Canal	99.7	0.1	0.2	98.9	1.0	0.2
Orchard Mesa Canal	99.8	0.1	0.1	99.5	0.3	0.2
Rocky Point A Canal	99.5	0.0	0.5	98.8	0.4	0.8
Grey Mountain Canal	99.4	0.0	0.6	99.2	0.4	0.4
Ouray School Canal	99.9	0.0	0.1	99.3	0.6	0.1
Leland Canal	99.8	0.1	0.1	98.9	1.1	0.0

It is notable that total efficiency, as defined here, does account for return of water to fields via R_f or S_f, but does not account for runoff or seepage return to the river system.

Evaluation of Runoff and Seepage to Fields

Within the DRC a field can receive water from irrigation applied to the field (Q_f), runoff from an adjacent field (R_f), and seepage water from unlined canals (S_f). Aggregated to the canal-scale, Table 2 provided the average annual amounts of water that fields receive from each of the three sources of water. Table 4 provides the percent of water from Q_f, R_f, and S_f that is supplied to the fields. As expected, none of the fields serviced by a piped or lined canal receive any water from seepage. As a percentage of the total water supplied to the field boundaries, the runoff from one field to another field is relatively low. This is partially due to many of the fields within the Duchesne River Basin using sprinkler systems (where runoff is often considered negligible). R_f was calculated based exclusively on topography, however with flood irrigation systems, a drain at the bottom of the field often carries excess runoff to be used by another field or to a natural drainage. These drains are not captured within the GIS networks and therefore are difficult to quantify within R_f.

In the development of the DRC, several parameters were set but not tested. In Eq. (4), S_f is impacted by D_{full} and $D_{\max}$, which limit the amount of water a field can gain from seepage based on the distance between the field and the canal. C_r, D_{full}, and $D_{\max}$ all impact R_f [Eq. (5)]. C_r defines how much irrigated water not consumed by the crop is available for runoff. D_{full} and $D_{\max}$ limit the amount of runoff water a field can gain from runoff based on the distance between the receiving field and the field that has the runoff. C_r, D_{full}, and $D_{\max}$ are most likely location dependent, meaning each canal will have their own value for each parameter. Additionally, D_{full} and $D_{\max}$ values could be different in the calculation of S_f and R_f. To test how C_r, D_{full}, and $D_{\max}$ impact the overall mass balance of water delivered to the field [Q_f, S_f, and R_f in Eq. (3)], the parameters were set to their highest values ($C_r = 1$, $D_{\mathrm{full}} = 1{,}000$ m, and $D_{\max} = 1{,}000$ m).

Table 4 shows how changes in C_r, D_{full}, and $D_{\max}$ impact the source of water, as a percentage, for the fields within the canal system. Not all fields are adjacent to canals and therefore increases in the D_{full} and $D_{\max}$ values did not result in a substantial change in the percent of water that S_f contributes to fields. The majority of fields are adjacent to other fields, and therefore increasing C_r, D_{full}, and $D_{\max}$ did increase the contribution of R_f, therefore reducing Q_f [see Eq. (3)]. Turnbow Ditch has the highest percentage of flood-irrigated area (84.4%), and therefore has the highest R_f values under both parameter test cases. By using the maximum C_r, D_{full}, and $D_{\max}$ parameter values, the percentage of water that a crop receives from R_f increased between 0.03% (New Tabby Canal) and 2.6% (Farm Creek Canal), with an average increase of 0.6%.

Applications for Evaluating System Modifications

One of the stated goals of the DRC is to demonstrate how changes within the irrigation system may affect diversion requirements. For this purpose, two simple tests were performed. All parameters were set to their default values. Because the DRC utilizes geospatial data sets, all changes to the system can be made to the GIS layers using GIS software. The first change scenario simulated the hypothetical impact of converting all earthen canals to pipe by changing lining attributes within the UDN data set and then simulating the flows within the DRC [173.16 km (107.60 mi)]. On average, this change shows that the conversion of earthen canals to pipes would reduce diversions from the river (Q_b) by approximately 611 hectare-meters (ha-m) [4,952 acre-ft (AF)] per year, or in other terms, approximately 5.0% of the total water diverted (note that approximately 21% of the total canal length in the Duchesne River Basin already uses pipe or lined canals). The 5.0% savings is realistic considering Cruff and Hood (1976) calculated seepage losses for the Grey Mountain Canal system as 8% of flow capacity and 6% of flow capacity for the Rocky Point Canal system.

As discussed in Lankford (2012), irrigation efficiency savings calculated using a "factorial" method [Eq. (9) is a factorial method] often neglect the secondary effects that changes to seepage or irrigation methods have on other fields or the overall water balance within the basin. In this test case, the diversions may be reduced by 611 ha-m (4,942 AF) per year, but the return of water to the rivers from canal seepage (approximately 20% of seepage water based on Cruff and Hood 1976) would be 0. Additionally, fields adjacent to the canals were receiving a basin-total of 47.96 ha-m of water from seepage (S_f, Table 2), which in the change case is simulated as 0 by the DRC due to lining of the canals. In the change case, the reduction in S_f resulted in an increase in Q_f, but an overall decrease in Q_c due to S_c becoming 0.

A separate test was conducted to simulate the hypothetical impact of converting all flood irrigation fields [2,804.9 ha (6931.1 acres)] to pivot/linear sprinklers with low-elevation spray application ($e_a = 0.90$). This change case was accomplished by changing the irrigation attributes within the WRLU data sets. Effectively, the e_a for flood-irrigated fields changed from 0.717 (average flood-irrigation efficiency) to 0.90. Approximately 29.5% of the irrigated land in the study area uses flood irrigation. The conversion to sprinkler irrigation reduces the annual average diversion (Q_b) by 535.2 ha-m (4,339.1 AF) per year, or in other terms, approximately 4.4% of the total water diverted. With no flood-irrigated fields, the DRC simulated R_f as 0, which added more requirement from Q_f to irrigate some fields. However, the increase in efficiency (e_a) resulted in lower Q_f and Q_c for all canals.

Although diversions may be reduced, the return of water to the rivers from runoff (approximately 10%–40% of water applied to field based on Washington State Department of Ecology 2005) would be reduced. Although the DRC accounts for the reduction of irrigation runoff that occurs based on topography, having additional information on drains will be important to better account for R_f and therefore how changes to irrigation methods will affect the water balance.

The simple system modification tests performed here were made by changing parameters in GIS software data. Due to the geospatial nature of the DRC, the effectiveness of various drought mitigation strategies can be evaluated in future efforts. For instance, in some cases, fallowing fields at the end of a canal system is preferable to fallowing fields near the river diversion as it would shorten the effective distance of water delivery for the canal. Thus, the fields would be fallowed (affecting CU_c) and L_c could be shortened, both reducing Q_c. As discussed with the previous tests, the DRC does account for some secondary effects (changes to R_f and S_f) that drought mitigation measures may have on other fields, canals, or the overall water balance within the basin, but does not currently account for runoff or seepage that may return to the river. Return flow, runoff, and seepage should be measured at a field-site and then evaluated within a modeling system, such as UCRAF-DST, to accurately characterize the water balance.

Discussion and Future Work

Several methods exist for estimating crop water requirements and consumptive use, including the Utah Tables (Hill 1998), GridET (Lewis and Allen 2017), and eeMETRIC (OpenET)/ET Demands (Melton et al. 2022; Pearson et al. 2024). This study introduces the DRC, which uses the eeMETRIC/ET Demands data set to quantify the amount of water crops consume at the field-scale, and then applies geospatial data sets (WRLU and UDN) to estimate diversion requirements at the canal- and basin-scales. An understanding of depletion and diversion values at the canal- and basin-scale is important for Utah and other western states for the planning, evaluation, and implementation of drought mitigation programs. Because of amply available diversion data, the Duchesne River Basin in northeastern Utah was selected as the test case to utilize consumptive use data from the eeMETRIC/ET Demands data set in the calculation of canal diversion requirements (Q_c). These diversion requirements were then compared to observed data at the canal- and basin-scales, where the efficiency of the irrigation systems was also explored.

The DRC is an important component of the UCRAF-DST. Together with the RiverWare model(s) within the UCRAF-DST, the DRC enables exploration and planning of different drought mitigation strategies. Baseline conditions can be evaluated using the current geospatial data sets that represent field-scale crop type, irrigation method (e.g., sprinkler, flood), irrigation status (e.g., fallowing), and canal length and type (lined, earthen, pipe). Changes to the irrigation method and irrigation status affect the water requirements at the field-scale, which when aggregated to the canal-scale change the diversion requirements for the canal. Similarly, changes to the length and type of canal will also affect the seepage rates within the canal, thus also changing the diversion requirements for the canal. Not discussed in this paper is how the DRC will account for changes in crop type. CU_f is a composite of measurements and calculations from eeMETRIC and ET Demands, and therefore crop type is not a characteristic that can be easily modified. Future work should evaluate how implementing a field-scale monthly modification factor (M_f) to CU_f could replicate how a change of crop type would affect the water consumption at the field-scale. For fields where a crop change is to be explored, M_f could initially be set to the NIWR_f of the changed crop type divided by the NIWR_f of the baseline crop type. Aggregation from the field-scale to the canal- and basin-scales would remain the same within the DRC, thus showing how changes in crop type of irrigated fields will affect diversion requirements.

Quantifying the resulting potential water savings with the DRC is important, but these savings will not be realized without mechanisms to protect this "saved" water as it flows downstream. Pérez-Blanco et al. (2020) completed a review of over 230 theoretical and empirical papers to assess whether higher physical irrigation efficiency ultimately conserves water within a basin. Based on their findings, they recommend that "agricultural policy design should be used to encourage investments in [water conservation technologies] in water-stressed areas only if downstream water availability for other productive uses and the environment is adequately protected, which requires a full understanding of current and future water flows." The goal of UCRAF-DST is to characterize both current and future water balances, with its RiverWare component enabling a full accounting of the "saved" water as it flows downstream.

So far, we have not discussed water rights information (such as duties, priority date, source of water, etc.), which is a critical aspect of water management. Although not used in this study, the UDN data set includes water rights data that are used by both the DRC and UCRAF-DST through incorporation in the RiverWare model. This work is timely given passing of Senate Bill 144 during the 2023 Utah Legislative Session, which provides authority for the State Engineer to legally protect water conserved through state and federally recognized water conservation programs (Section 73-3-30(4) Utah Code 2023). The financial aspect of irrigation is also an important consideration, as cost and potential revenue can play a significant role in determining irrigation application (English et al. 2002) as well as potential drought mitigation strategies. A method similar to the one used in Contor and Moore (2008) and applied in Contor and Taylor (2013), that accounts for the commodity price and the cost of water, could be adopted within the DRC and UCRAF-DST to account for the economics of irrigation water.

The main forcing data set discussed in the DRC is CU_f from the eeMETRIC/ET Demands data set. The eeMETRIC/ET Demands data are temporally and spatially dynamic and are consistent at the field-scale when compared to the more standard NIWR data from Utah Tables. The implementation of eddy-covariance towers to further quantify and potentially improve the accuracy of OpenET is also ongoing, as well as pilot programs to test on-the-ground implementation of drought mitigation strategies (Colorado River Authority of Utah 2022b). As improvements are made to existing data sets or as new data sets or methods are developed, they can be utilized within the DRC.

The DRC was developed to show how changes to the irrigation system affect diversion requirements at the headgate, and therefore could translate to savings of conserved water. Although the DRC does not currently account for irrigation runoff and canal seepage that returns to the river, it does account for irrigation runoff and canal seepage that can be utilized by adjacent fields. For instance, in the test case where all earthen canals were converted to pipe systems, the seepage in the canals was set to 0, which caused some fields adjacent to the canal to require more water from the canal. However, lining of the canal resulted in a net reduction in canal diversions by 5.0% due to the reduction in canal seepage. Due to the geospatial nature of the DRC and the ability to account for both direct and indirect consequences of potential changes in the system (i.e., seepage and runoff), this study has shown that the DRC can be used to evaluate drought mitigation strategies prior to implementation.

Although this study focused on a single area within the Colorado River Basin in Utah, it could be replicated in other areas of Utah and in other states. As previously noted, OpenET is available throughout the western United States, and although the WRLU data is specific to Utah, similar efforts for other states using LandSat imagery and the U-Net architecture are ongoing (Nouwakpo et al. 2023). The UND data that assign fields to the irrigation canals that supply them is also unique to Utah. For states without a similar data set, an initial data set can be created within GIS software that represents the connection between a field boundary data set (available from the Crop Scape data set, Han et al. 2012) and canal locations (many available within the NHDPlusV2 data set, Moore et al. 2019). The most limited data for applications in other basins may be X_c and canal diversion data, which are needed to calibrate e_i. Even with estimated X_c and e_i values, an initial estimation of the effects of changes to the crops, irrigation methods, or irrigation system could be evaluated within the DRC, albeit with relative differences in Q_c instead of absolute differences in Q_c.

Conclusions

As water demands in the western United States continue to grow, there is an increased need to understand current irrigation water requirements as well as the irrigation water requirements if drought mitigation strategies (e.g., fallowing fields, lining canals, etc.) are implemented. This paper describes the development and testing of the Diversion Runoff Calculator (DRC), a tool that uses recently developed field and canal geospatial data with consumptive use (CU) data from eeMETRIC/ET Demands to estimate the canal diversion requirements, field runoff, and canal seepage at the canal- and basin-scale. Using the Duchesne River Basin in Utah between 1991 and 2023 as a test case, the DRC simulated diversions (Q_c) at 15 canals which were then compared to observed canal diversions (Q_{obs}). To demonstrate how drought-mitigation strategies can be tested within the DRC, two tests were completed that resulted in realistic changes to the water balance within the basin. The main results from the study include the following:

- CU data from eeMETRIC/ET Demands were compared to net irrigation water requirement (NIWR) values from the State of Utah. Although the CU values had a large variability for fields with the same crop type and irrigation method, the NIWR and median CU values (CU_{med}) are similar for the GM-MT-PV Canal, with the annual peak values typically within approximately 2.54 cm (1 in.) of each other. The Rhoades Canal, which is in the upper part of the basin, had annual peak CU_{med} values 31% (Grass/Hay-Sprinkler) to 54% (Pasture-Sprinkler) higher than the NIWR values. These large differences in the upper basin could be attributed to edge-effects on smaller fields with the CU data (Mefford and Prairie 2022), or not properly accounting for subirrigation.
- Q_c was compared against Q_{obs} at 15 canals during the irrigation season between 2016 and 2022. Five of the 15 canals have NSE values greater than 0.5, indicating satisfactory agreement. PFR and VR were captured well by Q_c in most of the canals, with VR being the most critical to testing changes in drought mitigation strategies. When aggregated to the basin-scale the NSE value is 0.74, VR is 0.94, and PFR is 1.06. Accounting for system efficiency, application efficiency, canal efficiency, runoff, and seepage returning to fields, the amount of water diverted that is directly used by crops is approximately 50%.
- The DRC uses a simple topography method to determine which fields may benefit from canal seepage (S_f) and runoff from adjacent fields (R_f). Compared to the total water diverted, both R_f and S_f are relatively small. S_f is negligible in areas with piped or lined canals, and always accounted for less than 1% of irrigation water required for the fields serviced by a canal. R_f accounted for a maximum of 3.2% of irrigation water required for fields serviced by a canal. In addition to topography, accounting for drain systems within the DRC will likely increase the impact that R_f has on the canal- and basin-scale water budget.
- The input geospatial layers were modified to test two hypothetical drought mitigation scenarios. Lining all the earthen canals within the DRC resulted in a net reduction in canal diversions by 5.0% due to the reduction in canal seepage. Approximately 29.5% of the irrigated land in the Duchesne River Basin uses flood irrigation. When these lands were converted to sprinkler irrigation within the DRC, annual average diversion was reduced by approximately 4.4%.

The DRC is a single component of the Utah Colorado River Accounting and Forecasting–Decision Support Tool (UCRAF-DST). A primary goal of the UCRAF-DST and the DRC is to assess current irrigation water usage (consumptive use, runoff, seepage, and diversions) within a basin, which was accomplished in this study. UCRAF-DST will ultimately be used as a planning tool to help to support drought mitigation programs. The DRC can estimate how changes to the irrigated land (irrigation method, irrigation status) and conveyance system (canal type and length) affect diverted and consumptive water use. Future work will focus on continued development of the UCRAF-DST to evaluate and account for agricultural runoff back to the river, water rights, and interdependencies within the water budget.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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