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PHOSPHORUS FATE, MANAGEMENT, AND MODELING IN ARTIFICIALLY DRAINED SYSTEMS

Phosphorus Losses from an Irrigated Watershed in the Northwestern United States: Case Study of the Upper Snake Rock Watershed

David L. Bjorneberg,* April B. Leytem, James A. Ippolito, and Anita C. Koehn

Abstract

Watersheds using surface water for irrigation often return a portion of the water to a water body. This irrigation return flow often includes sediment and nutrients that reduce the quality of the receiving water body. Research in the 82,000-ha Upper Snake Rock (USR) watershed from 2005 to 2008 showed that, on average, water diverted from the Snake River annually supplied 547 kg ha^{-1} of total suspended solids (TSS), 1.1 kg ha^{-1} of total P (TP), and 0.50 kg ha^{-1} of dissolved P (DP) to the irrigation tract. Irrigation return flow from the USR watershed contributed 414 kg ha^{-1} of TSS, 0.71 kg ha^{-1} of TP, and 0.32 kg ha^{-1} of DP back to the Snake River. Significantly more TP flowed into the watershed than returned to the Snake River, whereas there was no significant difference between inflow and return flow loads for TSS and DP. Average TSS and TP concentrations in return flow were 71 and 0.12 mg L^{-1}, respectively, which exceeded the TMDL limits of 52 mg L^{-1} TSS and 0.075 mg L^{-1} TP set for this section of the Snake River. Monitoring inflow and outflow for five water quality ponds constructed to reduce sediment and P losses from the watershed showed that TSS concentrations were reduced 36 to 75%, but DP concentrations were reduced only 7 to 16%. This research showed that continued implementation of conservation practices should result in irrigation return flow from the USR watershed meeting the total maximum daily load limits for the Snake River.

The majority of irrigated cropland in the United States is located in the west, where the amount of water applied with irrigation far exceeds precipitation. In 2007, approximately 30% of harvested cropland in the United States was irrigated, which accounted for 40% of market value of agricultural products sold, making irrigated cropland some of the most productive lands in the United States (USDA NASS, 2008). Approximately 25% of the irrigated land in the United States has irrigation water supplied by off-farm sources (USDA NASS, 2008). These irrigation projects deliver water to fields through canals, laterals, and ditches. For large surface irrigation projects (e.g., >10,000 ha), it is difficult for diversions to match irrigation demand because it may take several days for diverted water to reach a field. Therefore, excess water is typically diverted to ensure that irrigation supply meets irrigation demands within the limits of the distribution system. This excess irrigation water becomes what is known as “irrigation return flow” when it cannot be utilized within the irrigated watershed and is ultimately “returned” to a water body. Irrigated watersheds may also have subsurface drains to remove excess water that has seeped from canals and ditches or to remove salts that were intentionally leached from fields. Both surface and subsurface drainage contribute to irrigation return flow, but rainfall seldom causes runoff in these arid areas.

In Idaho, there are approximately 1.3 million ha of irrigated cropland (USDA NASS, 2008), with a large percentage of the irrigation water being supplied via the Snake River. In the Upper Snake Rock (USR) watershed, approximately 65% of irrigated cropland is under furrow irrigation. Uniformly distributing water on sloping, open-ended, furrow-irrigated fields typically results in 20 to 50% of the applied water running off. Much of this water is reapplied to other fields within the watershed, but some flows from the watershed back to the Snake River through the return flow system. Irrigation return flow, like runoff or drainage from nonirrigated watersheds, can transport sediment and nutrients from agricultural fields to surface water sources. This transport of sediments and nutrients, in particular phosphorus (P), from

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*Corresponding author (dave.bjorneberg@ars.usda.gov).

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Abbreviations: CEAP, Conservation Effects Assessment Project; DP, dissolved phosphorus; PAM, water-soluble polyacrylamide; TFCC, Twin Falls Canal Company; TMDL, total maximum daily load; TP, total phosphorus; TSS, total suspended solids; USR, Upper Snake Rock.

agricultural fields to the Snake River has resulted in water quality concerns. Many segments of the Snake River have been identified as impaired with respect to sediment and P, so total maximum daily loads (TMDLs) have been set at 52 mg L^{-1} for total suspended solids (TSS) and 0.075 mg L^{-1} for total P (TP) (IDEQ, 2010).

This is not a unique situation, and many regions in the United States and abroad face the same challenges. For example, Ebbert et al. (2003) demonstrated that TSS and P concentrations in the Yakima River were greater downstream from irrigated land than upstream based on two sampling campaigns in 1988 and 1999. In that study, upstream TSS concentrations were 3 to 5 mg L^{-1} and TP concentrations were <0.01 mg L^{-1}, and downstream TSS and TP concentrations were 21 to 22 mg L^{-1} and 0.13 to 0.14 mg L^{-1}, respectively, during the irrigation season. Surface, sprinkler, and microirrigation were used in this watershed. Skhiri and Dechmi (2011) reported annual TP losses of 0.05 to 1.5 kg ha^{-1} in four irrigated watersheds, with 90 to 58,000 ha and both sprinkler and surface irrigation, in northeast Spain based on weekly sampling for 1 yr. In two of the watersheds that were primarily surface irrigated, TP losses during the irrigation season were 2.5 to 4.9 times greater than during the nonirrigation season. However, if most of the diverted irrigation water infiltrates within the irrigated watershed, there may be net retention of P in the watershed. Bondurant (1971) demonstrated via mass balance on a 220-ha surface-irrigated watershed in southern Idaho that 80 to 85% of the P in the irrigation water remained within the watershed. On two larger irrigated watersheds in southern Idaho, Carter et al. (1974) reported that approximately 90% of the P remained in the watershed when 75% of the land was sprinkler irrigated, compared with 50% remaining in the watershed when 90% of the land was furrow irrigated. In that study, the sprinkler-irrigated watershed had a net TSS accumulation of 0.7 Mg ha^{-1}, compared with a net TSS loss of 0.46 Mg ha^{-1} in the furrow-irrigated watershed (Brown et al., 1974).

Because irrigation return flow conveys sediment and nutrients to rivers, it is possible that these return flows could be regulated to meet TMDL limits. To reduce water quality impacts of irrigation on river systems, practices that reduce TSS and nutrient transport through irrigation return flow systems are necessary. In the USR watershed in southern Idaho, financial incentives have been use to convert fields from furrow irrigation to sprinkler irrigation. In addition, the Twin Falls Canal Company (TFCC), which controls irrigation water delivery in the USR watershed, has constructed 18 water quality ponds or wetlands in the last 20 yr to reduce sediment and nutrients in water returning to the Snake River, often with USEPA cost-share funding. These ponds receive water continuously during the irrigation season and have retention times on the order of hours, not days. Numerous studies have shown that constructed wetlands can retain sediment and nutrients from surface runoff (e.g., Carleton et al., 2001; Jordan et al., 2003; Rausch and Schreiber, 1981). However, most published studies quantify wetland performance for rainfall runoff events that have episodic inflow, not continuous inflow as occurs in irrigated watersheds. This case study evaluates the water quality in one irrigation tract over a period of 4 yr and examines management strategies that have been developed to reduce the transport of TSS and TP to the Snake River via the irrigation return flow system.

Materials and Methods

Water Quality Monitoring in the Upper Snake Rock Watershed

The USR watershed is an 82,000-ha watershed located along the south side of the Snake River in south central Idaho. This watershed is part of the Conservation Effects Assessment Project (CEAP), which is a multiagency effort to quantify the environmental effects of conservation practices and develop a science base for managing the agricultural landscape for environmental quality. The USR is one of 14 USDA Agricultural Research Service benchmark watersheds that participate in the CEAP. Watershed research for the USR CEAP began in 2005 by monitoring inflow and outflow of water, sediment, and nutrients in the watershed. Irrigation water, supplied by the TFCC, flows in canals, ephemeral streams, and coulees as it is delivered to fields or flows back to the Snake River (Fig. 1). Many streams flow only during the irrigation season (Apr.–Oct.), whereas others flow all year due to subsurface drain tiles and tunnels located sporadically throughout the watershed. Drain tunnels are 1.2 m wide by 1.8 m high tunnels that were dug horizontally into the basalt bedrock to remove excess groundwater that percolated up to the soil surface after 5 to 10 yr of irrigation. Rock Creek is the only stream that flows into the watershed. It is ephemeral upstream from the watershed, typically only flowing in spring and early summer from snowmelt in the mountains because rain seldom causes runoff in this area.

Unlike many watersheds, the USR has two inflow streams and numerous outflow streams. Twenty-two monitoring sites were established in 2005 to measure the quantity and quality of surface water returning to the Snake River (Fig. 1). Two additional return flow sites were added in 2006. Water flowing into the watershed was measured at two sites: the Mainline Canal and Rock Creek, which has much less flow than the canal. Flow rates at all 26 sites were measured with weirs or calculated from stage–discharge relationships. Flow rates were automatically recorded on data loggers (Campbell Scientific, Inc.) at 17 sites. Flow stage at nine minor sites was manually measured once a week. Automatic water samplers (Hach Co.) were used at eight sites with the highest flow rates to collect time-composite water samples (a 0.2-L subsample every 5 h in 2-L bottles). The three or four 2-L composite samples from each site were combined into a weekly composite sample. The 5-h interval was used so samples were not collected at the same time each day. One 2-L grab sample was collected weekly from the other 18 sites. During the winter (Dec.–Feb.), weekly grab samples (2-L) were collected from the 12 sites that flowed all year when freezing temperatures prohibited the use of automatic samplers.

All water samples were refrigerated until processed within 24 h of collection. During sample processing, samples were stirred for 1 to 2 min on a stir plate, and while stirring, a 50-mL aliquot was collected for TP analysis. A second 20-mL aliquot was filtered (0.45 μm) and stabilized with 0.2 mL of saturated boric acid for analysis of dissolved P (DP). A third aliquot was used to determine TSS concentration by filtering a known volume (~100 mL) through 0.45-μm filter paper and weighing the dried filter paper (60°C for 24 h) before and after sediment collection. Filtered water samples were analyzed by inductively

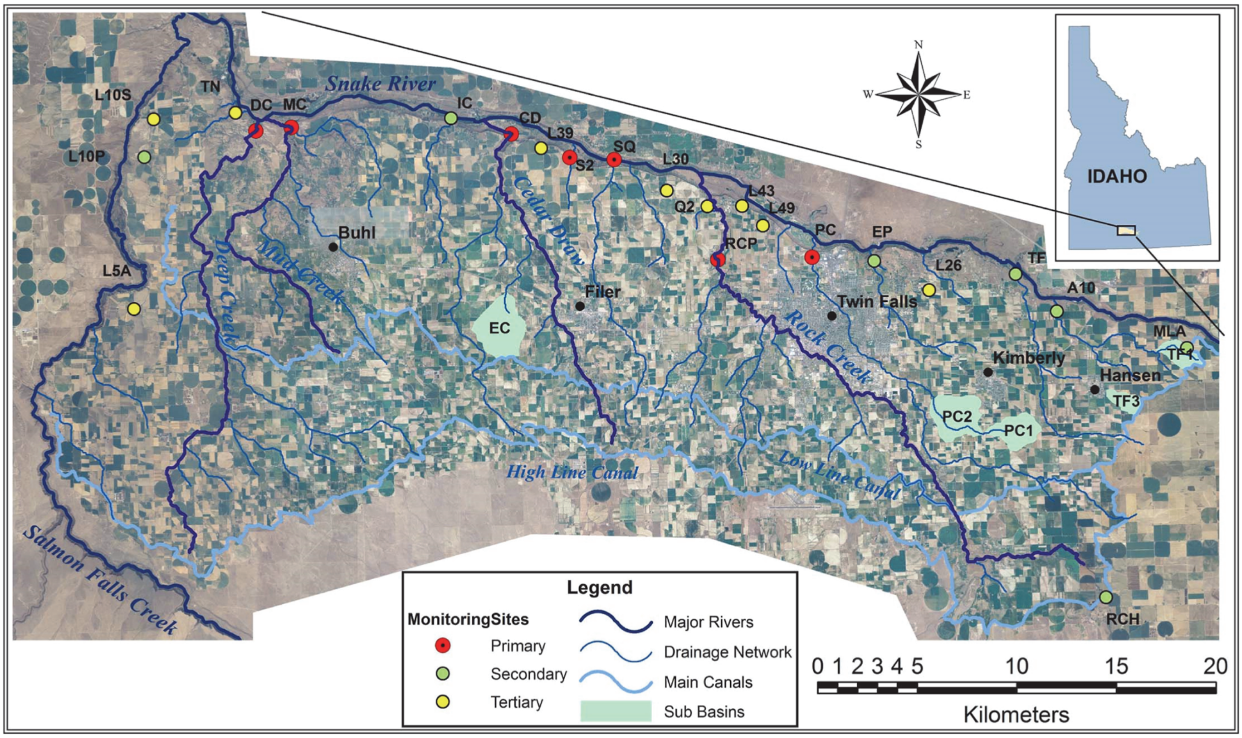

Fig. 1. Aerial photograph of the 82,000 ha Upper Snake Rock watershed showing monitoring locations. The two inflow locations are the main irrigation canal (MLA, upper right) and Rock Creek (RCH, lower right). Rock Creek is also a return flow site where it enters the Snake River (RCP).

coupled plasma–optical emission spectroscopy (PerkinElmer) to determine total DP concentration. An aliquot (~25 mL) of the unfiltered water sample was digested with a Kjeldahl procedure (USEPA, 1983) and analyzed by inductively coupled plasma–optical emission spectroscopy for TP.

The volume of flow at each site was calculated for each sample interval. This volume was multiplied by parameter concentrations from laboratory analysis to calculate mass loads. Loads were summed over appropriate intervals (e.g., yearly or monthly) to determine total input or output of a parameter. Flow-weighted concentrations were calculated by dividing the mass load for a time period by the total flow volume for the same period. Paired t tests were used to determine significant differences ($P < 0.05$) between annual inflow and outflow loads or concentrations.

Monitoring of Water Quality Ponds within the Upper Snake Rock Watershed

To determine the impact of water quality ponds on flows of TP, DP, and TSS in the return flow system, inflow and outflow were monitored during the 2008 irrigation season at five water quality ponds constructed by the TFCC. These ponds varied in size depending on site conditions and flow rate of the return flow stream (Table 1). Typical water quality ponds were designed with a narrow sedimentation cell to remove the majority of TSS before water flowed into a larger vegetated pond. The sedimentation cells were approximately 10 m wide, 40 to 150 m long, and 1 to 1.5 m deep to allow an excavator to periodically (typically annually) remove accumulated sediment. The type and amount of vegetation varied among the ponds depending on the age of the pond and how much vegetation was transplanted when the pond was constructed. Water flowed through these ponds continuously during the irrigation season. The Cedar Draw and S Coulee ponds continued to receive water from subsurface drainage after the irrigation season.

Pond inflow and outflow were sampled for three consecutive days during May, July, and September of 2008. Water stage (depth) at the inlet and outlet of each pond was measured at 15-min intervals with pressure transducers connected to data loggers to estimate flow rates using stage–discharge relationships for concrete structures, culverts, or open channels. Pond inflow and outflow water was sampled with automatic water samplers. Samplers collected 0.1-L subsamples each hour and composited four subsamples in

Table 1. Characteristics of the five water quality ponds monitored in 2008.

Pond	Size	Pond inflow	Retention time	Year constructed	Characteristics
	ha	$m^3\ s^{-1}$	h		
Britt	28	1.2	5	2003	sedimentation cell; dense cattail, bulrush, and pondweed in upper 25%; no vegetation on remaining area
Cedar Draw	0.3	0.3	15	1996	dense bulrush in upper 65% of pond; no vegetation on remaining area
Malone	13	0.2	10	2001	sedimentation cell, cattail, and bulrush near the inlet; floating and Sago pondweed on pond perimeter
S Coulee	0.9	0.5	5	2006	sedimentation cell; little vegetation
Perrine	0.1	0.1	2	2005	cattail, bulrush, and floating and Sago pondweed throughout the pond

one sample bottle, so each 0.4-L water sample represented a 4-h period. The same processing and analytical procedures (all samples run in duplicate) were used for pond samples as irrigation return flow samples (see above). Flow rate estimates for pond inflow and outflow were based on stage–discharge relationships with a limited range of values and provide only coarse flow rate estimates. Therefore, sediment and nutrient mass balances were not calculated for the water quality ponds. Pond surface areas and volumes were calculated from survey data collected with a GPS survey instrument. Approximate retention times for each pond were estimated by dividing average inflow rate by pond volume.

All data from the water quality pond study were tested for normality using the univariate procedure in SAS (SAS Institute, 2008). Pond inflow and outflow concentrations were analyzed using the MIXED procedure of SAS in two different ways. First, nutrient and sediment data from each pond were analyzed with sample location (inflow or outflow) and sample time as fixed effects and month as a random effect. Second, overall nutrient and sediment data from all ponds were combined and analyzed with sample location and sample time as fixed effects and month as a random effect. Statements of statistical significance were based on $P < 0.05$.

The S Coulee pond was constructed in August 2006 approximately 150 m upstream from a primary CEAP monitoring site, which enabled comparison of TSS and P loads before and after construction. Flow at this CEAP monitoring site was measured with a weir, and water samples were collected with an automatic sampler. Weekly concentrations and loads at this site were compared before and after pond construction with the Mann–Whitney U-test because the data were not normally distributed. Sediment and DP concentrations and loads were compared for two different time periods: (i) January to March when only water from subsurface drains flowed into the pond and (ii) June to July when sediment concentrations were greatest from furrow irrigation runoff.

Results and Discussion

Water Quality and Nutrient Loading in the Upper Snake Rock Watershed

The largest impact on hydrology and water quality in the USR watershed was diverted irrigation water from the Snake River, which accounted for approximately 80% of the water input into the watershed (Bjorneberg et al., 2008). Rock Creek, an ephemeral stream that originates in the mountains to the south of the watershed, was the only other water source flowing into the watershed and contributed <2% of the total water. Annual precipitation contributed 15 to 20% of the total water input to the watershed (Bjorneberg et al., 2008). Rain events were typically <10 mm and seldom caused runoff. From 2005 to 2008, only six precipitation events exceeded 20 mm at the Twin Falls, Idaho AgriMet site (USBR, 2014). Five of these events occurred in 2005 when precipitation was 20% greater than the annual average of 270 mm. Only 15 precipitation events were 10 to 20 mm.

Approximately 40% of the total water that entered the watershed as irrigation and precipitation returned to the Snake River via the irrigation return flow system (Table 2). Many return flow streams flowed only during the irrigation season, whereas others flowed all year due to subsurface drain tiles and tunnels. On average, water diverted from the Snake River annually supplied 547 kg ha^{-1} of TSS, 1.1 kg ha^{-1} of TP, and 0.50 kg ha^{-1} of DP to the watershed (Table 2). Irrigation return flow contributed 414 kg ha^{-1} of TSS, 0.71 kg ha^{-1} of TP, and 0.32 kg ha^{-1} of DP back to the Snake River. In 1971, Carter et al. (1974) measured 1380 kg ha^{-1} of TSS, 1.1 kg ha^{-1} of TP, and

Table 2. Total suspended solids, total phosphorus, and dissolved phosphorus loads and flow-weighted concentrations flowing in to and out of the Upper Snake Rock watershed.

	Year	Flow	TSS†	TP	DP	TSS	TP	DP
		mm	kg ha^{-1}			mg L^{-1}		
Inflow	2005‡	1149	327	1.01	0.88	28	0.09	0.08
	2006	1269	537	1.00	0.47	42	0.08	0.04
	2007	1249	443	1.31	0.56	35	0.11	0.04
	2008	1384	662	1.03	0.47	48	0.07	0.03
	average§	1301*	547 (ns)¶	1.11*	0.50 (ns)	42*	0.09*	0.04*
Return flow	2005‡	428	419	0.64	0.36	98	0.15	0.08
	2006	667	591	0.89	0.38	89	0.13	0.06
	2007	523	307	0.72	0.28	59	0.14	0.05
	2008	515	344	0.53	0.30	67	0.10	0.06
	average§	568	414	0.71	0.32	71	0.12	0.06
Difference	2005‡	720	−92	0.37	0.51			
	2006	602	−54	0.11	0.08			
	2007	726	136	0.59	0.28			
	2008	869	318	0.50	0.16			
	average§	733	133	0.40	0.18			

* Significant difference between inflow and return flow at the 0.05 probability level.

† DP, dissolved P; TP, total P; TSS, total suspended solids.

‡ Monitoring began in May 2005, so total loads represent only 8 mo.

§ Average values only include 2006 to 2008.

¶ Nonsignificant differences between inflow and outflow loads and concentrations.

0.31 kg ha^{-1} of DP returning to the Snake River via return flows from May to September. Return flow contained considerably more sediment in 1971 when 95% of the watershed was furrow irrigated, resulting in a net loss of 460 kg ha^{-1} TSS. Based on current observations, 65% of the crop land is furrow irrigated, and the remaining 35% is sprinkler irrigated. Although TSS losses were greater in 1971, DP losses were similar to the current study. The trend in 2007 and 2008 was that more TSS and TP were supplied to the watershed than returned to the Snake River (Table 2), indicating that conservation practices (e.g., converting from furrow to sprinkler irrigation and water quality ponds) have reduced losses from the USR watershed.

Significantly greater TP flowed into the watershed than returned to the Snake River, based on annual inflow and return flow loads (Table 2). There was no significant difference between inflow and return flow loads for TSS and DP. An average of 0.40 kg ha^{-1} of TP was deposited within the watershed annually, which is negligible from an agronomic perspective, but 33 Mg of TP per year was removed from the Snake River from 2006 to 2008. Even though return flow loads were similar to or less than inflow loads, annual flow-weighted TSS, TP, and DP concentrations were significantly greater in return flow than inflow (Table 2) because a large amount of irrigation water with low TSS and P concentrations was diverted into the watershed, whereas a smaller amount of water returned to the Snake River at relatively higher concentrations. Irrigating this 82,000-ha watershed removed 600 million m^3 of water (730 mm) from the river each year.

The average TSS and TP concentrations in the irrigation return flow were 71 and 0.12 mg L^{-1} (Table 2), which were greater than the TMDL limits of 52 and 0.075 mg L^{-1} for TSS and TP, respectively, for this reach of the Snake River. Average TSS and TP concentrations in the Snake River at the USGS monitoring site at King Hill (USGS-13154500, about 35 km downstream) were 18 and 0.08 mg L^{-1}, respectively. Greater concentrations in the return flow indicate that drainage from the USR watershed negatively affected water quality in the river. However, annual average return flow was 440 million m^3, or only 6% of the average annual flow in the Snake River at King Hill (7000 million m^3). The relatively small amount of return flow minimized the impact of the USR on Snake River water quality and emphasizes the need to reduce TSS and P concentrations.

Impacts on the Snake River were different during the winter compared with the irrigation season. During the winter, Rock Creek was the only source of water flowing into the watershed. Flow-weighted concentrations in Rock Creek were 0.03 mg L^{-1} TP and 0.02 mg L^{-1} DP, compared with 0.10 mg L^{-1} TP and 0.06 mg L^{-1} DP in the return flow (Fig. 2). The TP concentration in the winter-time return flow still exceeded the TMDL limit for this reach of the Snake River. Because Rock Creek had a relatively small flow and low P concentrations at the inflow, there was almost no P entering the watershed from November through March. Thus, the only source of TP and DP in return flow was the subsurface drain tunnels and tiles that flowed during the winter.

During the irrigation season, TP and DP loads were significantly greater in watershed inflow than irrigation return flow (Fig. 2), primarily due to the large amount of irrigation water flowing into the watershed. However, TP and DP concentrations were greater in the return flow, similar to annual average concentrations (Table 2). The main source of P in irrigation return flow during the irrigation season was runoff from furrow-irrigated fields. Sprinkler-irrigated fields seldom have runoff, and few precipitation events are large enough to cause runoff. During furrow irrigation, water flowing over the soil surface suspends soil particles that contain P and also may desorb P from soil particles, increasing DP concentrations in runoff (Bjorneberg et al., 2006). Because TSS losses during furrow irrigation can be large, TP concentrations are related to TSS and not soil test P concentration, as particulate P overwhelms the system (Bjorneberg et al., 2006; Westermann et al., 2001). The concentration of DP in furrow irrigation runoff is related to soil test P concentration and the amount of sediment detached by flow in irrigation furrows (Bjorneberg et al., 2006). Research investigating the transformations and transport of DP through the return flow system has suggested that DP in runoff from furrow-irrigated fields likely remains in the water until it returns to the Snake River (Ippolito and Nelson, 2013).

The loss of P from furrow-irrigated fields will vary depending on crop type and field slope. A 1978 study in this watershed documented annual TP losses from 30 furrow-irrigated fields of <0.3 to 130 kg ha^{-1}, with the greatest losses occurring on corn, dry bean, and sugar beet fields with slopes >2% (Berg and Carter, 1980). The smallest losses occurred on fields with close-seeded crops like barley, wheat, or alfalfa, regardless of slope. Annual

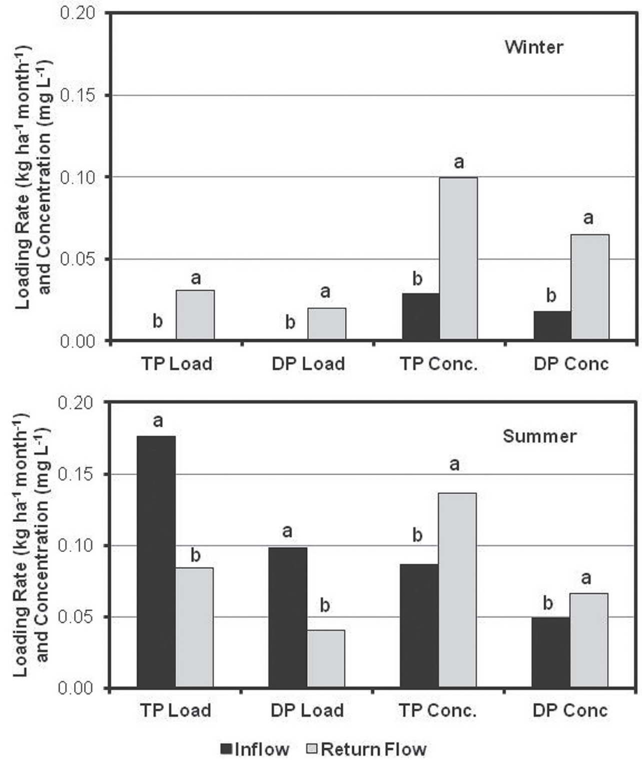

Fig. 2. Average total phosphorus (TP) and dissolved phosphorus (DP) loads and concentrations flowing in to and out of the Upper Snake Rock watershed during the winter (Nov.–Mar.) and summer (Apr.–Oct.) for 2005–2008. Columns with different letters indicate a significant difference (P < 0.05) between inflow and return flow.

DP losses were <0.02 to 1.7 kg ha^{-1} and were <10% of TP losses for 25 of the 30 fields. By comparison, average DP concentration was 45% of the TP in watershed inflow and irrigation return flow (Table 2), indicating that furrow irrigation runoff was diluted or that particulate P was removed before water returned to the Snake River.

Management Practices to Reduce Sediment and Nutrient Loading in the Return Flow System

Converting from furrow irrigation to sprinkler irrigation or changing cropping systems can reduce TSS and P losses from irrigated fields. For fields that continue to be furrow irrigated, erosion can be reduced 60 to 90% by applying anionic water-soluble polyacrylamide (PAM) with irrigation water (Lentz et al., 1992; Lentz and Sojka, 2009; Trout et al., 1995). Lentz et al. (1998) showed that PAM application during furrow irrigation reduced cumulative TSS and TP losses 90% and DP loss 85% compared with untreated furrows during four irrigations on a dry bean field. The effects of PAM in farmers' fields are usually less dramatic than in research plots because farmers typically do not carefully control furrow inflow rates and only apply PAM during one or two irrigations.

Sediment and P that enter the irrigation return flow system can be removed when the water flows through constructed water quality ponds. Average TSS concentrations were significantly less in water flowing out of the five ponds that were monitored for this study (Table 3). Average TSS reductions were 36 to 75% for each pond. Inflow TSS concentrations ranged from 4 to 240 mg L^{-1} and outflow concentrations ranged from 1 to 125 mg L^{-1} during all monitoring periods (data not shown). Overall average TSS concentration for all ponds decreased 57%, from 51 to 22 mg L^{-1} (Table 3). Relative TSS concentration reductions were similar to previous studies in the region with nonvegetated ponds that received water with 240 to 1000 mg L^{-1} of TSS (Brown et al., 1981; Robbins and Carter, 1975). Two of the ponds (Cedar Draw and Perrine) had significant reductions in TSS concentrations even though the inflow sampling locations were after the sedimentation cells for these ponds. Inflow concentrations in these two ponds tended to be less than the other ponds, indicating that the sedimentation cells removed some TSS, but additional reductions still occurred in the larger vegetated pond.

Average TP concentration significantly decreased by 13 to 42% in all ponds, and the overall average reduction was 27%, which was less than the relative reduction in TSS concentrations (Table 3). Average DP concentrations in pond inflow were <0.1 mg L^{-1} and significantly decreased 7 to 16% in all but the Perrine and Cedar Draw ponds (Table 3). Overall average DP concentrations for all ponds decreased only 7% from 0.058 to 0.054 mg L^{-1}. The short retention times in these ponds likely reduced the opportunity for soluble nutrients to be removed. Similarly, Leytem and Bjorneberg (2005) previously reported little change in DP concentrations in two water quality ponds within the irrigation return flow system.

Greater reductions in TSS and TP concentrations compared with DP concentrations indicate that the decreases in total P were due to decreases in sediment-bound P. Total suspended solids and TP concentrations in pond inflow were directly correlated ($P < 0.01$), with r^2 values of 0.44 to 0.85 for each pond and 0.82 overall. The TSS concentrations in pond outflow were also significantly correlated ($P < 0.01$) with TP concentrations for all ponds ($r^2 = 0.28–0.82$) except Cedar Draw. The DP/TP ratio was greater in pond outflow compared with inflow (Table 3), further indicating that TP reductions resulted from sediment-bound P being removed in the ponds.

One of the USR return flow monitoring sites was located 150 m downstream from the S Coulee ponds. Data from this sited showed a dramatic decrease in TSS loading rate during the summers of 2007 and 2008 after the installation of the pond in August 2006 (Fig. 3). However, DP loads downstream of the pond were similar before and after construction. The DP and TSS loading rates peaked in the summer when furrow irrigation runoff was the greatest. Dissolved P and TSS loading rates were relatively low during the winter when only water from subsurface drains flowed through the S Coulee ponds.

Table 3. Average inflow and return flow concentrations of total suspended solids, total phosphorus, and dissolved phosphorus for the three monitoring periods for the five water quality ponds monitored in 2008.

Pond	Location	TSS†	TP	DP	DP/TP ratio
		mg L^{-1}			
Britt	in	52.9*	0.12*	0.058*	0.50*
	out	13.1	0.07	0.054	0.79
Cedar Draw	in	25.9*	0.11*	0.083 (ns)‡	0.77*
	out	6.8	0.10	0.077	0.83
Malone	in	100.4*	0.22*	0.080*	0.40*
	out	43.8	0.14	0.069	0.53
S Coulee	in	84.0*	0.15*	0.034*	0.23*
	out	40.3	0.10	0.029	0.28
Perrine	in	22.3*	0.08*	0.038 (ns)	0.53*
	out	14.2	0.07	0.040	0.68
Average	in	50.9*	0.13*	0.058*	0.51*
	out	22.1	0.09	0.054	0.63

* Significant difference between inflow and outflow at the 0.05 probability level.

† DP, dissolved P; TP, total P; TSS, total suspended solids.

‡ Nonsignificant differences between inflow and outflow concentrations.

There were two exceptions (Dec. 2006 and Feb. 2008) when winter precipitation events caused excessively high DP concentrations for one sample interval each.

A comparison of TSS loading rates and concentrations downstream of the S Coulee ponds in June–July showed significantly less TSS in 2007 and 2008 compared with 2006 (Table 4). The DP loading rate was significantly lower in 2007 compared with 2006 because the flow rate in S Coulee was less in 2007. However, DP concentrations were not significantly different in the summer. During the winter period, TSS and DP concentrations were not significantly different before and after the ponds were constructed.

Because the water quality ponds had minimal effect on DP concentrations, which in some instances exceeded the TMDL thresholds for TP (0.075 mg L^{-1}), additional management practices have been investigated to remove DP from the return flow system. Leytem and Bjorneberg (2005), using laboratory and field studies, investigated the use of alum to reduce TP and DP from return flow systems. Laboratory studies using river water demonstrated that up to 67% of DP could be removed with an application of 40 mg L^{-1} of alum. In the field, alum was continuously applied to inflow in water quality ponds to test the effectiveness in continuously flowing water. An application rate of 45 mg L^{-1} reduced TP concentration by 98% (a 50% greater reduction than without alum application) and DP concentration by 95% in a water quality pond with inflow TP and DP concentrations of 0.55 and 0.16 mg L^{-1}, respectively. Based on modeled field data, a 53% reduction in DP could be achieved with an alum application rate of 20 mg L^{-1}. Although this would be cost prohibitive for treating all return flow in the USR watershed, alum could be applied to specific return flow streams with high DP concentrations during summer periods when concentrations are greatest.

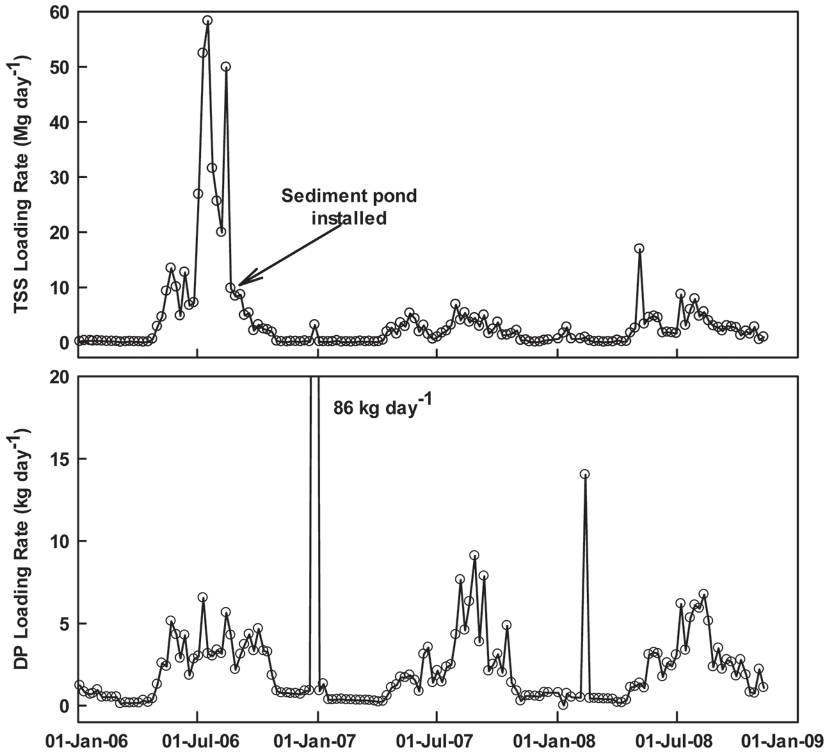

Fig. 3. Total suspended sediment (TSS) and dissolved phosphorus (DP) loading rates at a return flow monitoring site 150 m downstream from the S Coulee ponds.

Conservation practices implemented in the USR watershed have reduced TSS and TP losses from the watershed. The trends in 2007 and 2008 indicated that there was net deposition of TSS in the watershed, which was a major change from 1971, when there was a net loss of 460 kg ha^{-1} TSS (Carter et al., 1974). From 2005 to 2008, irrigation water supplied significantly more TP to the USR watershed than was returned to the Snake River with irrigation return flow. The TSS, TP, and DP concentrations, however, were significantly greater in return flow than inflow. Improved irrigation water management at the field and watershed scale will reduce TSS and P loads returning to the Snake River but may not reduce TSS and TP concentrations to below the TMDL limits. A combination of practices, such as applying PAM with furrow

Table 4. Median water flow, loading rates, and concentrations of total suspended solids and dissolved phosphorus before (2006) and after (2007 and 2008) construction of S Coulee ponds. Water flowing in the coulee contained runoff from furrow irrigated fields during June–July and only subsurface drain flow during January–March.

Sampling period	Flow	Loading rate		Concentration	
		TSS†	DP‡	TSS	DP
	m^3 d^{-1}	Mg d^{-1}	kg d^{-1}	mg L^{-1}	
June–July					
2006	53,900	11	3.0	150	0.06
2007	39,300*	2.5*	1.8*	60.0*	0.04
2008	52,700	3.9*	3.1	66.0*	0.05
Jan.–Mar.					
2006	17,700	0.17	0.53	9.9	0.03
2007	17,100	0.10*	0.34	6.2	0.02
2008	21,700*	0.37	0.43	20.	0.02

* Significantly different from 2006 at the 0.05 probability level.

† Total suspended solids.

‡ Dissolved P.

irrigation, converting from furrow irrigation to sprinkler irrigation, installing water quality ponds, and applying P-sorbing materials, will be needed for irrigation return flow to meet TMDL limits for TSS and TP.

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