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Patterns and associations between dominant crop productions and water quality in an irrigated watershed

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Abstract: Irrigation consumes the largest share of freshwater resources, but is a necessary practice to boost agricultural output to meet increasing global demand for food and fiber. Irrigation not only impacts water quantity but can also degrade water quality. Research efforts have explored various aspects of irrigation efficiency and irrigated crop productivity, but few studies have examined how different crops collectively modulate water utilization and water quality at the watershed scale. The objective of this study was to determine how the fractions of evapotranspiration (fET) water ascribed to major crops impact water quantity and quality in irrigation return flow. In this study, long-term water quantity and quality monitoring data, collected as part of the Conservation Effects Assessment Project (CEAP), combined with crop and evapotranspiration (ET) modeling products, were used to build relationships between water quantity and quality metrics and fET associated with major crops during the first 15 years of the CEAP Twin Falls irrigation project. Results suggest that subwatershed size and subsurface flow contribution in regional drainage tunnels influenced the observed hydrologic patterns and led to two distinct groups. Subwatersheds in group 1 were large, typically included subsurface drain tunnels, and had high return flow volumes and low sediment concentration, while those in group 2 were smaller in size, had low return flow volumes, and high sediment concentration. Multiple linear regression analyses showed that spring and summer irrigation return flow volumes normalized by subwatershed area increased as a function of fET of potato (*Solanum tuberosum*) in group 1 (regression coefficients [coef.] = 4.42 in spring and 1.54 in summer) but were inversely associated with small grains in the fall (coef. = –1.67 and –0.60 in groups 1 and 2). Spring sediment concentration had negative regression coefficients with fET of sugar beet (*Beta vulgaris*) (coef. = –911.00) and alfalfa (*Medicago sativa*) + pasture crops (coef. = –424.85) in group 2. When statistically significant, a negative association was found between phosphorus (P) load per return flow volume and fET of alfalfa + pasture (coef. = –0.68 to –1.07), corn (*Zea mays*) (coef. = –0.64 to –0.89), dry beans (*Phaseolus vulgaris*) (coef. = –1.25 to –1.87), and sugar beet (coef. = –1.54 to –2.83) across aggregation periods and subwatershed groups. Nitrate (NO_3-N) load per return flow volume was negatively associated with potato and corn fET in group 1 especially during the spring (coef. = –31.13 for potato and –9.60 for corn) and fall (coef. = –14.54 for potato and –4.43 for corn) months but positively associated with dry beans (coef. = 4.87) over the irrigation season. While direct cause and effect were not established with this analysis, results from this study provide valuable information about various crop production systems that may impact observed hydrologic responses.

Key words: Conservation Effects Assessment Project—crop evapotranspiration—hydrology—irrigated watershed—irrigation return flow—water quality

Agriculture utilizes 70% of global fresh water supplies, with most of these agricultural waters used for irrigation. Irrigation withdraws the largest share of freshwater resources, consuming 446 of 1,063 billion L d^{-1} in the United States (data from 2015), closely followed by thermoelectric power (360 billion L d^{-1}) (Dieter et al. 2018). Demand for freshwater has grown six-fold in the last 100 years (Wada et al. 2016) and has continued to increase in recent years at a rate of 1% per year (FAO 2018). Future growth in freshwater demands is also expected, mainly driven by population growth, economic development, and changing consumption patterns (UN-Water 2018). The need to increase food production with an increasingly limited freshwater supply is further complicated by loss of prime agricultural lands worldwide (van Vliet 2019). Irrigation offers many advantages to help solve the need for increased agricultural output but is also associated with many challenges that need to be addressed to minimize adverse environmental impacts.

Irrigation can improve farm productivity and agricultural market value by reducing the impact of climate variability on crop yield (Troy et al. 2015). Approximately 40% of the market value of crops sold in the United States is created on 6% of US farmland where irrigation is used to supply water demands (USDA NASS 2019). This disproportionate share of irrigated land in agricultural output is also observed at the global scale where 40% of food and fibers are produced on 17% of the land receiving irrigation water (Evans and Sadler 2008). Nevertheless, water withdrawals for irrigation can adversely impact water availability for other uses. Jägermeyr et al. (2017) noted that 41% of current global irrigation water withdrawals reduce flow in river systems below levels needed to sustain life-supporting functions. Improvements in irrigation practices and water harvesting technologies (Jägermeyr et al. 2017) combined with greater adoption of water-conserving practices (Jägermeyr et al. 2016) can reduce agricultural water use while boosting production.

The impact of irrigation on water quality has typically been as much of a concern as its effect on water quantity (Park et al. 2018; van Vliet et al. 2021). Surface irrigation methods such as furrow irrigation have received a great deal of attention for their association

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with high discharge of sediment and other dissolved elements in surface waters (Koluvek et al. 1993). Furrow irrigation involves water flowing by gravity in crop rows for many hours to supply sufficient infiltrating water for plant growth. Furrow flow rates typically decrease down slope due to infiltration such that suspended soil particles can no longer be transported and are deposited in the furrow. Water leaving the field carries sediments along with adsorbed chemicals, which degrades the quality of receiving water bodies. Soil loss from furrow irrigation often exceeds 2 to 11 Mg ha^{-1} (Koluvek et al. 1993), and rates of up to 100 Mg ha^{-1} have been measured in experimental studies (Berg and Carter 1980; Evans et al. 1995; Fernández-Gómez et al. 2004; Trout 1996). The application of chemical soil additives such as polyacrylamide polymers have been found to reduce furrow irrigation-induced soil and phosphorus (P) losses (Krauth et al. 2008; Lentz et al. 1992; Sojka et al. 2007; Yu et al. 2003) in some parts of the world while further sediment and total P losses were achieved when these additives were combined with sedimentation ponds in the northwestern United States (Bjorneberg and Lentz 2005). In general, improving irrigation water efficiency ameliorates water quality since practices that promote water efficiency are those that match water application to crop needs, thus reducing excess runoff or deep percolation.

Considerable opportunities exist to improve irrigation water use efficiency, owing to the currently low fraction of overall agricultural water that is used for crop transpiration. The global share of agricultural water available for crop transpiration is only 10% to 30% and as low as 5% in arid and semiarid environments (Wallace 2000). This suggests that a significant fraction of agricultural water ends up as evaporation, deep percolation, runoff, or unused soil moisture storage. Irrigation affords unique controls on water delivery and is particularly suited for the integration of novel technologies to optimize the efficiency of agricultural water used for crop production. In irrigated systems, efficiency can be improved by minimizing water losses at various stages of the irrigation process, from water diversion and distribution to method and timing of water application, and agricultural practices used in the field. Research efforts have been traditionally invested in topics related to water conservation along irrigation water delivery infrastructures (Wachyan and Rushton 1987; Zhang et al. 2017), the efficiency of different types of irrigation systems (Battikhi and Abu-Hammad 1994; Bjorneberg et al. 2020b), and field- and crop-level water productivity (Bouman and Tuong 2001; Pan et al. 2017; Tarkalson et al. 2018). While information on individual crop water productivity and production functions might be available to inform water utilization on individual fields, what is much less understood is how different crops collectively modulate water utilization and water quality in an irrigated watershed.

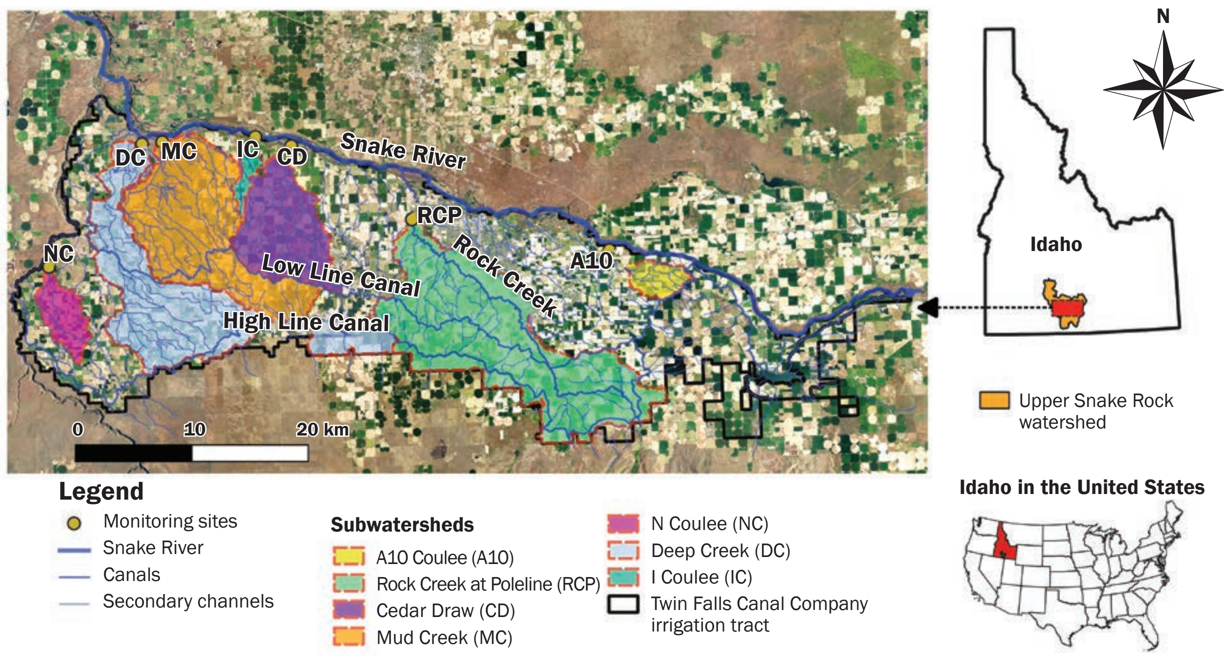
The agricultural landscape is constantly rearranged as crops, fallow practices, or other field treatments are varied in space and time. The role of these spatio-temporal agricultural land use variations in controlling water quantity and quality processes is seldom the object of experimental research. Most studies on the impact of land use on water quantity and quality typically group land use into broad categories that contrast agricultural to other land use types (e.g., forested, urban, etc.) (Donner et al. 2004; Rogers et al. 2012; Vezina et al. 2006; Wang et al. 1997). Some studies have nevertheless explored linkages between crop area and water quality using either hydrologic models or correlational approaches. Research in biofuel feedstock motivated modeling studies on the consequence of expanding the production of these crops (mostly corn [*Zea mays* L.], sorghum [*Sorghum bicolor* L.], or perennial grasses such as switchgrass [*Panicum virgatum* L.]) on water quality (Chen et al. 2017; Secchi et al. 2011; Thomas et al. 2008; Wu et al. 2012). Hydrologic models used for these types of studies include the Soil and Water Assessment Tool (SWAT) (Neitsch et al. 2011) or the Agricultural Policy Environmental eXtender (APEX) (Williams et al. 2008), which offer the advantage of intrinsically incorporating causal relationships between the production and management of specific crops and their consequence on water quantity and quality. Correlational studies may not establish direct cause and effect between water quantity and quality metrics and crop production and management, but they play an important role in understanding water quantity and quality patterns at broad spatial scales where experimental studies are impractical and no well-tested hydrologic modeling approach exists. Using a correlational approach, Donner (2003) found a strong link between the spatial extent of corn, soybean (*Glycine max* [L.] Merr.), and wheat (*Triticum aestivum* L.) and mean levels of nitrogen (N) and P at 25 tributaries of the Mississippi River. With multiple linear regressions, Yin et al. (2021) showed positive associations between corn and soybean production and N content in surface waters of the Illinois River basin.

As in many other parts of the world, irrigation in the northwestern United States faces challenges related to water quantity and quality. In drier areas of this region such as southern Idaho, agriculture relies almost exclusively on irrigation provided by surface and ground water supplies. Annual water balance in the Twin Falls Canal Company (TFCC) irrigation tract in southern Idaho revealed that precipitation accounted for only 10% to 23% of total water inflow into the watershed (Bjorneberg et al. 2020b). Historical water quality challenges in the region have revolved around high sediment (Berg and Carter 1980; Evans et al. 1995; Trout 1996) and P load (Bjorneberg et al. 2006) associated with furrow irrigation. The development of erosion mitigation strategies (Bjorneberg and Lentz 2005) and the continued conversion from furrow to sprinkler irrigation have appreciably improved water quality in the region (Bjorneberg et al. 2020a). Statistical analysis of future US irrigation water demand has showed that climate change is expected to increase irrigation rate in dry areas if significant improvements to irrigation efficiency are not made (McDonald and Girvetz 2013). While water quantity has not historically been a concern in the TFCC irrigation project, future challenges to water supply are expected due to climate change.

Irrigated areas such as the TFCC irrigation tract tend to exhibit greater agricultural diversity (variation in the number of different crops in space) than their rainfed counterparts (Goslee 2020). Combined with this agricultural diversity, the availability of long-term water quantity and quality monitoring data through CEAP (Bjorneberg et al. 2020a) present a unique opportunity to learn from patterns in water quantity and quality as related to interannual variations in crop production. Furthermore, evapotranspiration (ET) estimates modeled from satellite-derived observations (Allen et al. 2007) are now available over the region at regular time intervals. These data enable linkages to be made between water used by crops and water quantity and quality metrics. In this study, we hypothesize that hydrology and water quality characteristics of irrigation return flow are

Figure 1

Map showing monitoring sites in the Twin Falls Canal Company irrigation tract located in the Upper Snake Rock watershed of southern Idaho. Colored polygons delineate boundaries of the subwatersheds draining through return flow monitoring sites Cedar Draw (CD), Deep Creek (DC), Mud Creek (MC), Rock Creek at Poleline (RCP), I Coulee (IC), N Coulee (NC), and A10 Coulee (A10).



controlled by intrinsic characteristics of the irrigated areas but also by agricultural management factors inherent to the various crops irrigated. These management factors can be approximated by the proportion and performance of various crops in the watershed. In other words, a portion of the variability in irrigation return flow quantity and quality metrics can be explained by the fraction of ET (fET) associated with a particular crop.

The goal of this study is to determine how fET corresponding to major crops in the TFCC project impact water quantity and quality of irrigation return flow. The study uses a correlational approach to develop relationships between downstream water quantity and quality metrics and fET associated with major crops in subwatersheds of the TFCC irrigation tract.

Materials and Methods

Study Area. This study uses water quantity and quality monitoring data collected as part of CEAP in the Upper Snake Rock (USR) watershed (figure 1). The 6,300 km^2 USR watershed is located in south-central Idaho with the Snake River as its major river system. The region has an average annual precipitation of 250 mm and multiple irrigation projects supply as much as five times the natural annual precipitation to support a thriving agricultural industry. Land use within the USR is 37% irrigated agriculture, <1% dryland agriculture, and 60% rangeland and forest land with the remainder urban (USDA NRCS 2006). Created in 1905, the TFCC is one of the main irrigation projects in the USR and has been the focus of CEAP water quality monitoring. The TFCC diverts water from the Snake River at Milner Dam (42.5245 N, 114.0097 W) to provide irrigation water to 82,000 ha of land. Deeply incised canyons (100 to 150 m deep) of the Snake River and Salmon Falls Creek form the north and west boundaries of the irrigation tract. Water is routed by gravity through a 180 km network of main canals and more than 1,600 km of small channels and laterals. Most canals and secondary irrigation channels flow between April and October when irrigation water is supplied to the system. A combination of regional underground drain tunnels and relief wells were constructed in the early half of the twentieth century to address water logging issues that developed in the early years of the project. The relief wells are vertical shafts drilled at multiple locations across the irrigated landscape to promote the rapid transport of water upward through bedrock to drain tunnels. Lateral drain tunnels 1.2 × 1.8 m wide were dug into the underlying basalt bedrock to intercept the relief wells and provide a rapid drainage of excess groundwater into the surface hydrologic network at various low elevation locations in the watershed. Drain tunnels maintain water flow in some of the irrigation channels after October when diversion has ended. The TFCC irrigation tract also receives water from Rock Creek, the only natural stream contributing to the Snake River along this section of the river. At the downstream end of the irrigation project, the excess diversion (i.e., unused irrigation water mixed with agricultural tailwater) in irrigation canals and laterals are returned to the Snake River.

Water Quantity and Quality Monitoring Data. CEAP water quantity and quality monitoring started in TFCC in 2005 with continuous data available from 2006 to 2008 and after 2011. Seven sites (figure 1) with continuous data since 2006 were selected in this study to evaluate relationships between crops and water quality. Monitoring sites were part of the Idaho Department of Water Resources (IDWR) Water Diversion Measurement Network, equipped with control structures and pressure transducers logging continuous stage measurement for flow rate calculation.

One 2 L water grab sample was collected at each site weekly during the irrigation season (April to October) and every other week during the off-season. Samples were stirred for one to two minutes before measuring pH and electrical conductivity. Suspended sediment concentration in return flow samples was determined by filtering a 100 mL aliquot through a 0.45 μm filter paper, which was dried and weighed to get sediment concentration in grams per liter. Filtered and unfiltered samples were analyzed for a suite of chemical constituents using approaches described in detail by Bjorneberg et al. (2015) and summarily presented here. Filtered subsamples were analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES) for ortho-P, potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), aluminum (Al), iron (Fe), manganese (Mn), zinc (Zn), and sulfur (S) concentrations, and by flow injection colorimetry for nitrate (NO_3-N), ammonium (NH_4-N), and chlorine (Cl) concentrations. Unfiltered subsamples were digested with the Kjeldahl procedure and analyzed by ICP-OES for total N (TKN) and total P (TP) and finally by flow injection colorimetry for NO_3-N and NH_4-N (USEPA 1983). For this study we used the following analytes: sediments, dissolved (nondigested) NO_3-N concentration, and TP concentration (digested) to evaluate water quality aspects related to erosion processes and P loss and NO_3-N transport.

Calculation of Water Quantity and Quality Metrics. Monitoring sites used in this study were the seven sites with continuous records from 2006 to 2008 and 2011 to 2018: Cedar Draw (CD), Deep Creek (DC), Mud Creek (MC), Rock Creek at Poleline (RCP), N Coulee (NC), I Coulee (IC), and A10 Coulee (A10) (figure 1). Drainage tunnels contribute flow to every site except NC and A10. Cumulative annual volumes of return flow (Volm3) were calculated using the CEAP data. Total incremental masses of suspended sediments (TSS), TP, and total NO_3-N (TNO3) at each sampling date were obtained by multiplying the observed concentrations of these constituents by the volume of return flow water that elapsed since the preceding sampling date. Normalized return flow volumes (VolNrm [m]) were obtained by dividing total volumes by the size of the catchment area (see watershed delineation section) draining to a given monitoring site. Average annual flow-weighted mean concentrations of sediment (TSSc), P (TPc), and NO_3-N (TNO3c) were calculated by dividing total mass of these contaminants by total return flow volumes. VolNrm, TSSc, TPc, and TNO3c were aggregated in time periods representing different stages of the growing season. These periods were February to May to represent early season spring processes, June to August to represent midseason summer processes when ET demand is high and irrigation is at its maximum, and September to October during the fall when irrigation demand starts to decline, as many crops have gone past peak ET demand and are either harvested or close to harvest. A fourth aggregation period from April to October was added to capture the entire irrigation season.

Catchment Delineation and Crop Evapotranspiration Estimation. A 30 m resolution digital elevation model (DEM) of the TFCC was conditioned in GRASS GIS (GRASS Development Team 2019) to facilitate the delineation of catchment areas draining to monitoring sites. The DEM conditioning consisted of first filling local depressions to force surface flow out of the TFCC boundary. A shapefile of the surface drainage network was obtained from the National Hydrographic Data NDHPlus HR (Moore et al. 2019) to carve the DEM by forcing a 2 m deep by 30 m wide depression along the channel network. This carving step ensured that the flow accumulation and drainage network determined with the DEM would be consistent with the NHDPlus HR data set, which contained both natural and manmade drainage features such as canals. The conditioned DEM was used to compute the flow accumulation over the entire TFCC irrigation tract. The result of the flow accumulation calculation was a raster indicating the accumulated weight of all cells flowing into each downslope cell. Cells with high flow accumulation are areas of concentrated flow coinciding with drainage networks. In this study, return flow networks were assumed to pass through these high flow accumulation areas, but mapped monitoring sites did not always coincide with pixels of high flow accumulation. To ensure that the monitoring sites overlap high flow accumulation pixels, the location of each of the seven sites was manually moved to the maximum flow accumulation pixel within a 100 m radius. From the flow accumulation map and the revised monitoring site locations, subwatershed areas draining to the seven sites were computed (figure 1).

Since the goal of the study was to determine how the amount of water allocated to various crops impacts overall return flow water quality and quantity, we used estimated ET to reflect the amount of water used by various crops. We used ET estimates provided by IDWR for the years 2006 to 2018. These ET estimates were developed using the Mapping EvapoTranspiration at high Resolution with Internalized Calibration (METRIC) model (Allen et al. 2007). Cumulative ET (mm) for the entire irrigation season (April to October) was provided and used in this analysis. In each of the seven subwatersheds, ET volumes by crop were calculated by masking ET estimates with ET pixels corresponding to the crop in consideration. Crop maps were obtained from the USDA National Agricultural Statistics Service (NASS) Crop Data Layers (CDL) (https://nassgeodata.gmu.edu/CropScape). CDL maps for 2006 were not available so this year was excluded from the spatial analysis. ET volumes (m^3) allocated to each crop were obtained by multiplying season ET depth by the 900 m^2 pixel size and summing all the pixels in a subwatershed corresponding to the crop in consideration. Total crop area in each subwatershed was also calculated by automatically computing the number of pixels of a given crop inside a subwatershed and multiplying it by the pixel size.

To identify common crops grown in the region, a preliminary analysis was performed on the CDL by selecting crops that consistently occupy at least 1% of the agricultural areas every year during the study period. These crops were alfalfa (*Medicago sativa* L.) (22.8 % of the agricultural land across all years), grass pasture (12.1%), corn (14.5%), dry bean (*Phaseolus vulgaris* L.) (9.1%), barley (*Hordeum vulgare* L.) (8.0%), winter wheat (5.2%), potato (*Solanum tuberosum* L.) (2.7%), and sugar beet (2.3%). To reduce uncertainties due to crop misclassifications in the CDL data, crops that were similar in management and in plant appearance were grouped. As such, alfalfa and grass pastures were grouped into alfalfa/pasture category and wheat and barley were grouped into a category labeled "small grains." These groupings also helped reduce the number of explanatory variables used in the statistical analysis described below.

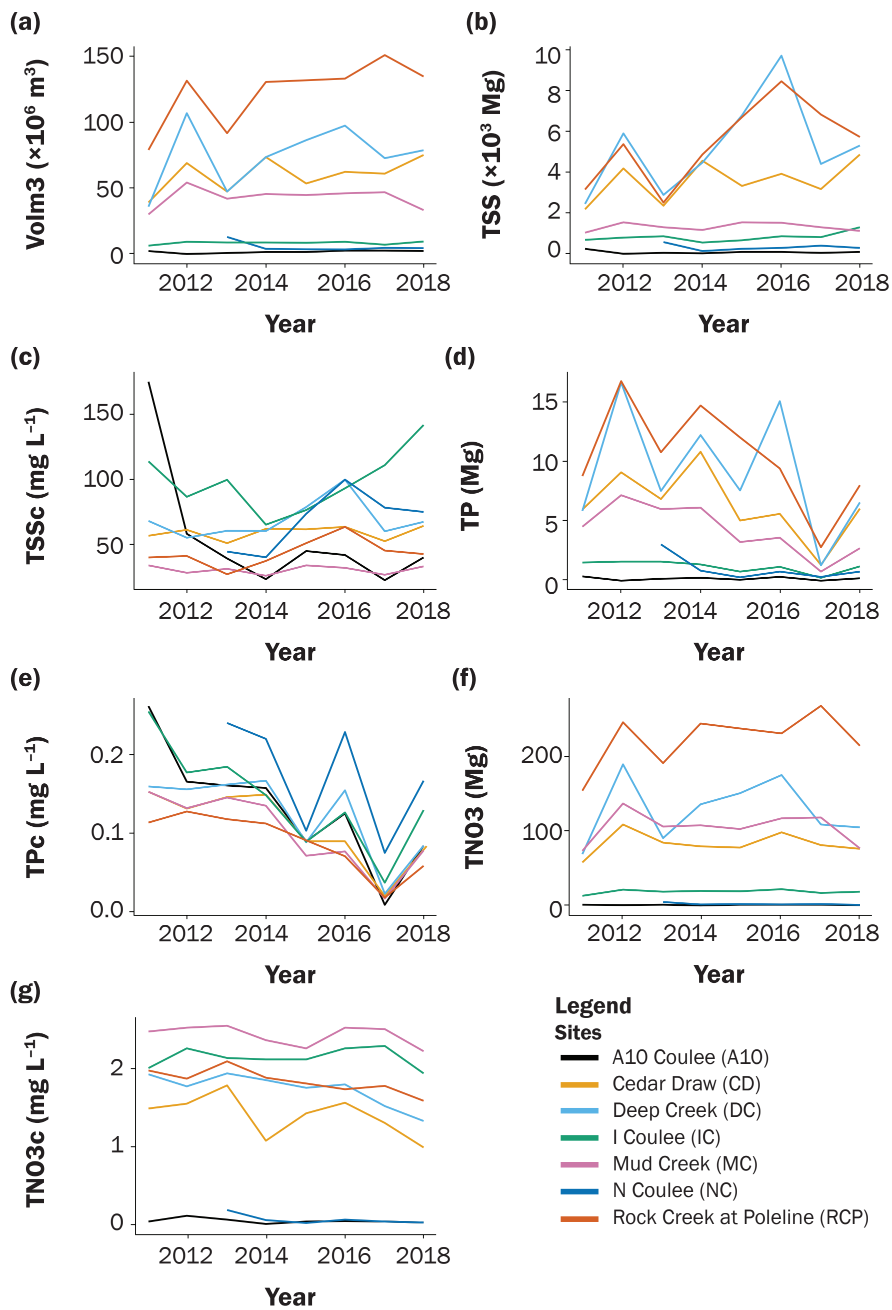
In each subwatershed, the total ET volume calculated for each of these crops was divided by the total ET volume for all major crops in the subwatershed to obtain crop-specific fET. These fET values were calculated for each major crop for each study year and each subwatershed. The fET values were used as explanatory variables in the statistical analysis described below. The fET indicates the relative demand on irrigation resources for each crop in contrast to the amount of land where crops were planted.

Statistical Analyses. Mann Kendall trend analyses (Pohlert 2020) were performed on yearly totals of return flow volumes as well as masses of sediments, TP, and TNO3 and concentrations TSSc, TPc, and TNO3c at each monitoring site for the period of 2011 to 2018 with uninterrupted water quality records. A principal component analysis (PCA) was performed on the fET values and water quantity and quality metrics for each subwatershed and all the years of available data. Variables were scaled to have unit variance prior to PCA to ensure that all variables have equal weight. The PCA was used as a data exploration method to examine the overall structure in the data, visually identify variables that are positively or negatively correlated, and group sites that cluster along principal axes.

Multiple linear regressions were performed by regressing variables VolNrm, TSSc, TPc, and TNO3c against the fET allocated to the major crops identified above in the corresponding subwatersheds. Sites were grouped using the PCA clustering described above and linear regressions performed separately in each group. In addition to the fET variables, a categorical variable (Site) was added to account for any site effect. Following the multiple linear regression, a bidirectional stepwise variable selection procedure was performed to reduce the linear model to only explanatory variables that contributed significantly to the coefficient of determination (R^2). An analysis of variance (ANOVA) was also performed to check that a given explanatory variable had a significant effect on explained variables. An explanatory variable was considered to influence explained variable if the *p*-value of the ANOVA is less than 0.05 and the coefficient of the variable is different than 0 (coefficient *p*-value < 0.05). Normality tests were performed on the residuals of all multiple linear regressions and multicollinearity between explanatory variables assessed with the variance inflation factor (VIF). Variables that exhibit strong multicollinearity (VIF > 10) were examined and redundant variables removed from the regression models. Statistical analyses were performed using the R statistical software (R Development Core Team 2015).

Figure 2

Water quantity and quality data for years 2011 to 2018. (a) Yearly return flow volumes (Volm3); (b) annual mass of suspended sediments (TSS); (c) average sediment concentration (TSSc); (d) total phosphorus loss (TP); (e), average phosphorus concentration (TPc); (f) total dissolved nitrates loss (TNO3); (g) and average nitrate concentration (TNO3c) measured at monitoring sites.



Results and Discussion

Water Quantity, Quality, and Crop Evapotranspiration. Water quantity and quality data for years 2011 to 2018 are presented in figure 2. Annual measured Volm3, TSS, TP, and TNO3 varied by site and year and were consistently highest at RCP and lowest at A10. Mann Kendall trend analyses on the data collected between 2011 and 2018 revealed a significant increasing trend in return flow volume at RCP (7.25×10^6 m^3 y^{-1}) and at A10 (2.35×10^5 m^3 y^{-1}). No significant trend was noted in return flow volume at the remaining five sites. Annual total masses of transported contaminants (TSS, TP, and TNO3) did not show any significant trend during the same time frame. Average annual sediment concentration (TSSc) did not exhibit any significant trend over time at any of the sites, whereas TPc and TNO3c showed significant decreasing trends at some sites. TPc decreased at CD (–0.01 mg L^{-1} y^{-1}), IC (–0.02 mg L^{-1} y^{-1}), and A10 (–0.03 mg L^{-1} y^{-1}), while TNO3c decreased at DC (–0.07 mg L^{-1} y^{-1}).

Average annual ET associated with common crops in the study area are presented in table 1. Sugar beet and alfalfa/pasture produced the greatest ET and did not differ ($p > 0.05$), with 894 mm and 864 mm of ET, respectively. These were followed by potato, corn, and small grains, which consumed similar amounts of water (ET ≈ 800 mm). Dry bean had the lowest water requirement with a total of 614 mm of ET. As indicated in figure 3, the fET associated with a crop in a subwatershed generally approximated the fraction of agricultural land allocated to the crop, as most points in figure 3 followed the 1:1 line and their slopes were close to 1. For dry beans, the slope of this relationship was 0.77 ± 0.01, owing to the significantly smaller water requirements of this crop. For the more water-demanding sugar beet the slope of this relationship was 1.21 ± 0.02. For alfalfa and pasture, fET values were systematically greater than their areal fraction, but the slope of the relationship remained close to 1 (0.98 ± 0.02) with a nonzero intercept (0.04). Overall, figure 3 suggests that the fET for a given crop in a subwatershed captures both the spatial coverage of the crop in the subwatershed and the associated water demand.

Characterization and Grouping of Monitoring Sites. The first and second components of the PCA (figure 4) captured 58.06% of the variability in the crop and water quality data. Component 1 of the PCA was mainly controlled by variables related to the size of the subwatersheds. As indicated by the orientations and magnitude of the loading vectors in figure 4, variables representing subwatershed area by crop and those representing cumulative water quantity and quality metrics (Volm3, TSS, TP, and TNO3) had greater eigen values on the first component compared to the second component. Component 2, which accounts for 12.36% of the variability, is mainly driven by a combination of variables, most notably the proportion of alfalfa/pasture, sugar beet, and potato grown in a subwatershed. Other findings suggested by the PCA include (1) subwatersheds with greater proportions of alfalfa/pasture and to a lesser extend corn tended to have lower fractions of small grains, dry bean, and sugar beet cultivated; (2) the fraction of small grains and dry bean in a subwatershed tended to be correlated; and (3) annual average sediment concentration and subwatershed size tended to be inversely related.

Using results of this PCA, the monitoring sites can be categorized into two groups along the first component. Group 1 was characterized by large subwatersheds, large annual return flow volumes, and low sediment concentrations. These sites include RCP, DC, MC, and CD. Small subwatershed area and high sediment concentration characterized group 2, which included A10, IC, and NC. It is important to note that sites in group 1 all received flow from subsurface drain tunnels, while in group 2, only IC contained such tunnels. This explains the

Table 1
Average evapotranspiration (ET) estimated across all sites for each crop in the Twin Falls Canal Company irrigation tract.

Crop	Average ET (mm)
Sugar beet	894a
Alfalfa/pasture	864a
Potato	817b
Corn	804b
Small grains	794b
Dry bean	614c

Note: Letters a, b, and c denote average ET values that were not statistically different.

Figure 3
Relationship between fraction of average annual evapotranspiration (fET) and fraction of area covered by major crops in the Twin Falls Canal Company irrigation tract.

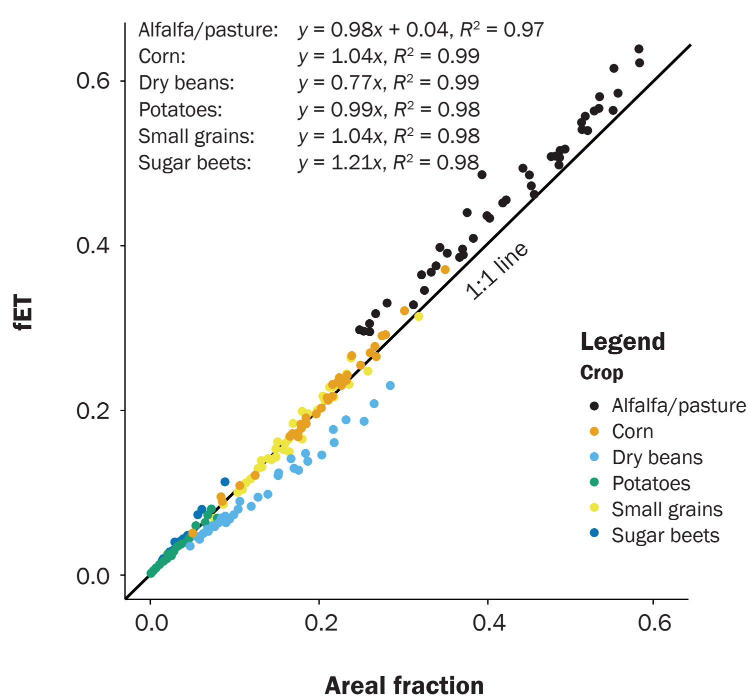
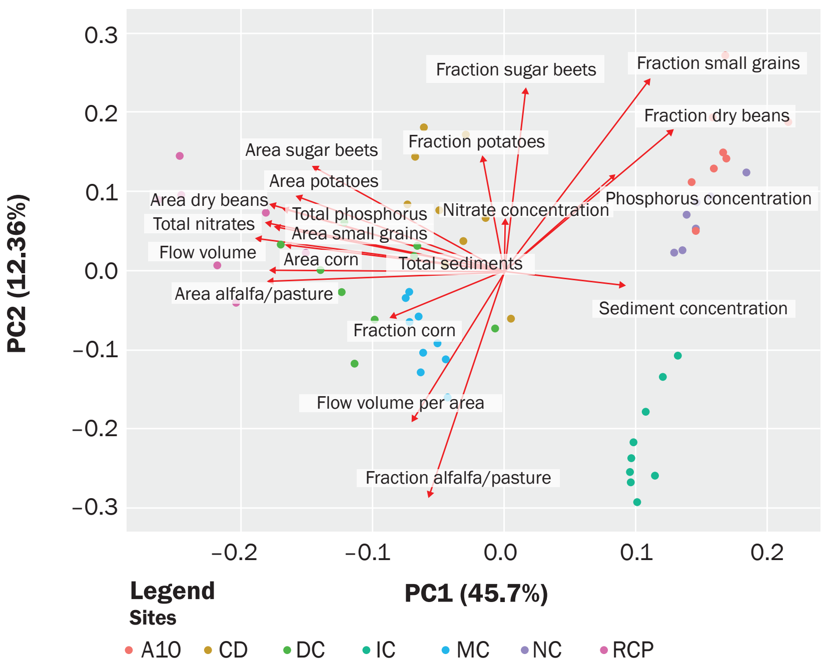


Figure 4

Principal component (PC) analysis of hydrologic and water quality information at monitoring sites, and crop cover information of the associated subwatersheds. Site names are A10 Coulee (A10), Cedar Draw (CD), Deep Creek (DC), I Coulee (IC), Mud Creek (MC), N Coulee (NC), and Rock Creek at Poleline (RCP).



separation in figure 4 between IC and the other two sites of the same group.

For the statistical analyses presented below, reference sites selected to evaluate site effects on hydrologic and water quality response were CD in group 1 and A10 in group 2. Annual return flow volume at the CD site ranged from 38 × 10⁶ to 75 × 10⁶ m³ during the study period, which was on average greater than the flow at MC (30 × 10⁶ to 54 × 10⁶ m³) but lower than DC (36 × 10⁶ to 107 × 10⁶ m³) and RCP (78 × 10⁶ to 156 × 10⁶ m³). Like other sites in group 1, flow at CD occurred year-round and was sustained by subsurface tunnel water after irrigation delivery had ceased. Among sites in group 1, RCP was the only site receiving water from Rock Creek, the only natural tributary to the Snake River in the TFCC irrigation project. In group 2, annual return flow volume during the study period ranged from 0.1 × 10⁶ to 2 × 10⁶ m³ at the reference site A10, from 6 × 10⁶ to 11 × 10⁶ m³ at IC, and from 0.5 × 10⁶ to 12 × 10⁶ m³ at NC.

Crop and Site Effects on Normalized Return Flow Volume. The results of the multiple linear regression on the effect of crop production on VolNrm are presented in table 2. Additional details on the multiple linear regression and ANOVA performed to determine the statistical significance of explanatory variables are provided as supplemental materials (table S1). Between the months of February and May, potato production was associated with increased VolNrm in group 1 (table 2), with a regression coefficient (coef.) of 4.42 (R^2 = 0.71). In the June to August period, the association of potato production with VolNrm remained but with a lower coefficient compared to the preceding period (coef. = 1.54 versus 4.42). In September and October, the cultivation of small grains was associated with decreasing VolNrm in both groups 1 and 2. Regression

Table 2

Statistically significant coefficients of the multiple linear regressions of normalized return flow volume (VolNrm) measured by season as a function of crop evapotranspiration fraction (fET) and site for group 1 (Cedar Draw = CD, Deep Creek = DC , Mud Creek = MC, and Rock Creek at Poleline = RCP) and group 2 (I Coulee = IC, N Coulee = NC, and A10 Coulee = A10).

Season	Group 1	Group 2
February to May	$4.42\text{fET}_{\text{Potato}}$ + | −0.15 if Site = MC; 0 Otherwise, R^2 = 0.71	| +0.33 if Site = IC; 0 Otherwise, R^2 = 0.98
June to August	$1.54\text{fET}_{\text{Potato}}$ + | −0.12 if Site = DC; −0.17 if Site = MC; 0 Otherwise, R^2 = 0.85	| +0.35 if Site = IC; 0 Otherwise, R^2 = 0.64
September to October	$-1.67\text{fET}_{\text{S.grains}}$ + | −0.13 if Site = DC; −0.19 if Site = MC; 0 Otherwise, R^2 = 0.82	$-0.60\text{fET}_{\text{S.grains}}$ + | 0.28 if Site = IC; 0 Otherwise, R^2 = 0.94
April to October	| −0.44 if Site = DC; −0.76 if Site = MC; +0.25 if Site = RCP; 0 Otherwise, R^2 = 0.82	| +0.78 if Site = IC; 0 Otherwise, R^2 = 0.88

Note: S.grains = small grains.

Table 3

Statistically significant coefficients of the multiple linear regressions of sediment loss per runoff volume (TSSc) measured by season as a function of crop evapotranspiration fraction (fET) and site for group 1 (Cedar Draw = CD, Deep Creek = DC, Mud Creek = MC, and Rock Creek at Poleline = RCP) and group 2 (I Coulee = IC, N Coulee = NC, and A10 Coulee = A10).

Season	Group 1	Group 2
February to May	–36.38 if Site = MC 0 Otherwise , R^2 = 0.62	$-424.85\text{fET}_{\text{Alfa. Past.}} - 911.00\text{fET}_{\text{Sug. beet}}$, R^2 = 0.86
June to August	–21.52 if Site = DC –69.80 if Site = MC –41.34 if Site = RCP 0 Otherwise , R^2 = 0.68	$235.63\text{fET}_{\text{Alf. Past.}}$, R^2 = 0.30
September to October	–31.45 if Site = MC –25.95 if Site = RCP 0 Otherwise , R^2 = 0.57	NS, R^2 = 0.51
April to October	–39.94 if Site = MC –22.14 if Site = RCP 0 Otherwise , R^2 = 0.70	NS, R^2 = 0.40

Notes: Alfa. Past. = alfalfa pasture. Sug. beet = sugar beet. NS = not statistically significant.

coefficients for small grains were –1.67 in group 1 and –0.60 in group 2. When all monthly monitoring data were aggregated per irrigation season (April to October), no crop association was noted.

Statistical differences in VolNrm between sites of the same group were noted in some seasons and over the irrigation season (table 2). For the February to May period, VolNrm values at MC of group 1 were 0.15 lower than those at the reference site CD. In group 2, VolNrm values at IC were 0.33 greater than reference site A10 for the same period. Flow from subsurface drains at IC provided sustained flow throughout the irrigation season and beyond, thus resulting in additional flow to when compared to in-season irrigation water. In comparison, A10 and NC relied only on in-season irrigation water. From June to August, DC and MC both had VolNrm values lower (–0.12 and –0.17, respectively) than CD in group 1, while IC had greater VolNrm values (0.35) compared to A10 in group 2. In the September and October timeframe, VolNrm was again lower at DC (–0.13) and MC (–0.19) compared to CD. In group 2, VolNrm at IC was 0.28 greater than at A10. Over the entire irrigation season, VolNrm values were statistically different at DC (–0.44), MC (–0.76), and RCP (0.25) in group 1, while in group 2, VolNrm measurements at IC were 0.78 greater than they were at A10, owing to the additional subsurface drain flow at the former site.

Crop and Site Effects on Flow-Weighed Sediment Load. Results of the multiple linear regression on TSSc as a function of crop fET and monitoring site are summarized in table 3. Additional details on the multiple linear regression and ANOVA performed to determine the statistical significance of explanatory variables are provided as supplemental materials (table S2). For the February to May period, alfalfa/pasture and sugar beet were inversely associated with TSSc in group 2. In this group, the regression coefficient between crop fET and TSSc was –424.85 for alfalfa/pasture and –911.00 for sugar beet. In the months from June to August, alfalfa/pasture was positively associated with TSSc (coef. = 235.63) in group 2. In September and October and for the aggregated irrigation season, no statistically significant crop association with TSSc was observed in either group 1 or 2.

Some site effects were also noted on seasonal and yearly TSSc data. In the February to May period, MC had a lower TSSc (–36.38) compared to CD, despite having a lower return flow volume per unit drainage area during the same period (table 3), suggesting lower levels of soil loss transported through the former monitoring site. From June to August, TSSc at the DC, MC, and RCP monitoring sites of group 1 were lower than they were at CD (–21.52, –69.80, and –41.34, respectively). TSSc remained lower at MC (–31.45) and RCP (–25.95) for the months of September and October, while no site effect was noted in group 2. TSSc during the entire irrigation season was lower at MC and RCP compared to CD by 39.94 and 22.14, respectively.

Crop and Site Effects on Flow-Weighed Phosphorus Load. Results of the multiple linear regression on P concentration (TPc) are presented in table 4. Additional details on the multiple linear regression and ANOVA performed to determine the statistical significance of explanatory variables are provided as supplemental materials (table S3). All crop associations with TPc were negative, and this was true in both groups across seasons and for the overall irrigation season. Alfalfa/pasture, dry bean, and corn were frequently found to have statistically significant associations with TPc. From February to May, alfalfa/pasture, sugar beet, and corn were associated with decreasing TPc in both groups. In group 1, regressions coefficients were –0.68, –1.54, and –0.64 for alfalfa/pasture, sugar beet, and corn, respectively, while in group 2, these coefficients were –0.82, –2.83, and –0.65 for the February to May period. TPc from June to August were associated with dry bean (–1.22) and corn (–0.89) in group 1. In the latter part of the growing season (September and October), dry bean was associated with decreasing TPc (–1.87) in group 1. During the irrigation season, TPc was mainly associated with alfalfa/pasture, dry bean, potato, and corn. Regression coefficients for these crops were –1.07, –1.25, –1.26, and –0.76, respectively, in group 1, while significant coefficients in group 2 were –1.27 for dry bean and –0.71 for corn.

Site effects on TPc were only noted in group 2 between September and October where TPc at NC were 0.31 lower than those at A10.

Crop and Site Effects on Flow-Weighed Nitrates Load. Results of the multiple regression on TNO3c are reported in table 5.

Table 4
Statistically significant coefficients of the multiple linear regressions of average phosphorus concentration (TPc) measured by season as a function of crop evapotranspiration fraction (fET) and site for group 1 (Cedar Draw = CD, Deep Creek = DC, Mud Creek = MC, and Rock Creek at Poleline = RCP) and group 2 (I Coulee = IC, N Coulee = NC, and A10 Coulee = A10).

Season	Group 1	Group 2
February to May	$-0.68fET_{Alf.\ Past.} - 1.54fET_{Sug.\ beet} - 0.64fET_{Corn}$, $R^2 = 0.66$	$-0.82fET_{Alf.\ Past.} - 2.83fET_{Sug.\ beet} - 0.65fET_{Corn}$, $R^2 = 0.77$
June to August	$-1.22fET_{Dry\ bean} - 0.89fET_{Corn}$, $R^2 = 0.67$	NS, $R^2 = 0.44$
September to October	$-1.87fET_{Dry\ bean}$, $R^2 = 0.51$	$\begin{cases} -0.31 \text{ if Site = NC} \\ 0 \text{ Otherwise} \end{cases}$, $R^2 = 0.62$
April to October	$-1.07fET_{Alf.\ Past.} - 1.25fET_{Dry\ bean} - 1.26fET_{Potato} - 0.76fET_{Corn}$, $R^2 = 0.67$	$-1.27fET_{Dry\ bean} - 0.71fET_{Corn}$, $R^2 = 0.58$

Notes: Alfa. Past. = alfalfa pasture. Sug. beet = sugar beet. NS = not statistically significant.

Table 5
Statistically significant coefficients of the multiple linear regressions of average nitrate concentration (TNO3c) measured by season as a function of crop evapotranspiration fraction (fET) and site for group 1 (Cedar Draw = CD, Deep Creek = DC, Mud Creek = MC, and Rock Creek at Poleline = RCP) and group 2 (I Coulee = IC, N Coulee = NC, and A10 Coulee = A10).

Season	Group 1	Group 2
February to May	$-31.13fET_{Potato} - 9.60fET_{Corn} + \begin{cases} -1.37 \text{ if Site = RCP} \\ 0 \text{ Otherwise} \end{cases}$, $R^2 = 0.77$	$\begin{cases} +4.00 \text{ if Site = IC} \\ 0 \text{ Otherwise} \end{cases}$, $R^2 = 0.98$
June to August	$-7.53fET_{Potato} + \begin{cases} 0.78 \text{ if Site = MC} \\ 0 \text{ Otherwise} \end{cases}$, $R^2 = 0.80$	$\begin{cases} +1.80 \text{ if Site = IC} \\ 0 \text{ Otherwise} \end{cases}$, $R^2 = 0.99$
September to October	$-14.54fET_{Potato} - 4.43fET_{Corn} + \begin{cases} 0.65 \text{ if Site = MC} \\ 0 \text{ Otherwise} \end{cases}$, $R^2 = 0.83$	$\begin{cases} +2.54 \text{ if Site = IC} \\ 0 \text{ Otherwise} \end{cases}$, $R^2 = 0.98$
April to October	$4.87fET_{Dry\ bean} - 4.95fET_{Potato} + \begin{cases} 0.17 \text{ if Site = DC} \\ 1.11 \text{ if Site = MC} \\ 0.34 \text{ if Site = RCP} \\ 0 \text{ Otherwise} \end{cases}$, $R^2 = 0.97$	$\begin{cases} +2.17 \text{ if Site = IC} \\ 0 \text{ Otherwise} \end{cases}$, $R^2 = 0.99$

Additional details on the multiple linear regression and ANOVA performed to determine the statistical significance of explanatory variables are provided as supplemental materials (table S4). Crop association with TNO3c was only found in group 1. Potato and corn crops were negatively related to TNO3c from February to May and from September to October. Regression coefficients between potato and TNO3c were –31.13 for the February to May period and –14.54 for the September to October period. For the same periods, regression coefficients for the explanatory variables for corn were –9.60 and –4.43, respectively. From June to August, only the association of TNO3c with potato was statistically significant (coef. = –7.53). During the irrigation season, potato fET maintained an inverse relationship with TNO3c (coef. = –4.95), but a significant and positive relationship with dry bean was also noted (coef. = 4.87).

Site effects on TNO3c were present in both groups. In group 1, TNO3c was lower at RCP (–1.37 compared to CD) from February to May but greater at MC in the other 2 periods (0.78 and 0.65, respectively). During the entire irrigation season, TNO3c was greater at DC (0.17), MC (1.11), and RCP (0.34) compared to CD. In group 2, TNO3c was greater at IC compared to A10 (4.00, 1.80, 2.54, and 2.17 for the four data aggregation periods).

Discussions. Our results show that hydrology in a highly managed irrigated agricultural watershed like the TFCC is complex and influenced by management of both the irrigation water and the crops being cultivated. One of the major management changes occurring in the TFCC and the surrounding region is the continued conversion of field irrigation systems from furrow to sprinklers. On individual fields, sprinkler irrigation applies water more efficiently and causes less soil loss than furrow irrigation. However, these effects are not always evident at larger scales. We found in this study that return flow volumes increased at two monitoring sites (RCP and A10). This may have resulted from less irrigation water being used on sprinkler irrigated fields and more unused irrigation water flowing back to the Snake River as return flow. TFCC has a flow rate allocation scheme, meaning that farmers have an allocated flow rate available for a farm for the entire irrigation season. If the farmer is not irrigating and does not request that their headgate be closed, all of their irrigation water will flow down the return ditch. This finding is consistent with that of Bjorneberg et al. (2020b) who noted that conversion from furrow to sprinklers improved the TFCC project efficiency (ET divided by total diversion) during the month of July as water savings resulting from the conversion are not used to increase production but simply returned to the Snake River. As the proportion of sprinklers in TFCC increased over time, sediment loss was expected to gradually decline but no trend in TSS and TSSc were found, suggesting that erosion benefits of conversion to sprinklers may be obscured by other factors at the basin scale. The decline in TPc at CD, IC, and A10 despite the trendless sediment data likely captures the benefit of increased adoption of sprinkler irrigation, as less runoff is produced on sprinkler-irrigated fields, leading to a decrease in P transport (Bjorneberg et al. 2006).

A complexity inherent to managed irrigated systems like TFCC relates to the high variability in irrigation water quality depending on farm location in the irrigation tract. While some fields closest to the main diversion canals may receive water similar in quality to the Snake River, irrigation water further downstream may contain sediment and nutrients lost from other upstream fields. Furthermore, subsurface water re-emergence via drainage wells and tunnels further complicates hydrology of the whole system.

The associations between crops and return flow water quality found in this study are driven by a combination of factors including inherent crop water and nutrient demands, crop water management, and crop rotation. Discussing these factors per crop may provide insight into the associations found in this study.

Alfalfa/Pasture. Grass pastures and most alfalfa crops are typically grown as perennial crops (Shewmaker 2005). These perennial crops leave some vegetative cover on the ground during the spring season, thus reducing the risk of sediment detachment and erosion during early spring irrigation compared to other annual crops that require spring irrigation on bare ground to improve germination and plant establishment. The presence of ground cover in the early spring under perennial alfalfa/pasture cropping systems may explain the inverse association between alfalfa/pasture and spring sediment concentration in group 2. This inverse association was statistically significant at both IC and NC and not at A10 (data not presented), suggesting that the contribution of subsurface drain flow to return flow did not alter this inverse association. The lack of alfalfa/pasture association with return flow at the latter site is likely due to the comparatively very low return flows recorded from February to May at this site compared to the former two. In the summer, the relationship between alfalfa pasture and sediment concentration turned positive in group 2. However, this positive relationship was mostly driven by a slightly higher sediment concentration at IC where alfalfa/pasture crops were grown in greater proportion than they were at A10 and NC.

Factors described above that explain the beneficial effect of alfalfa/pasture on sediment concentration in group 2 are likely responsible for the lower effect of this crop on P concentration (TPc) during the spring months in both subwatershed groups. It is interesting to note that the negative association between alfalfa/pasture and TPc was statistically significant in group 1 even though the effect of this crop on TSSc was not significant. Once erosion processes occur, a fraction of the P removed with sediment dissolves in the water column and is retained in the aqueous fraction (Ramos et al. 2019; Sharpley and Kleinman 2003) even after deposition of solids has occurred in erosion mitigation structures such as sedimentation ponds. The presence of cover on alfalfa/pasture fields when most other annual crop fields are bare means that less sediment would be detached in the spring under alfalfa/pasture. Even though erosion mitigation structures such as sedimentation ponds might appear to negate the beneficial effect of alfalfa/pasture on TSSc compared to other crops, the lower soil detachment rate under the former cropping system means that less P would dissolve in the runoff water.

Dry Bean. The low water requirement of dry bean combined with a poor tolerance of this crop to water logging conditions (Myers 2002) may lead to greater volumes of irrigation water passing through the system without being applied to fields where sediment and P pickup and transport might occur. These conditions likely favored the association between this crop and lower TPc in both watershed groups. Nevertheless, the positive association between this crop and TNO3c over the irrigation season points to leaching processes of NO_3-N occurring with this crop. Symbiotic N fixing legume crops such as dry beans have been linked to enhanced NO_3-N leaching events in experimental studies (Campiglia et al. 2011; Hauggaard-Nielsen et al. 2009; Mariotti et al. 2015). Improved water management combined with the use of N removal strategies such as intercropping (Mariotti et al. 2015) or catch/cover cropping (Hauggaard-Nielsen et al. 2009) are options to reduce leaching potential under dry bean cultivation. More experimental research is needed in the TFCC irrigation tract to further investigate this positive association between dry bean and return flow NO_3-N concentration.

Sugar Beet. Sugar beet was associated with a lowering effect on spring TSSc (group 2) and TPc (groups 1 and 2). The inverse relationship between sugar beet and TSSc was mostly driven by the lower sediment concentration at the A10, which also included a higher proportion of sugar beet fET (6%) compared to IC (1%) and NC (0.4%). Early vegetation cover may have been responsible for a beneficial effect of sugar beet on spring water quality. Sugar beet may be planted early in the season to maximize yield (Khan et al. 2021) and may provide enough cover early in the season to limit soil detachment and transport by irrigation water. Considering the relatively small amount of sugar beet cultivation in the A10 subwatershed, other factors inherent to this subwatershed may be at play in the reduction of TSSc. Further investigations are needed to identify these factors.

Potato. Our results revealed that potato production was associated with an increase in normalized return flow volume (VolNrm) in group 1 during the spring and summer months. Increase in return flow volumes can be achieved via reduction in irrigation withdrawals along diversion pathways, increase in runoff from irrigated fields, or increase in subsurface re-emergence through drainage tunnels. Many factors could explain the positive relationship between potatoes and VolNrm. Potatoes are managed with a tight control on soil water content and are particularly susceptible to water stress, which reduces yield and tuber quality (King et al. 2020). Excessive fluctuations in water content can also lead to misshapen tubers, which degrade quality rating. Excess water can also be detrimental to potato production as it increases susceptibility to diseases (Bauske et al. 2018; Wharton and Wood 2013) and promotes nutrient leaching to groundwater (King et al. 2020). These stringent soil water content requirements by potato plants may act as inherent feedback mechanisms modulating water withdrawals based on plant needs (Pehrson et al. 2010). The common practice of growing potatoes on ridges has also been shown to cause uneven distribution of rainfall and irrigation water and greater water loss in the adjoining furrows (Harms and Konschuh 2010; Robinson 1999). Greater nutrient leaching from furrows in these ridge/furrow configurations have also been documented (Leistra and Boesten 2010). Our study showed that potato was associated with reduced TNO3c in return flow water of group 1 subwatersheds. A more careful water management of this crop may result in more unused return flow water and a dilution effect on NO_3-N concentration. More experimental research is needed to better understand how potato farming may impact surface and groundwater resources in the TFCC irrigation tract.

Corn. Corn did not have a significant association with VolNrm and TSSc but was inversely related to TPc and TNO3c. The presence of the inverse relationship between corn and TPc in both watershed groups suggests that surface processes are the primary drivers of the interplay between corn and return flow TPc. Potential factors to explore in attempting to better understand these results include low runoff and erosion from corn fields and greater P uptake by corn plants compared to other crops. The inverse relationship between this crop and TNO3c in group 1 watersheds suggests reduced NO_3-N leaching with this crop. Corn has been associated with excess NO_3-N leaching in many studies (Hussain et al. 2019; Klocke et al. 1999; Ochsner et al. 2018; Zhu and Fox 2003). For NO_3-N leaching to occur, water percolation beyond the root zone needs to occur. Irrigation and NO_3-N uptake studies on corn under linear move irrigation systems in the Northwest have, however, shown a depletion of soil moisture in the top 1.2 m profile from corn emergence to harvest (King et al. 2022; Tarkalson et al. 2022). NO_3-N leaching under corn in the semiarid Northwest is constrained by the limited availability of water in the soil profile. More research is needed to identify management and mechanisms inherent to corn cultivation that may help modulate P and NO_3-N concentration in return flow channels of the irrigated systems.

Small Grains. Small grains crops (i.e., wheat and barley) were associated with a decrease in fall and irrigation season return flow volumes in groups 1. Winter wheat planting occurs during the fall when ET demand has started to decline. Water withdrawals to irrigate wheat in the fall after most other crops are senescent or already harvested is likely to have an appreciable lowering effect on return flow volumes. Spring and winter grains use similar total seasonal water but differ in their temporal patterns of water utilization. Winter-planted grains predominate the TFCC and utilize fall and winter precipitation and soil reserves that are unavailable to the spring-planted grains. During the spring, winter grains will not be tilled and will begin using soil water as soon as temperatures rise to appropriate levels, whereas spring crops must be planted and emerge before this happens (Neibling et al. 2017). Winter grains will typically have around two less irrigations applied during the growing season compared to spring planted small grains.

Implications for Watershed Management. Results of this study can inform irrigation water demand forecasting and planning of water quality improvement measures. With the advent of artificial intelligence and other modern computational technologies, efforts are underway to develop useful irrigation water demand forecasting tools (Perea et al. 2021; Pulido-Calvo and Gutierrez-Estrada 2009; Pulido-Calvo et al. 2007). The use of crop data in such irrigation demand forecasting models has been shown to improve prediction performance compared to models based on climate and prior demand data alone (Pulido-Calvo et al. 2003). Results from our study confirm that return flow volumes respond to fET (and by correlation areal fraction) of specific crops, and this response may differ at various times of the growing season. Another takeaway from our study is that irrigation water demand forecasting in the TFCC may require more complex modeling strategies than simplistic process-driven accounting of water demand based on specific crop needs. Field conditions, weather, and water-related crop management practices also play a strong role in patterns and amount of water delivery to individual fields. With a flow rate water allocation scheme and in the absence of in-basin water storage infrastructure in TFCC, unused irrigation water simply returns to the Snake River. Our study found potato to be associated with increased return flow volumes in spring and summer, suggesting that better knowledge of potato management factors associated with these unused waters may help improve system efficiency.

Knowledge of associations between crop and sediment and nutrient load may also be helpful in the development of basin-level water quality improvement strategies. This study revealed that most associations between crops and P and NO_3-N were negative. This suggests that factors that favor performance in certain crops may also be effective strategies for retaining excess NO_3-N and P on the farm. The positive association between TNO3c and dry beans suggests that practices such as intercropping or cover crop may be options to reduce NO_3-N leaching under this crop. More experimental and modeling research is needed to clarify the causal interactions underlying the associations found in this study.

Summary and Conclusions

This study demonstrates that surface water monitoring data collected through CEAP were useful to gain insight into associations between crops and water quantity and quality in the TFCC irrigation project. Return flow volumes across the project were mostly stable during the study period but showed an increasing trend from 2011 to 2018 at two (RCP and A10) of the seven sites. Improvements in annual average P and NO_3-N concentrations were noted at four sites (CD, IC, A10, and DC) between 2011 and 2018. Return flow volume was positively associated with potato ET in the early season and inversely associated with small grains in the latter part of the growing season. Alfalfa/pasture and sugar beet appeared to have beneficial associations with spring sediment concentration. Corn, sugar beet, alfalfa/pasture, and dry beans had inverse associations with average P concentration, while NO_3-N concentration was inversely associated with corn and potatoes and positively associated with dry beans. In interpreting the results of this study, some associations could be directly linked to factors inherent to crop attributes, agronomic practices, and water requirement, while others required considerations of farming practices, nutrient and water management strategies, and watershed characteristics. While direct cause and effect relationships were not established between crops and specific water quantity and quality responses, results from this study provide valuable information on potential nutrient and water management factors associated with various crops that may control observed hydrologic response and point to areas of additional research needs.

Supplemental Material

The supplementary material for this article is available in the online journal at https://doi.org/10.2489/jswc.2023.00176.

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