Report for 2001ID4561B: Phosphorus Source/Sink Dynamics in a Flood-Irrigated Agricultural System

- Conference Proceedings:
  - Sánchez, M., D. Davidson, E.S. Brooks, S.M. McGeehan, J. Boll. 2000. Estimation of phosphorus loading from irrigated pasture land to Cascade Reservoir in central Idaho. Presented at the 2000 PNW-ASAE Regional Meeting, Sept 21-23, Paper 2000-08, ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659, USA.
  - Davidson, D, J Boll, S.L. McGeehan. 1999. Assessing BMP Effectiveness in Reducing Phosphorus Loading in Irrigated Pastures. "Water Quality - Beyond 2000", Boise, ID, Jan 27-29, 1999.
- Other Publications:
  - Article in Long Valley Advocate, September 30, 1998.

Report Follows:

PROBLEM AND RESEARCH OBJECTIVES:

Water quality protection through restoration and management of watersheds is receiving tremendous attention in the United States at all levels of government and in local communities. Since contributions of most point sources (e.g., sewage treatment plants and industrial sites) have been reduced to acceptable levels, the main emphasis presently is on the control of non-point sources originating from urban, forest, agricultural, and recreational lands. Non-point sources are covered by sections 208, 303(d) and 319 of the Clean Water Act. Approximately 1000 water bodies are currently classified as impaired or use-limited in Idaho.

Many water bodies are classified as P-limited due to their high nitrogen:phosphorus ratios (N:P >> 10) (Sharpley et al., 1994; Chapra, 1997). Consequently, water pollution abatement strategies frequently focus on reductions in P loading. State and local agencies throughout the U.S. are in the process of setting permissible load allocations, expressed as Total Maximum Daily Load (TMDL), and developing water quality management plans for all use-limited water bodies. A management plan for Cascade Reservoir in central Idaho was submitted to and approved by the Environmental Protection Agency (EPA) in January of 1996.

Prior to the development of this plan, water quality data were collected at different levels of comprehensiveness for forest, urban and agricultural land uses. Partitioning the total P load into the various land uses was a difficult and somewhat subjective process. In particular, P loading from agriculture, mainly flood-irrigated pasture and hay land, was not done very accurately due to limited monitoring data and the lack of representative model parameters. The agricultural P load is currently estimated to be ~15,800 kg P/yr or 44% of the annual P load to the reservoir. This value is determined from the area-weighted difference between the estimated total nonpoint load (~35,700 kg P/yr) and estimates for natural (~11,000 kg P/yr), forest (~5,900 kg P /yr) and urban sources (~3,000 kg P/yr). Clearly, better estimates of phosphorus (P) loading from agricultural land use in western states are needed.

Although P loading has received considerable attention in the research literature in the past two to three decades, annual estimates of P loading from subsurface/flood or sprinkler irrigated pasture land have not been reported. Many reports available on non-irrigated pastures are mostly applicable to soils in the eastern and midwestern portions of the United States (e.g., Edwards et al. 1996; Austin et al. 1996; Beaulac and Reckhow, 1982; Loehr, 1974; Harms et al., 1974). Miller et al. (1984) reported net loss of P from flood irrigated grass and alfalfa hay land in Nevada, but measurements only covered the irrigation season, ignoring P loading during spring snowmelt.

Several studies show that loading from nonpoint P sources is seasonally dependent, a fact not addressed in the current Cascade Reservoir load allocations. Given the inherent uncertainties associated with estimating nonpoint P sources, it seemed critical to pursue an improved assessment of the agricultural contribution. This study contributes to this need by documenting relationships between P loading and field parameters. It is hoped that this study will 1) provide a more accurate value for agricultural P loading in the Cascade Watershed and 2) provide information that will be transferable to other agricultural regions in the western United States. The relationships in this study are developed from direct measurement of flow volumes and soil-water P concentrations monitored throughout the year to determine seasonal P dynamics.

Objectives

The overall objective of this proposal is to develop seasonal P source/sink relationships for irrigated pastures. P source/sink relationships are compared during *i)* spring snowmelt and rain-on-snow events, and *ii)* the growing season which is characterized by subsurface irrigation.

Source/sink relationships are determined by measuring enrichment ratios, extraction coefficients, P desorption in soil/sediment samples and dissolved (DP), particulate (PP), and total (TP) in water samples.

Specific objectives in this study were:

Objective 1. To determine surface and sub-surface P inputs and outputs on a seasonal basis for two subsurface irrigated pasture/hay fields.
Objective 2. To measure P desorption as a function of soil depth, total soil P, soil temperature and soil saturation history in the same fields as in Objective 1.
Objective 3. To develop seasonal P transport relationships for dissolved and particulate P and predict annual P loading.
Objective 4. To determine the dynamics of P transport beyond pasture fields in irrigation ditches.

Important questions we attempt to answer are: "What are the relative magnitudes of P sources from agriculture in the Cascade Reservoir watershed?", "What time of year do these sources release the greatest P loading?", and finally, "When is the impact of an individual source noticeable in downstream aquatic ecosystems?".

Note: During Year 1, we experienced unusual weather conditions, which made data collection during part of the Spring snowmelt period difficult. In order to assure meaningful results in this project, we initiated a laboratory flume study to simulate flow conditions observed in the field. This laboratory study will be discussed in this report. Objective 2 was partly achieved during the laboratory study instead of in the fields because Dr. McGeehan no longer holds a research position in the Soils Department. Specific hypotheses for the laboratory study are provided in the Methodology section below.

METHODOLOGY:

Location and Description of Study Area

Geological and Hydrogeological Setting

Cascade Reservoir watershed is located in Long Valley, which is part of the mountain building Idaho batholith orogeny occurring during the Cenozoic period. The parent material consists of crystalline igneous granitic intrusive rock formations with other accessory minerals. The valley floor consists of deposits derived from the adjacent mountain with past glacial activity present in the upper portion of Long Valley. The thickness of the alluvial deposit is estimated at over 7000 feet in the north end of the watershed with the thickness decreasing as the valley trends to the south.

Streams in the watershed have gradients which vary from very steep in the mountains to flat as they move towards the reservoir. Stream flow is made up of spring melt off of valley and mountain snows, storm events on snow, overland flow and base flow from ground water. Generally, two melting events occur in the watershed when the valley floor has an early melt during March -April and the higher elevation areas a late season melt in June - July. The water from the streams is diverted for land application during the summer irrigation season through a complex system of diversions, canals and laterals. Stream flow during the summer irrigation season is depleted to very low levels. Vegetation in subsurface irrigated pastures have been altered toward hydrophilic (water loving) species thereby altering vegetative water requirement and producing an artificially high water table. Because of the low flow levels and the artificially high water tables, ground water - surface water interaction is believed to occur throughout the irrigation season. Approximately 150 mm of precipitation is received during the growing season in the valleys.

Ground water in the valley is present at multiple depths. Areas with extremely shallow ground water are abundant due to high input of irrigation water and shallow confining layers. Deep confined aquifers exist within the valley but have largely been undeveloped except by some municipalities. Ground and surface water are of good quality except for the existence of reduced iron oxides Fe(III) near the Donnelly-Roseberry region.

Agricultural Setting

Land use within the Cascade Reservoir watershed primarily consists of forest, agriculture and urban/suburban. Steep sloping mountain ranges make up the adjoining forested land, while the flat valley floor adjacent to the reservoir is used for agriculture. Small tracts of land are used for housing development, subdivisions, villages and towns. The agricultural land uses are irrigated pasture, irrigated cropland, non-irrigated pasture and cropland, and private forest. Irrigated lands are the dominant land use type within the valley with irrigated pasture being the dominant agricultural land use. Riparian and non-irrigated pasture make up the majority of the remaining land.

Cattle are the dominant grazing animals with a small amount of sheep and horses also present. Most animals are located in the valley only during the summer grazing season which starts in early May and may run through October - November.

The Study Area

The study area is located in the Boulder/Willow Creek watershed, a subwatershed of the North Fork Payette River in Valley County, Idaho. Irrigation water is taken from the Roseberry ditch, a diversion of Boulder Creek and delivered to Willow Creek, which drains directly into Cascade Reservoir. Cascade Reservoir is on the 303(d) list as an impaired water body due to eutrophication. A TMDL for phosphorus has been in place since 1999.

Elevation at the study site is approximately 1495 m above sea level. The valley floor has little relief (1-4%) sloping from north to south. Average temperature at this site is 5°C with an average of 72 frost-free days, and the average precipitation is 584 mm. The field is composed of two soil types: the Roseberry [*mixed Humic Cryaquepts*], a sandy, deep poorly drained medium acid soil, and the Donnel [*mixed Typic Cryumbrepts*], a coarse-loamy, deep and well drained medium acid soil. Roots in these soils extend to more than 1.5 m.

The study site consisted of two pasture fields. These fields are labeled Field 1 (~18 ha) and Field 2 (~15 ha) (see Figure 1). Currently, both fields are used as grazing pastures for beef cattle without addition of feed or fertilizer. Cattle graze the fields only from May or June through October. The irrigation technique used in Fields 1 and 2 consisted of flood irrigation, with one main inlet ditch and one main outlet ditch (Figure 2). In 2001, this irrigation technique was changed to sprinkler irrigation in Field 2. Flood irrigation consists of diverting water into small feed ditches starting at the head of the field. Water infiltrates the soil and raises the water table to the soil surface. A small collection ditch at the bottom of the field channels water away from the field. Typically, the fields receive irrigation water from the supply ditches for five to seven days.

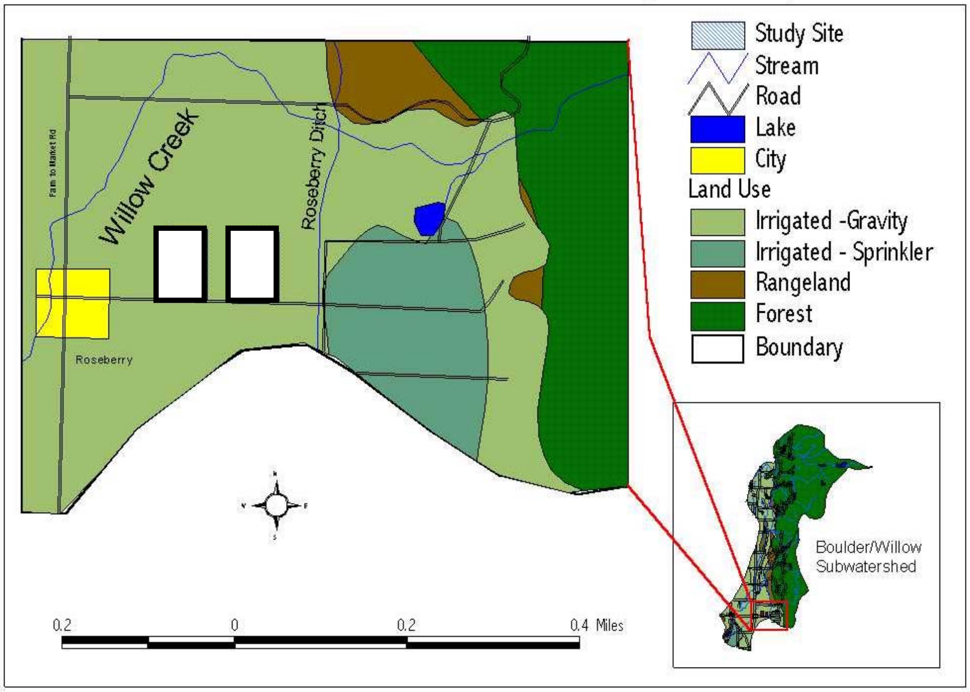

Figure 1. Location of Study Area in the Boulder/Willow Creek subwatershed (see inset) in Valley County, Idaho. The rectangles identify Field 1 and Field 2.

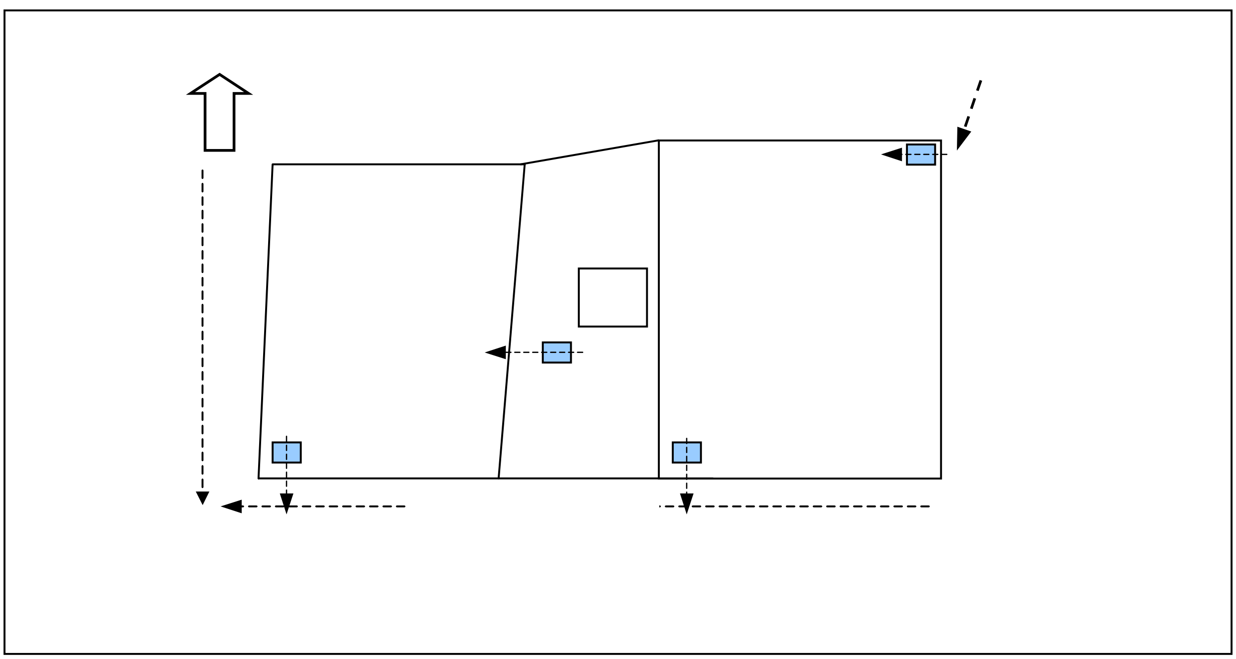

Figure 2. Schematics of the fields (Field 1 ~ 18 ha; Field 2 ~ 15 ha) showing the well locations (filled circles) and the inlet and outlet flumes. Irrigation water comes from Boulder Creek-Roseberry Ditch at the north-east. Willow Creek discharges south into Cascade Reservoir.

Predictive Equations and Parameter Selection

Due to limited funds, P source/sink relationships for P loading are determined for three forms: TP, PP and DP (see Table 1). Predictive equations have been reported in the literature and are reviewed briefly to show which parameters are to be estimated and which water quality constituents are measured in our study. These equations serve as a starting point for the data analysis.

PP in runoff sediments: As soil erosion is a selective process with respect to particle size, selectivity has been observed for P loss in runoff sediments, with the result that eroded soil is usually richer in P than the surface soil from which the eroded soil comes (Sharpley, 1980). Particulate P transport, therefore, is predicted from an equation of the form (Edwards et al., 1996):

$$PP = TSS_y \times \text{Soil TP} \times ER \qquad (1)$$

where PP is the (event) particulate P transport (kg/ha), TSS_y is the event total suspended sediment yield (kg/ha), Soil TP is the TP content of the surface soil (kg/kg), and ER is the enrichment ratio (= PSED/Soil TP where PSED is the TP content of eroded soil). We assume that the use of TSS_y for total sediment yield is reasonable for pasture land (Edwards et al., 1996). Sharpley (1980) developed a relationship between ln(ER) and $\ln(TSS_y)$ as:

$$\ln(ER) = a_0 + a_1 \times \ln(TSS_y) \qquad (2)$$

where coefficients a_0 and a_1 appear to vary with soil and land use with approximate values of 2.2 for a_0 and -0.24 for a_1 representing a variety of soil and cover conditions.

DP in runoff water: A general, predictive equation for DP in runoff water is as follows (Edwards et al., 1996):

$$DP = 0.01 \times D \times \text{Soil TP} \times XC \qquad (3)$$

where DP is (event) soluble P transport (kg/ha), D is event runoff (mm) and XC is an extraction coefficient considered to represent the mixing of soil and runoff as well as the P desorption properties of the soil. The factor 0.01 assures consistent units. High runoff interaction and easily desorbed soil P would be reflected in an increase in XC.

To develop and test above relationships for subsurface irrigated pastures, we are determining all parameters in Eqns. 1- 3 either by direct measurement or derived from measured parameters. Exceptions are a_0, a_1, and XC, which are determined by regression analysis. Table 1 summarizes the parameters measured and derived, and includes abbreviations used throughout this section of the report.

Table 1. Measured and calculated parameters in the proposed study and abbreviations used.

Parameter	Abbreviation	Measured/Derived	Origin
runoff depth	D	derived	measured discharge (Q)
total P	TP	measured	runoff water
dissolved P[1]	DP	measured	runoff&subsurface water
particulate P	PP	derived	runoff water: TP - DP
total suspended solids	$TSS_{y\ or\ l}$	measured	runoff water
total P in soil	soil TP	measured	surface soil in field
enrichment ratio	ER	derived	runoff water & soil: $TP_{eroded\ soil}$/soil TP
a_0 & a_1	-	derived	Eqn. 2 (regression)
extraction coefficient	XC	derived	Eqn. 3 (regression)

[1] dissolved P is assumed to consist mostly of ortho-phosphate (Sharpley et al., 1994).

Field Instrumentation and Data Collection

Surface Water

Each inlet and outlet ditch in Field 1 and 2 was instrumented with a circular flume (Samani et al., 1991), a CR10X data logger (Campbell Scientific, Inc., Logan, Utah), and an ISCO model 3700 water sampler (ISCO, Inc, Lincoln, NE). All equipment was placed in an insulated wooden housing with kerosene heaters during the first two years and propane heaters during the third year. Locations of inlet and outlet are shown in Figure 2.

The circular flumes at the inlet consisted of a 45 cm (18 inch) diameter corrugated plastic pipe with a 7.5 cm (3 inch) diameter PVC stilling well, placed 90 cm from the inlet. At the outlet, two flumes were installed side by side, one of similar dimensions as at the inlet, the other consisting of a 25 cm (10 inch) diameter PVC pipe with a 5 cm (2 inch) diameter PVC stilling well, placed 90 cm from the inlet. In all flumes, a float was suspended from a chain in the stilling well using a counter weight. Water levels were recorded every 15 minutes using a potentiometer connected to the data logger. The water level was directly related to discharge using the following relationships (1) $Q\ (L/min) = 0.0484 \times (h)^{2.021}$ for the 45 cm pipe and (2) $Q(L/min)=0.0484 \times (h)^{2.124}$ for the 25 cm pipe (Samani et al., 1991) where h is the head stage in mm. The circular flume design was pre-tested in the Hydraulics Laboratory at the University of Idaho to confirm the above relationships. Due to high standing water in both outlet locations in Spring, 1999, the equipment in both fields was removed from March 10 through April 20 when automated sampling was resumed. Spring flow in Field 2 had ceased at this time.

Water samples were collected on a flow proportional basis using the ISCO water sampler, which was connected to the CR10X data logger. If the water level changes in the stilling well remained within 1 cm per 15-minute interval, one full water sample of 500 ml was obtained every 24 hours consisting of four 6-hour composites. If the water level change was equal to or greater than 1 cm per 15-minute interval, one full water sample was obtained every hour consisting of four 15-minute composites. Water samples were retrieved after a snowmelt event or irrigation event was completed. Upon retrieval of water samples, grab samples also were taken.

Groundwater

Nine groundwater wells (5 cm (2 inch) inside diameter) were placed uniformly across each field (see Figure 2) in July 1998. Each well penetrated to the depth of a semi-impermeable layer usually found at 1.8 m below the soil surface. The wells were perforated in the bottom 30 cm, screened, and backfilled with fine sand. At the surface, each well was capped and a metal screen placed to protect them from animals. Water levels were recorded manually on a monthly basis. Water samples were withdrawn manually using a battery-powered pump. These samples were filtered on site using a 0.45 um hand-held filter. Water was removed from the well and discarded before an actual water sample was taken for analysis.

Soil and Manure

Eighteen soil samples were taken from each field before and after each irrigation season to determine total soil phosphorus, except in 2000 when eight samples were taken from each field. One set of soil samples was taken in May 2000 from three locations in each field at depths of 1, 2, 3, 5, 10, 20, 40, 60, 80, and 100 cm to determine total soil phosphorus. In addition, at one time in 2000, three soil samples were taken to a depth of 30 cm from three different locations in each field to determine the soil bulk density using the saran method (Brasher et al., 1966). These samples consisted of soil clods (approximately 4 cm in diameter) that were analyzed in triplicate to insure accurate bulk densities. After the irrigation season in 2001, an additional group of samples was taken to determine trace metal content of Fe, Al, and Mn. Three manure samples were collected in 2001 for analysis of total phosphorus content.

P desorption determination

P desorption was determined on 48 soil samples taken from field 1 and 2. The procedure is explained below in Analytical Methods. Twenty-four samples were analyzed after air-drying and 24 samples were analyzed at field-moisture content.

Seasonal P transport relationships and annual P loading

PP was determined as the difference between TP and DP. ER was calculated as the ratio of PP in eroded soil to TP in soil samples. The parameters a_0 and a_1 in Eqn. 2 then were determined by applying simple linear regression to TSS and ER. Values for XC in Eqn. 3 were determined from measured data of D, Soil TP and DP in runoff water. Annual TP loading (mg P ha^{-1} yr^{-1}) was estimated using measured TP in runoff water and the discharge measurements.

The dynamics of P transport beyond pasture fields in irrigation ditches.

Six locations were selected for ditch sampling: locations #1 and #2 were before the inlet to field 2, locations #3 and #4 were the inlet and outlet of field 2, respectively, and locations #5 and #6 were after the outlet of field 2. The established flow path connected Roseberry Ditch to Willow Creek. Measurements at each location included the determination of flow rate and P concentrations during one irrigation event on September 7, 1999. Each location was visited twice. Unfortunately, irrigation was ceased for the year afterwards and natural events have not occurred since. Two of Dr. Boll's graduate students and Mr. Davidson performed the sampling.

Flow rates in irrigation ditches were determined as the product of cross-sectional area (m^2) and velocity (m/s). Flow velocity (v) was determined using a portable current meters using the Velocity-Area method. During each visit, a sample for P determination was collected using depth-integrated sampling procedures outlined in Edwards and Glysson (1988). Where waters were of sufficient depth, the US-DH48 depth integrated sampler was used. For shallow waters, grab samples were taken at different locations in the cross-section. During this first sampling event, ditch sediments and vegatation samples were not collected.

Laboratory flume study

During Spring of Year 1 (1999), we experienced severe flooding of the fields forcing us to take out all instrumentation. During the Fall of Year 1 (1999), weather conditions did not cause runoff events. To assure data collection for specific field conditions while controlling environmental conditions, we have initiated a laboratory flume study. This laboratory study has not produced results, but the design is discussed here briefly.

The objectives of the flume study in essence were the same as for the field study. However, objective 2 was eliminated for the field study but was included partly in the laboratory study. P mobilization and transport parameters was determined in triplicate in aluminum flumes 1 m long, 0.2 m deep, and 3x0.1 m wide (Figure 3). Soils from field 1 and 2 were collected on October 10, 1999 including the undisturbed surface sod layer. Soil was packed in the flumes to the same bulk density as at the field sites. Subsurface flow, surface flow and rainfall were simulated followed by event-based sample collection. P sorption/desorption capacity were related to soil redox potential and concentration of dissolved metals to better explain chemical mechanisms controlling P mobilization. These experiments were performed by Morella Sanchez to fulfill the requirements of her Ph.D. dissertation.

To understand the outcome of the laboratory study, its relationship to field conditions is given here. Environmental conditions that occur in the Cascade area vary through the year according to temperature changes (Table 2). This determines different soil treatments and different water flow paths in the soil that are crucial to consider in the simulation of the field conditions.

Table 2. Seasonal variations affecting water flow paths and soil conditions in the Cascade Reservoir Area.

Season/Water Temperature	Water source	Water flow paths	Soil Saturation Conditions
Late summer ~15°C	Flood or sprinkler irrigation	Some flow horizontally but mostly vertically down, and then slowly back up while evaporating or transpiring.	Soil is fully aerobic. Soil is dry; it may shrink and crack, allowing air to enter lower levels.
Fall into winter ~4°C	Rain	Most water is absorbed into the soil with some surface runoff. Evaporation or transpiration is very small.	Soil experiences periods of wetness with time to drain in between.
Winter <0°C	Snow	There is not much flow. Water close to the surface may be frozen. Water deep within the soil can flow but it is not replenished.	Soil may be frozen at the surface with snow cover. Any melt due to warming on sunny days remains in the snow.
Spring >0°C	Snow melt & rain.	Big surface flows, flows into and out of the soil lenses. Evaporation is small.	Soil is saturated and has been submerged for months.
Late spring into summer >4°C	Rain or irrigation	Rainfall generally is absorbed and drains into the soil, which emerges as subsurface flow.	Soil is warming and drying with air following the retreating waters into the soil.

Water flow paths from the input source--precipitation or irrigation-- to the runoff destination are modified in nature by the seasons of the year. For example, in summer, or during dry periods, the water table remains below the surface and the runoff follows a subsurface path, unless the pasture is irrigated, and the water table rises. During this period the water is relatively warm. On the other hand, during early spring, snowmelt saturation conditions bring the water surface level to the top layer of the soil and produce an overflow runoff to the surrounding water bodies. During this period, water temperature is relatively low.

Soil conditions also cycle seasonally, as follows: 1) A dry, completely aerated, occasionally subsurface-irrigated soil observed from June through September, 2) A moist, cool soil observed during early fall in October and November, 3) A saturated soil observed during winter, and 4) a completely waterlogged soil during spring runoff after a prolonged period of saturation, in April-May. The different water flow paths through the soil, the duration of the soil saturation period, and consequently, the different degrees of interaction between water and the soil's surface layer (mixing layer) represent a set of physical and biochemical mechanisms that affect P mobility and, consequently, enhance its transport to surrounding water bodies.

The main objective of the flume study, therefore, was to characterize the physical and biochemical mechanisms that provoke P transport to adjacent water bodies. Important in this objective is the main hypothesis that P release is enhanced when (1) the mixing layer is traversed, and (2) the soil profile experiences biochemical changes after prolonged periods of water saturation. To accomplish the main objective we tested the following specific hypotheses:

- Different runoff routes, especially those taversing the P-rich-surface or "mixing layer", are chiefly responsible for the varying amount of phosphorus leaving the study site. When water traverses the mixing layer, the phosphorus concentration at the flumes outlet will be higher than when the mixing layer is not traversed.
- The release of P in any of the sampling ports of the flumes will be higher as the saturation period is more prolonged. This would be a consequence of the progression of soil saturation from water, decreases in redox potential (Eh), and increases in soil and water pH.
- The release of P will be more pronounced at higher temperatures.

Description of the Flumes

The flumes are waterproofed troughs, open on the top, and with several holes in both ends to facilitate the introduction and removal of water at various depths (Figure 3). The flumes are filled with field soil and water flows from a tank at the inlet through selected ports to selected ports at the outlet (Figure 4). A representative sample of the soil from the Cascade pasture fields was obtained to fill the flumes.

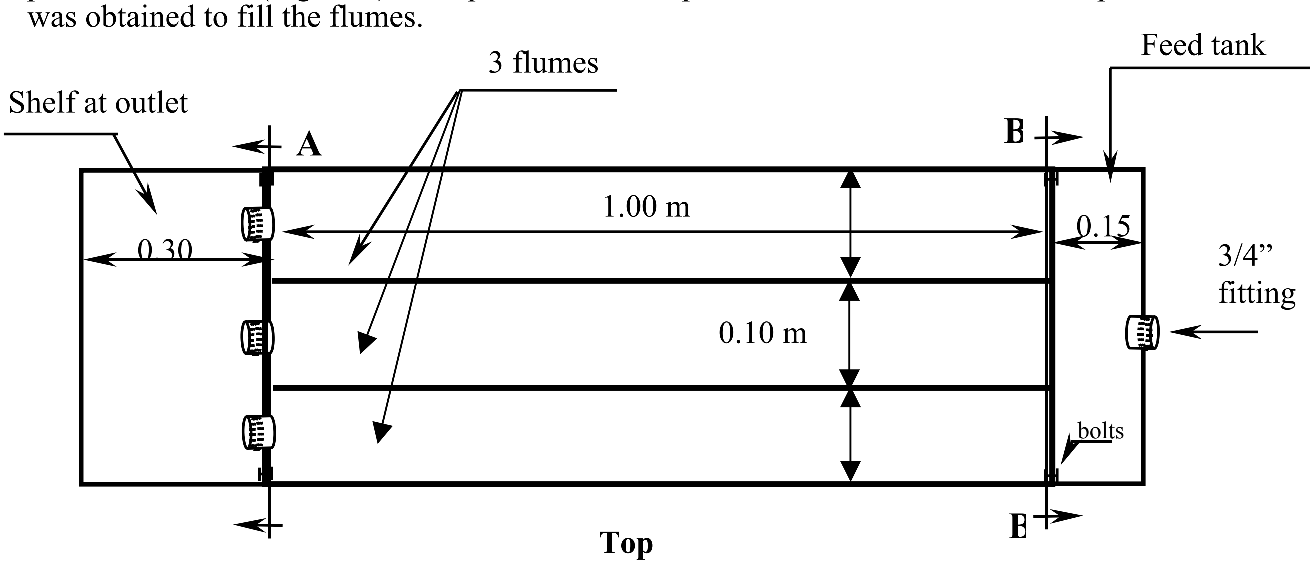

Figure 3. Top view of the flumes.

A tank was located at one end of the flume with holes at the points A, B, C, and D. Any combination of feed or water introduced through these holes was used to simulate the field environment. Water was also introduced to the soil by overflowing a level in the tank onto the surface of the soil as indicated by "A". Rainfall or sprinkler irrigation was accomplished using a rainfall simulator, and snow was applied on top during wintertime. Water was removed by overflowing at "E", via the V-notch, or by flowing out of F, G, or H.

Experiments were conducted working with two flumes at the same time. Flume 1 is the control, containing only soil and no P-enriched mixing layer on top. Flume 2 was spiked on top with a simulated P-enriched mixing layer at P concentration equal to 1000 mg/kg. This P concentration is representative of the P concentration in the top soil layers in the fields.

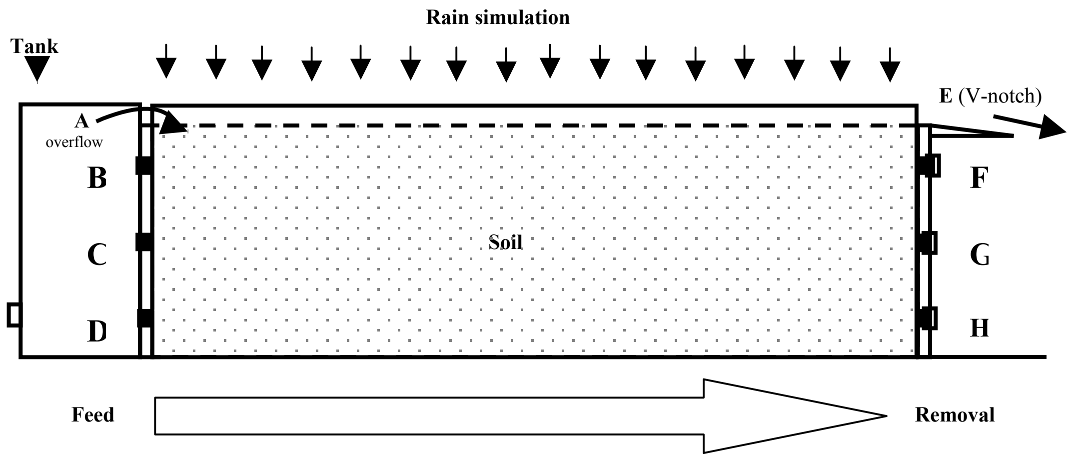

Figure 4. Side view of the flumes.

Simulations

We evaluated P release by simulations of the different seasonal-changing water flow paths and different conditions of soil saturation controlling the soil saturation period (flooding period), the method of water application, and the temperature, (Table 3 and Figure 5). The experiments were performed at two temperatures: 6°C and 25°C by using an environmental chamber. Each configuration is described as follows:

Table 3. Seasonal variations on water flow paths and soil saturation conditions in the Cascade Reservoir Area.

Season	Water source	Water flow paths
Late summer ~15°C	Subsurface flow Flood irrigation/ Sprinkler irrigation	Two phases: (1) Subsurface flow prevails because the soil is very dry and the water table is very low. (2) Water table rises after irrigation and emerges as return flow and surface runoff.
Fall into winter ~6°C	Rain	Infiltration at the beginning and later some surface runoff.
Winter <0°C	Snow	There is not flow. Water close to the surface is frozen.
Spring >0°C	Snow melting rains.	Big surface flows. Water table emerges as return flow and travels to the neighboring streams as surface runoff.
Late spring into summer >6°C	Rain or irrigation	Rainfall infiltrates into the soil as subsurface flow, and later, water table surfaces as return flow or surface runoff.

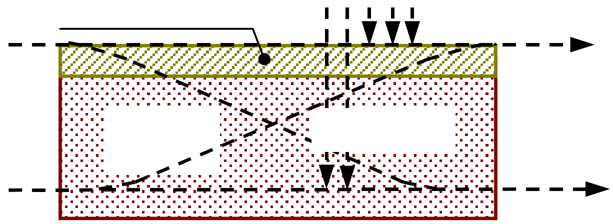

Figure 5. Physical mechanisms linked with SRP release: interaction between water (within its different routes though the soil) and the P-enriched mixing layer.

Laboratory Analyses

Sample Handling and Preservation

All water and soil samples collected at the study site were stored at –10°C (APHA 4500-P, 1995), and transported to the University of Idaho laboratories. Water samples were collected in plastic bottles that were acid washed in a 12N HCl solution and rinsed thoroughly with distilled water before use. Before filling a bottle with the sample, the bottle was rinsed three times with the water to be collected. Samples for SRP analysis were filtered immediately upon retrieval from the water sampler or after pumping from the groundwater wells, and analyzed within one day of arrival at the laboratory at the University of Idaho. Samples for TP analysis were preserved at pH < 2 (APHA 1060, 1995) adding 1mL concentrated HCL/1L, and analyzed within 20 days after collection. Eh is measured with platinum electrodes. P desorption profiles were determined using a 10-cycle sequential technique described by Oloya and Logan (1980). Cumulative desorbed P was calculated from the total P released from each sample through 10 desorption cycles. TSS (Total Suspended Solids) were determined by filtering a well-mixed sample through a weighed standard glass-fiber filter (0.4 μm) and drying the residue retained on the filter to a constant weight at 103 to 105°C (Method 2540 D in APHA, 1995). pH is measured with a standard probe attached to an Orion desktop meter. For quality control purposes, spiked samples and blanks were added to sample batches.

Phosphorus and Trace Metals in Water and Soil

Three forms of phosphorus were considered in this study: (1) Total P (TP), or total reactive P (Haygarth and Sharpley, 2000), which is a measure of phosphorus in suspended and dissolved states; (2) orthophosphate, a dissolved P (SRP) form that is readily available for biological uptake; and (3) particulate P (PP), which is the difference between TP and SRP.

Water samples filtered using a 0.45 μm pore size were analyzed for SRP. Unfiltered water samples were analyzed for total phosphorus (TP) and for total suspended solids (TSS). Table 4 summarizes the laboratory analyses performed to obtain SRP, TP, and TSS in water samples and TP and trace metals in soil. Water samples were analyzed at the Water Quality Laboratory of the Department of Biological and Agricultural Engineering at the University of Idaho with the help of Morella Sanchez and one undergraduate student trained through this project. Soil samples were analyzed by ICP spectroscopy at the Holmes Research Center at the University of Idaho.

Table 4. Methods of laboratory analysis used to determine P and trace metal content in water and soil samples.

Parameter	Method of analysis
SRP(1) in water	Ascorbic Acid Method (Murphy and Riley, 1962).
TP(2) in water	Sulfuric Acid-Nitric Acid digestion (EPA method 365.2)
TSS in water	Total Dissolved Solids Method (APHA 2540D, 1995).
TP in soil	Phosphorus, Total Colorimetric, Automated method (EPA method 3050 365.4.)
Trace metal in soil	Total Recoverable Trace Element Screen (EPA 3050/6010)

(1) SRP is defined as reactive phosphorus RP (<0.45 µm).
(2) TP is defined as total phosphorus (unfiltered) (Haygarth and Sharpley. 2000).

Standard Quality Assurance procedures were followed as outlined in the Standard Methods for the Examination of Water and Waste Water (APHA, 1995) and Standard Methods of Soil Analysis (Klestra and Bartz, 1996). All sampling and analytical procedures followed written Standard Operating Procedures. Water samples, except those for TP analysis, were filtered on site prior to transport. To address field soil variability, a series of subsamples were collected and thoroughly mixed to form a composite sample. Chemical analysis of the samples followed Good Laboratory Practices regarding sample storage, timeliness of analysis, analytical precision and accuracy, data collection and record keeping. Each analytical batch included 10% quality control samples such as duplicates, spikes, and reagent and field blanks. Determination of DP in water samples took place within 48 hours of collection and filtration in the field. TP was preserved at pH<2 using H_2SO_4 and analyzed within 24 days.

Data Analysis

Loading in Surface Water

Loading of phosphorus in surface water (i.e., for inlet and outlet) for a given event j was denoted as $SRP_{Loading,j}$, $TP_{Loading,j}$, and $PP_{Loading,j}$, respectively. The event loading calculation was as follows:

$$P_{loading,j} = \sum_{i=1}^{n} (P_{i,j} \times Q_{i,j} \times t_{i,j}) \qquad (4)$$

where $P_{i,j}$ is the SRP, TP, or PP concentration of sample i in event j, $Q_{i,j}$ is the average discharge i in event j straddling the time interval when sample i was collected, and $t_{i,j}$ is the time interval i when sample i was collected. Note that the PP concentration was the difference between TP and SRP. Subsequently, summation of $SRP_{Loading,j}$, $TP_{Loading,j}$, or $PP_{Loading,j}$, respectively, was done for all events in a season, year or the study period. Loading of TSS was calculated in a similar manner substituting TSS for P in Equation 4.

Filling in Missing Data

Missing data from flow events in Spring 1999 (equipment evacuation), Spring 2001 (leaking flumes), and Summer 2001 (no inlet concentrations in Field 2) caused an underestimation of the actual loading from the pasture fields. To provide more realistic loading estimations from this field study, these missing data were filled in as follows:

Spring 1999: SRP, TP, and TSS concentrations were assumed based on data at the outlet of Field 1 after April 20, 1999. Flow volumes were estimated in relative proportion to outflow at the outlet of Field 1 during Spring 2000 using the difference in the snow pack in both years (as recorded at the McCall weather station). From December to March 1999, a total of 400 mm of snow water equivalent were recorded at McCall, whereas during the same period in 2000, only 300 mm were recorded. Approximately 30% of the flow at the outlet of Field 1 in 1999 (recorded volume: 6605 m^3) was not recorded. Hence, the outflow was incrementing to 8587 m^3 (see Table 5). Furthermore, flow volumes in Field 2 were estimated knowing that Field 1 produced approximately 20% more surface water at the outlet station than Field 2, reflecting the difference in field area (18 ha vs. 15 ha).

Spring 2001: Since concentrations in both fields were recorded, only flow volumes needed to be adjusted. The adjustment was done proportionately with the difference in snow water equivalent recorded at McCall for 2000 and 2001: 300 mm and 125 mm, respectively (see Table 5).

Summer 2001: SRP, TP, and TSS concentrations at the inlet of Field 2 were assumed to be the same as these concentrations in Field 1 given that they had the same source water. SRP was estimated as 0.023 mg/L. In 2000 and 2001, TP and TSS were in the range of 0.041-0.069 mg/L and 14-30 mg/L, respectively--the 1999 values were not considered for estimation purposes, because in this year the P concentrations were very high and not comparable with the 2000 and 2001 values. TP and TSS concentrations were estimated as 0.051 mg/L and 20 mg/L, respectively, using a weighed average of inlet values during 2000 and 2001.

Table 5. Extrapolation of water volumes to improve loading estimation at the outlet of the pasture fields in Spring 1999 and Spring 2001.

Snowmelt event		Assumption	Water Volume (m^3)
Field 1	1999	30% of the data were not recorded	8587
	2000	Data complete	9832
	2001	Outflow was 50% lower than in 2000	4916
Field 2	1999	Volume is 20% lower than at the outlet of Field 1	6870
	2000	Data complete	8007
	2001	Volume is 20% lower than at the outlet of Field 1	3935

Calculation of ER, XC, a_0 and a_1 in Equations 1-3

All parameters in Equations 1-3 were either measured directly, or calculated from measured data. Table 6 summarizes how ER, XC, a_0, and a_1 were calculated.

Table 6. Measured and derived parameters to calculate the P transport parameters

Equation	Parameter	Measured /Derived	Origin
From Equation 1: $ER_j = \frac{PP_{Loading,j}}{TSS_{Loading,j} \times TP_{soil}}$	*PP*, particulate P	derived	runoff water: *TP* - *DP*
	TSS, total suspended solids	measured	runoff water
	$TP_{soil,}$ total P in soil	measured	surface soil in field
From Equation 2: $XC_j = \frac{SRP_{Loading,j}}{0.01 \times D \times TP_{soil}}$	*SRP*[1], soluble reactive P	measured	runoff & subsurface water
	D , runoff depth	derived	discharge (*Q*)
	$TP_{soil,}$ labile soil P	derived	Eqn. (5) & (6) in Edwards et al. (1996)
Equation 3: $Ln\ (ER) = a_0 + a_1 \times Ln(TSS_{Loading,j})$	a_0, a_1	derived	regression analysis
	TSS, total suspended solids	measured	runoff water

(1) dissolved P is assumed to consist mostly of ortho-phosphate (Sharpley et al., 1994).

Loading in Groundwater

Loading of phosphorus in groundwater was calculated as the product between the SRP concentration in groundwater by the groundwater discharge, which was estimated using the Darcy's law:

$$Q_g = -K_s \ x\ A\ x\ di/dl \qquad (5)$$

where Q_g is the volumetric discharge (m^3/sec), K_s is the saturated hydraulic conductivity (m/sec), A is the cross-sectional area of the water table perpendicular to the direction of the flow (m^2), and di/dl (m/m) is the gradient or hydraulic head derived from water level measurements (Fetter, 1999). The hydraulic conductivity was determined using the single borehole test (Maidment, 1992).

Mass Balance Calculations

Annual P mass balance calculations were made to understand the relative proportions of P input, output, and storage at the study site. The area occupied by each field defined the boundary of the control volume and the mass balance components were P_{in}, P_{out}, and $\Delta storage$. P_{in} consisted of P (kg) entering the fields in surface water during irrigation events, and in groundwater. P_{out} consisted of P (kg) leaving the field in surface water, groundwater or in cattle (only for TP mass balance calculations). $\Delta storage$ consisted of the total amount of P (kg) stored in the surface soil, which was calculated using the average of the soil TP concentrations, the average soil bulk density in each field applied to the first 10 cm of each field.

TP removed by cattle was calculated using the Phosphorus Uptake and Removal from Grazed Ecosystem (PURGE) simulation model developed to estimate P uptake by grass and retention in bodies of grazing cattle (Shewmaker, 1997). PURGE includes three methods to estimate P retention in cattle (see Appendix A for details on each method). Input variables include known, approximate, and assumed values based on measurements, literature, and the researcher's personal experience. These variables are listed in Table 7. P removal by cattle for

Equation 6 was the average of estimates from the three methods. Since cattle rotated through both fields during the grazing seasons, the estimate for Field 1 and 2 was the same.

Table 7. Input variables for the PURGE model (Shewmaker, 1997) to estimate P removal by cattle.

Method	Input variables	Constraints used
1	P digestibility (%) Yearling weight (lbs) Daily DM consumption (%) P conc. in grass (%) Stocking rate (hd-mon/ac) Area grazed (ac) Rate of gain (lb/hd-day)	70 600 2.5 0.3 1.7 45 2
2	Forage production (lb/ac) P conc. In grass (%) Ratio P removed/plant uptake (%)	4000 0.30 5
3	Total weight gain Bone growth P content in fresh bone	(result from Method 1) ~ 20% animal growth ~ 14.5 % P

The dynamics of P transport beyond pasture fields in irrigation ditches.

Six locations were selected for ditch sampling: locations #1 and #2 were before the inlet to field 2, locations #3 and #4 were the inlet and outlet of field 2, respectively, and locations #5 and #6 were after the outlet of field 2. The established flow path connected Roseberry Ditch to Willow Creek. Measurements at each location included the determination of flow rate and P concentrations during one irrigation event on September 7, 1999. Each location was visited twice. Unfortunately, irrigation was ceased for the year afterwards and natural events have not occurred since.

Flow rates in irrigation ditches were determined as the product of cross-sectional area (m^2) and velocity (m/s). Flow velocity (v) was determined using a portable current meters using the Velocity-Area method. During each visit, a sample for P determination was collected using depth-integrated sampling procedures outlined in Edwards and Glysson (1988). Where waters were of sufficient depth, the US-DH48 depth integrated sampler was used. For shallow waters, grab samples were taken at different locations in the cross-section. During this first sampling event, ditch sediments and vegatation samples were not collected.

PRINCIPAL FINDINGS AND SIGNIFICANCE:

Soil and Manure Characterization

Bulk density of the soil near the surface averaged 1.347 g/cm^3 in Field 1 and 1.276 g/cm^3 in Field 2. Average concentrations of trace metals determined in 2001 were 26,600 mg Fe /kg, 31,400 mg Al /kg, and 484 mg Mn /kg. From April 1999 to July 2001, soil TP concentrations averaged 932 mg/kg in Field 1, and 1,100 mg/kg in Field 2 (Table 8). TP concentrations with depth to 100 cm measured after the snowmelt event in 2000 were variable with a reduction in TP content below 60 cm (Table 9). TP in the soil was always higher in Field 2 than in Field 1. TP in manure was 2000 mg/kg.

Table 8. Mean and standard deviations of TP concentrations in soils in mg/kg determined from samples taken before and after the irrigation season.

Year	# samples from each field	TP mean concentration (std dev) (mg/kg)	
		Field 1	Field 2
1998	18	880 (107)	922 (169)
1999	18	892 (102)	1028 (139)
2000	8	1026 (372)	1461 (562)
2001	18	931 (99)	988 (188)
Mean 1998-2001		915 (159)	1100 (262)

Table 9. Soil TP concentrations (mg/kg) with depth up to 100 cm in Field 1 and 2.

Field	Depth (cm)									
	1	2	3	5	10	20	40	60	80	100
1	770	870	360	1400	1800	890	660	810	250	280
2	1900	1500	360	2000	2100	1100	850	820	450	690

Characterization of Discharge, and P and TSS Concentrations

Surface Water

Whether the pasture fields acted as P sinks or P sources at different times during the year depends on differences in discharge and concentration. Two examples of flow patterns with associated SRP and TP concentrations are shown in Figure 6 for an event during spring snowmelt season, and an event during the irrigation season. During snowmelt (Figure 6a), daily cycles in discharge were a result of daily temperature fluctuations. During flood irrigation in Figure 6, water was turned on one or two days prior to July 15, 2000, and it was turned off on July 20, 2000. Flow during the irrigation events was more or less continuous (Figure 6b).

Figure 6. An example of flow events and times when water samples were taken. (a) snowmelt event in April 1999 from the outlet of Field 1; (b) irrigation event in July 2000 from the outlet in Field 2.

During irrigation events, flow at the inlet was much higher than at the outlet due to effects of evapotranspiration and initial losses to subsurface storage. Discharge (m^3/s) and flow volumes (m^3) on a seasonal basis at the field outlets during snowmelt events were up to three and eight times, respectively, higher than during irrigation events. Total flow volumes at the field inlet during flood irrigation were up to 20 times higher than at the field outlet. During Spring flow, total water volumes in Field 2 were about 20% lower than in Field 1. Note that during snowmelt events, surface water did not enter the fields.

During the study period, SRP and TP concentrations at the field inlet and outlet in both fields, in many cases, were much higher than concentrations associated with surface water eutrophication (0.01 - 0.02 mg/L) (Vollenweider, 1968; Sallade and Sims, 1997). SRP concentrations at the inlet ranged from 0.014 to 0.092 mg/L in Field 1, and from 0.017 to 0.028 mg/L in Field 2. SRP concentrations at the outlet ranged from 0.040 to 1.548 mg/L in Field 1, and from 0.063 to 1.021 mg/L in Field 2. TP concentrations at the inlet ranged from 0.035 to 1.141 mg/L in Field 1, and from 0.037 to 0.433 mg/L in Field 2. TP concentrations at the outlet ranged from 0.053 to 2.038 mg/L in Field 1, and from 0.264 to 1.164 mg/L in Field 2. P concentrations in Field 1 tended to be higher than in Field 2.

PP concentrations were obtained as the difference between TP and SRP. The highest PP concentrations were observed in 1999. In spring 1999, PP was 0.387 mg/L at the outlet of Field 1 (no data in Field 2) and later, during irrigation, PP was 0.150 mg/L and 0.132 mg/L at the inlet and outlet of Field 1 and 0.245 mg/L and 0.298 mg/L in Field 2. In Spring 2000, PP concentrations were similar in both fields (0.049 mg/L in Field 1 and 0.045 mg/L in Field 2). Later, in Summer 2000, PP was 0.016 mg/L and 0.133 mg/L at the inlet and outlet of Field 1, and 0.023 mg/L and 0.097 mg/L at the inlet and outlet of Field 2. In spring 2001, PP was the same for both fields (0.145 mg/L) and during irrigation 0.045 mg/L and 0.170 mg/L at the inlet and outlet of Field 1.

TSS concentrations were similar in both fields. At the inlets, TSS ranged from 0 to 55 mg/L (mean = 14 mg/L). At the outlets, TSS ranged from 0 to 245 mg/L (mean = 51 mg/L). The outlet TSS concentrations were slightly higher during the irrigation seasons (overall mean = 50 mg/L) than during the snowmelt events (overall mean = 39 mg/L). Exception to this was the snowmelt event in 2001, when TSS in runoff was higher (overall mean = 100 mg/L) than during irrigation (mean = 76 mg/L in Field 1; no data in Field 2).

Groundwater

SRP concentrations in groundwater were much lower than in surface water. Figure 7 shows the mean and standard deviation of SRP concentrations observed in the nine wells each in Field 1 and 2. SRP concentrations ranged from 0.009 to 0.230 mg/L in Field 1, and from 0.009 up to 0.698 mg/L in Field 2. Wells 3 and 4 in Field 2 consistently showed the highest SRP concentrations. These two wells were located next to a wetland, which may explain these high SRP concentrations. However, well 9 also was located near the wetland, but it showed SRP concentrations below the mean. The groundwater hydraulic gradient (di/dl) did not show seasonal variations during the years of the study period. The average was 0.005 (std.dev. 0.002) in Field 1 and 0.009 (std.dev. 0.003) in Field 2. The hydraulic gradient was consistently two times higher in Field 2 than Field 1. The saturated hydraulic conductivity was 9.97×10^{-6} m/s in Field 1 and 6.25×10^{-6} m/s in Field 2.

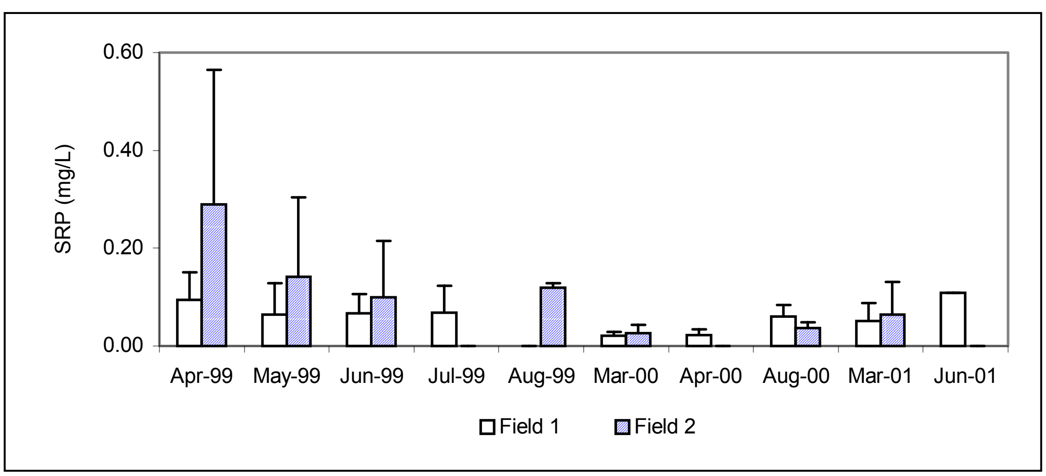

Figure 7. Mean SRP concentration in groundwater from April 1999 through June 2001 (from nine wells in each field). Whiskers represent standard deviation for each set of nine wells.

Spring Snowmelt Event in 1999

The highest P concentrations in surface and groundwater were observed during the spring of 1999 when, prior to snow melt, the soil surface had been frozen and the soil had been fully saturated for several months. A strong sulfur odor was observed when probing through the frozen layer suggesting anaerobic conditions, which enhance reduction and dissolution of iron oxides, which, in turn, are associated with P desorption. In groundwater, the highest SRP concentrations were observed in Field 2 in well 3 (0.439 mg/L) and in well 4 (0.698 mg/L).

P Loading Estimation

Loading in Surface Water

Equation 6 was applied to SRP and TP concentration data in surface water to estimate P loading by season (i.e., spring snowmelt and summer irrigation), by water year, and by study period. Results of the P loading estimation are summarized in Tables 10, 11, 12, and 13, and described in the following sections with a focus on the sink/source behavior of the pasture fields. TSS, SRP, TP, and PP loading in Tables 10, 11, 12, and 13 were obtained using Equation 4 by substituting $TSS_{i,j}$, $SRP_{i,j}$, $TP_{i,j}$, and $PP_{i,j}$ in surface water for $P_{i,j}$, respectively, for Field 1 and Field 2. For purposes of comparison, the total surface water volumes, and mean and standard deviations of TSS, SRP and TP concentrations during each season are shown where appropriate. Missing concentration and flow volumes were estimated as described in the Materials and Methods section.

Estimation by Season: Summer Irrigation (Table 10)

Field 1 was a clear source of SRP in 1999, whereas, in 2000 and 2001 the field did not display a tendency towards being a source or a sink of SRP. In 1999 and 2001, Field 2 acted as a net sink for SRP, while in 2000, this field acted as a source for SRP. More interestingly, however, given the relatively constant SRP concentrations at the inlet and outlet by field, the SRP loading at the inlet and outlet appears proportional to the overall water volume entering or leaving each field. A combination of high water input and low water output would tend each field to act as a sink, or, vice versa, low water input with high water output would tend each field to act as a source.

Both fields acted as sinks for TP, TSS and PP each irrigation season during the study period. In this case, the product of high inlet volumes and low inlet concentrations generated more TP (kg), TSS (kg) and PP (kg) than product of low outlet volumes and high outlet concentrations. At the outlet, flow volumes were proportional to TSS and TP loading, but not to PP loading. During the 2001 irrigation season Field 2 acted as a sink for SRP, TSS, PP and TP because the sprinkler irrigation system did not generate any surface outflow.

Table 10. Summary of TSS, SRP, TP and PP loading estimation during irrigation events at inlet and outlet of Field 1 and Field 2 using Equation 4. Water volumes and mean and standard deviations (between brackets) of TSS, SRP and TP concentrations are shown for comparison.

Sample port / Irrigation events			Water Volume (m^3)	Mean TSS (std.dev) (mg/L)	Mean SRP (std.dev) (mg/L)	Mean TP (std.dev) (mg/L)	TSS load (kg)	SRP load (kg)	TP load (kg)	PP load (kg)
Field 1	1999	Inlet	18977	5.2 (6.0)	0.023 (0.002)	0.199 (0.300)	108	0.4	2.7	2.3
		Outlet	2825	57.9 (65.3)	0.548 (0.335)	0.625 (0.305)	190	1.5	1.7	0.2
	2000	Inlet	23598	20.0 (18.1)	0.023 (0.001)	0.041 (0.003)	544	0.5	0.9	0.4
		Outlet	1239	66.8 (30.9)	0.506 (0.130)	0.618 (0.168)	101	0.5	0.7	0.2
	2001	Inlet	31996	30.2 (12.1)	0.022 (0.01)	0.069 (0.009)	949	0.9	2.4	1.5
		Outlet	1907	75.8 (35.8)	0.672 (0.303)	0.872 (0.341)	154	1.0	1.3	0.3
Field 2	1999	Inlet	47343	23.3 (38.6)	0.023 (0.004)	0.273 (0.076)	884	1.0	13.9	12.9
		Outlet	4237	28.6 (22.3)	0.243 (0.035)	0.503 (0.334)	333	0.7	2.2	1.5
	2000	Inlet	69030	13.5 (12.1)	0.025 (0.001)	0.046 (0.004)	1127	1.4	2.8	1.4
		Outlet	8923	45.3 (34.9)	0.377 (0.203)	0.443 (0.202)	467	2.0	2.7	0.7
	2001	Inlet	30000	20 (N/A)	0.023 (N/A)	0.051 (N/A)	600	0.7	1.5	0.8
		Outlet	-	Irrigation technique: sprinkler irrigation (no surface water flow).						

Estimation by Season: Spring Snowmelt (Table 11)

Since no water entered the fields at the inlet during spring snowmelt, obviously, both fields acted as a source of SRP, TSS, PP and TP. P concentrations and loading in 1999 were much higher than those observed in 2000 or 2001.

Table 11. Summary of TSS, SRP, TP, and PP loading estimation at inlet and outlet of Field 1 and Field 2 using Equation 4 during Spring snowmelt. Water volumes and mean and standard deviations (between brackets) are shown for comparison. (1)

Sample port / snowmelt events			Water Volume (m^3)	Mean TSS (std.dev) (mg/L)	Mean SRP (std.dev) (mg/L)	Mean TP (std.dev) (mg/L)	TSS load (kg)	SRP load (kg)	TP load (kg)	PP load (kg)
Field 1	1999	Outlet	8587(2)	42.2 (49.8)	0.929 (0.416)	1.297 (0.504)	441	7.5	10.4	2.9
	2000	Outlet	9832	26.8 (19.5)	0.163 (0.091)	0.205 (0.091)	247	1.2	1.7	0.5
	2001	Outlet	4916(2)	99.1 (52.6)	0.077 (0.027)	0.217 (0.082)	486	0.4	0.8	0.4
Field 2	1999	Outlet	6870(2)	42.2(2) (N/A)	0.929(2) (N/A)	1.297(2) (N/A)	280	6.4	7.3	0.9
	2000	Outlet	8007	49.7 (25.6)	0.201 (0.019)	0.397 (0.007)	410	1.7	2.0	0.3
	2001	Outlet	3935(2)	100.3 (30.1)	0.089 (0.042)	0.257 (0.031)	404	0.1	0.5	0.4

(1) During snowmelt events there is no inflow water.
(2) Missing data were estimated as described in the Materials and Methods section.

In Spring 1999, Field 1 released 7.5 kg of SRP and 10.4 kg of TP in 8587 m^3 of water. In Spring 2000 in Field 1, although the outflow volume was larger than the previous year, P loading was five times lower than in 1999, because the concentrations of both SRP and TP in 2000 were 85% lower than in 1999. During Spring snowmelt, flow volumes at the outlet were not proportional to SRP, TSS, or TP loading as was seen during the irrigation seasons.

Estimation by Season: Spring - Summer Combined

Figure 8 illustrates the SRP, TP, PP, and TSS loading estimates for Spring snowmelt and irrigation seasons at the inlet and outlet by combining data from both fields. The overall surface water volumes are shown as well. Similar to the groundwater concentrations shown in Figure 7, the greatest loading occurred during 1999 as a result of the prolonged saturation conditions described above. It appears that the high P loading upstream of the pasture fields during Spring 1999 elevated the P loading at the inlet during Summer 1999. Figure 8 also shows that the high water volumes in 2000 did not translate into high loading at the inlet.

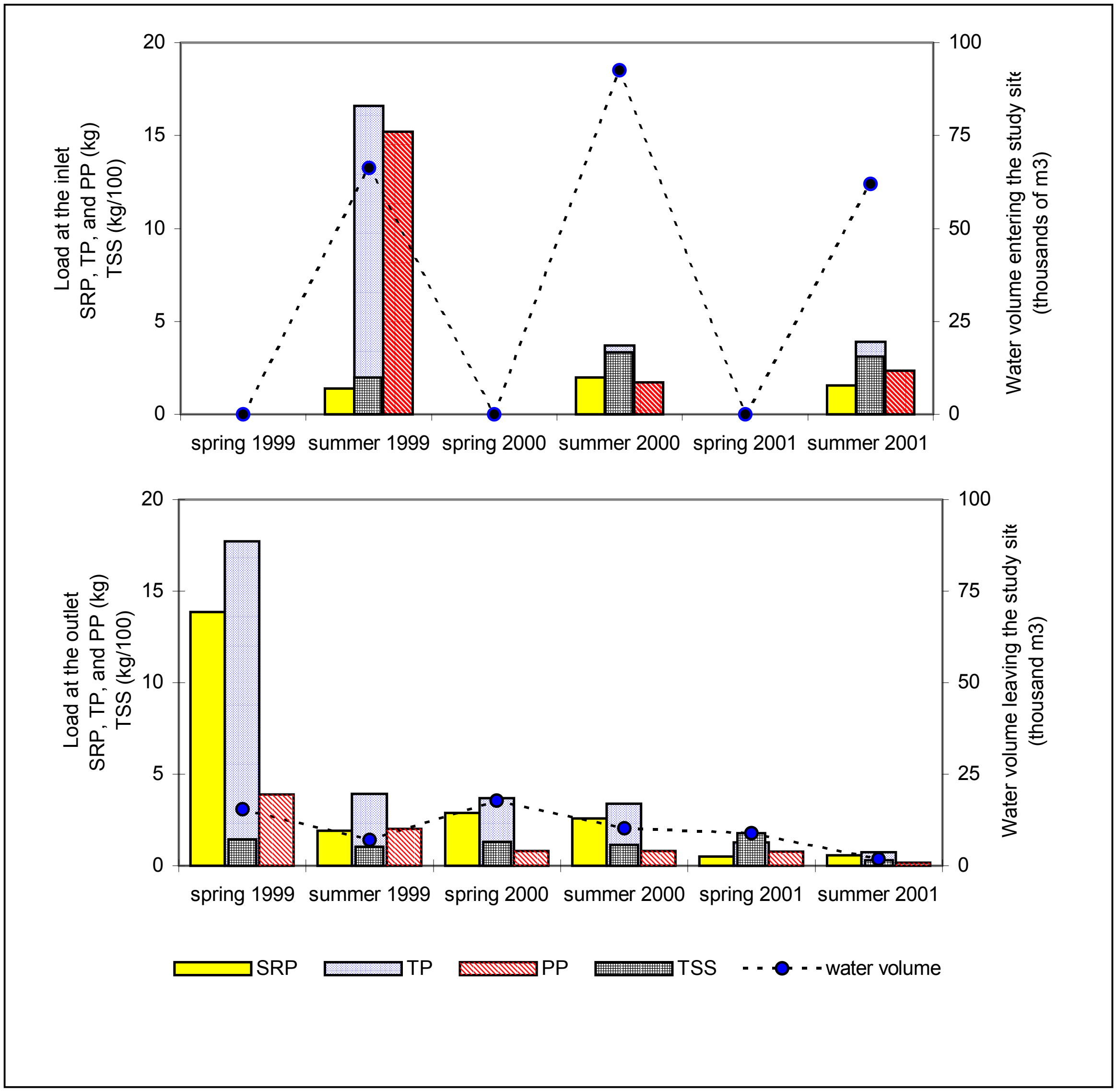

Figure 8. SRP, TP, PP, and TSS loading, and surface water volumes for Spring snowmelt and irrigation seasons at the inlet (a) and outlet (b) by combining data from both fields.

Estimation by Water Year (Table 12)

Field 1 and 2 acted as sources for SRP and TP on an annual basis. Exceptions to this are the estimates in 2001, which may have been affected by the leaking flumes in Spring 2001, and the TP estimate in Field 2 in 1999, which was affected by the evacuation of equipment during Spring snowmelt. Both fields mostly acted as a sink for TSS, while for PP Field 1 was a source in two out of three years, and Field 2 acted as a sink each year.

Table 12. Summary of annual SRP and TP loading estimation at inlet and outlet of Field 1 and Field 2 using Equation 4. Water volumes are shown for comparison.

Sample Port		Period (irrigation+snowmelt)	Water volume (m^3)	TSS load (kg/yr)	SRP load (kg/yr)	TP load (kg/yr)	PP load (kg/yr)
Field 1	Inlet	Oct 98 - Sept 99	18977	108	0.4	2.7	2.3
	Outlet	Oct 98 - Sept 99	11412[1]	631	9.0	12.1	3.1
	Inlet	Oct 99 - Sept 00	23598	544	0.5	0.9	0.4
	Outlet	Oct 99 - Sept 00	11071	348	1.8	2.4	0.6
	Inlet	Oct 00 - Sept 01	31966	949	0.9	2.4	1.5
	Outlet	Oct 00 - Sept 01	6823[1]	640	1.0	1.5	0.5
Field 2	Inlet	Oct 98 - Sept 99	47343	884	1.0	13.9	12.9
	Outlet	Oct 98 - Sept 99	11107[1]	613	6.8	8.4	1.6
	Inlet	Oct 99 - Sept 00	69030	1127	1.4	2.8	1.4
	Outlet	Oct 99 - Sept 00	16930	877	3.7	4.7	1.0
	Inlet	Oct 00 - Sept 01	30000	600[1]	0.7[1]	1.5[1]	0.8[1]
	Outlet	Oct 00 - Sept 01	3935[1]	404	0.1	0.5	0.4

(1) Missing data were estimated as described in the Materials and Methods section.

Estimation During the Full Study Period (Table 13)

Field 1 acted as a source for SRP and TP when considering the full study period. After correction for missing data at the outlet of Field 2 during Spring 1999, Field 2 also acted as a source for SRP and TP. When combining data from both fields, the fields acted as a source for SRP and TP. Both fields combined acted as a sink for TSS and PP.

Table 13. Summary of annual SRP and TP loading estimation during the full study period at inlet and outlet of Field 1 and Field 2 using Equation 4. Water volumes are shown for comparison.

Field	Sample Port	Period	TSS load (kg)	SRP load (kg)	TP load (kg)	PP load (kg)
Field 1	Inlet	Full study period (Apr'99-Jul'01)	1601	1.8	6.0	4.2
	Outlet	Full study period (Apr'99-Jul'01)	1619	11.8	16	4.2
Field 2	Inlet	Full study period (Apr'99-Jul'01)	2611	3.1	18.2	15.1
	Outlet	Full study period (Apr'99-Jul'01)	1894	10.6	13.6	3.0
Both fields	Inlet	Full study period (Apr'99-Jul'01)	4212	4.9	24.2	19.3
	Outlet	Full study period (Apr'99-Jul'01)	3513	22.4	29.6	7.2

Mass Balance Components

An annual evaluation of the mass balance components (averaged over the three year period) shows that an overwhelming amount of P is resident in the soil at our study site (see Table 14). A total of 1256 kg P/ha and 1700 kg P/ha, on average, were present in just the top 10 cm of soil. Given the high adsorption capacity of soils in general, this 10-cm layer presumably represents the highest interaction between P and the surface water. Compared to this large pool of P in the soil, only a small fraction entered or exited the fields. Interestingly, cattle removed more P than surface water and groundwater combined. Groundwater load was negligible when compared with the other inputs and outputs.

Table 14. Mass balance components using averages over the three year study period for Field 1 and Field 2.

Field	*P inputs (kg/ha/yr)*		*P outputs (kgha/yr)*			*Δ (P stored in soil) (kg/ha)*	
	surface water		surface water		cattle	groundwater	soil
	SRP	TP	SRP	TP	TP	SRP	TP
1	0.03	0.11	0.22	0.29	2.4	0.002	1256
2	0.07	0.41	0.23	0.30	2.4	0.011	1700

P Transport Parameters

Given the similarities in P and TSS concentrations in both fields, SRP, TP, PP, TSS, and SoilTP data from both fields were combined to obtain the parameters *ER*, *XC*, a_0, and a_1 for the study site using Equations 1 - 3. This provided a sufficient number of observations (n=115) for the regression analysis used to obtain a_0 and a_1.

Enrichment Ratio (ER)

Values of ER were higher during the Spring snowmelt than during summer irrigation, with the exception of 2001 when flumes were leaking in both fields during Spring snowmelt (see Table 15). The difference between both seasons was the highest snowmelt outflow as compared to irrigation outflow and the difference between the 2001 events as compared to 1999 and 2000 events was that outlet water volumes in 2001 were about 50% lower than in the previous years. In addition, a clear seasonal inverse relationship existed between the average TSS concentrations and the ER values. The highest ER values occurred in Spring and corresponded to the lowest TSS concentrations. Conversely, the lowest ER values occurred in Summer when the TSS concentrations were highest.

Coefficients a_0 and a_1

When considering the full study period, the values of a_0 and a_1 in Equation 3 were equal to 2.0, and -0.36, respectively. The range of coefficients of determination for regression (r^2) in Table 15 for the period 1999-2000 was 0.35 - 0.60.

Table 15. ER, TSS in surface water, the coefficients a_o and a_1, and coefficients of determination for regression of ln(ER) and ln(TSS) by season and the full study period.

Event	Spring 99	Summer 99	Spring 00	Summer 00	Spring 01	Summer 01
ER	31.1	12.5	9.8	4.0	1.5	4.1[(1)]
TSS (kg/ha)	72.0	24.5	20.3	17.3	17.6	4.5[(1)]
TSS (mg/L)	42	43	38	56	100	76
a_0	4.07	2.40	2.40	1.50	0.30	1.30
a_1	-0.39	-0.59	-0.75	-0.39	-0.01	-0.03
r^2	0.38	0.33	0.60	0.35	0.00	0.00

[(1)] Low event sediment yield (<10 kg/ha) affects the prediction accuracy of *ER* in Equation 1 (Edwards et al., 1996).

Figure 9 shows the *ln(ER)* versus *ln(TSS)* plot for the spring event in 2000. This example was the best-fit straight line obtained during the full study period. The intercept a_0 (2.43) was higher than the mean a_0 (2.0) for our study but very similar to values in Edward et al. (1996) and in Sharpley (1980). The a_1 value (-0.75) was lower than the mean in this study and also lower than the reported values.

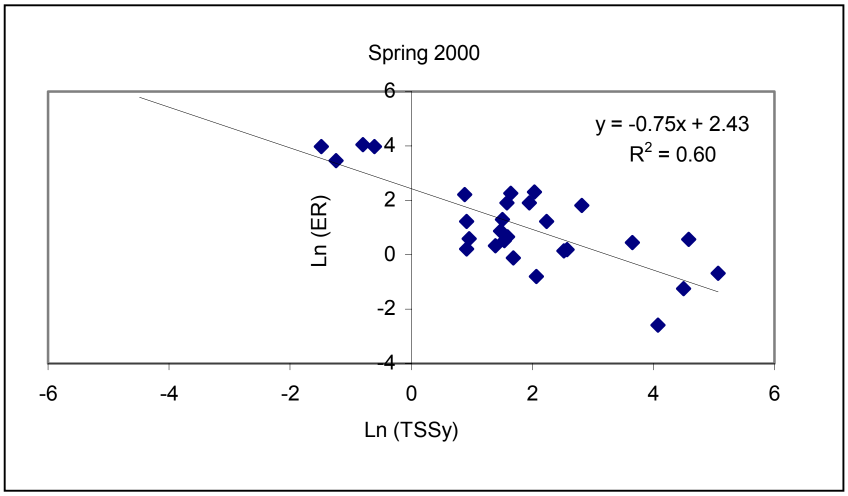

Figure 9. Relationship between ER and TSS_y to obtain the regression parameters a_0 and a_1 (period spring 2000).

Extraction Coefficient (XC)

Extraction coefficients for this study did not show a clear seasonal trend (Table 16) and did not correlate well with the runoff depth (*D*), similar to findings of Edwards et al. (1996). The highest value of 0.021 was obtained during Spring 1999—the event with the highest D (11.5 mm)-- followed by XC= 0.016 in Summer 2001—the event with the lowest D (0.5 mm). *XC* values did not correlate well with the runoff depth (*D*), similar to findings of Edwards et al. (1996).

Table 16. Average *XC* values (minimum and maximum values between brackets) and runoff depth *D* (mm) by season obtained in this study.

Event	Spring-99	Summer-99	Spring-00	Summer-00	Spring-01	Summer-01
XC	0.021 (0.009-0.035)	0.006 (0.001-0.020)	0.006 (0.002-0.012)	0.008 (0.003-0.020)	0.002 (0.001-0.004)	0.016 (0.007-0.030)
D (mm)	11.5	2.01	4.4	2.6	1.01	0.50

Flume Experiments

Flume experiments were performed at two different temperatures, 6°C and 25°C**.** Figure 10 shows the SRP concentration at the outlet ports for various flow configurations at both temperatures; the mixing layer was added on top of soil in Flume 2 at the beginning of the run and was left intact during the experimental period. Only the water flow path was changed, as indicated in each region of the plot. Return flow (D -> E), which is the water route during flood-irrigation, was the flow path that transported the most SRP. This suggests that a water flow path that traverses the mixing layer would transport more SRP than a flow path that does not, like surface runoff (A->E) and (RM -> E). Subsurface water (H port) carried the lowest SRP, regardless of the water input and flow path, this finding corroborates the low SRP concentrations in groundwater measured in the field study. SRP desorption in surface runoff (E port) decreased with time.

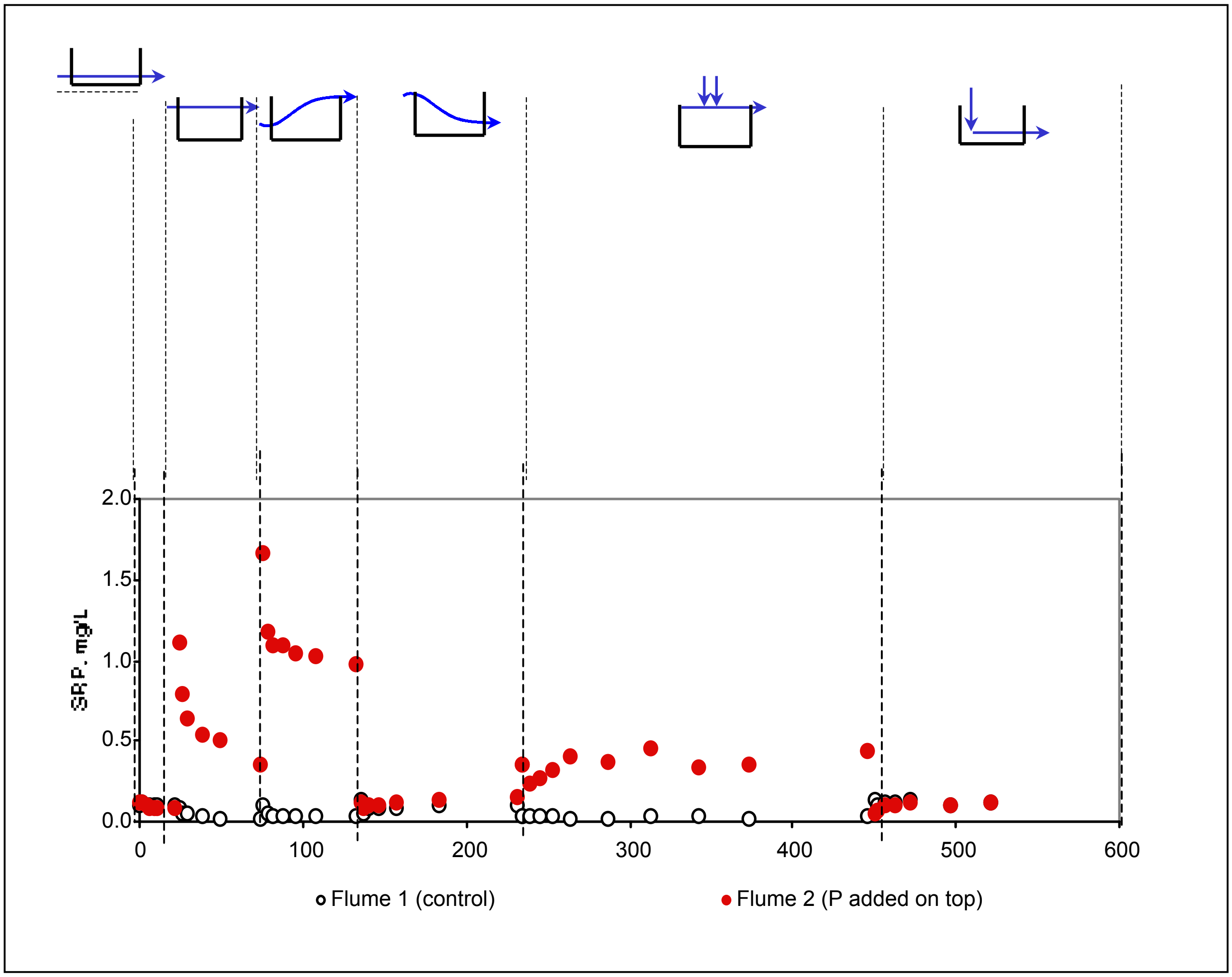

Figure 10. Effluent concentrations of SRP versus time while modifying the water flow path through the flumes: (top) experiments at 6°C; (bottom) experiments at 25°C.

Water pathway: subsurface flow

Saturation Duration

The soil gradually saturated at a temperature of ~25 °C. Sample retrieval was in succession at the H, G, F, and E ports (DP in E are not included in Figure 10). Daily recording of dissolved P in water samples, Eh, and pH was carried out. The duration of the saturation period provoked changes in the DP concentration values as pH and Eh changed over time. Eh decreased from ~ +400 mv to a ~ (-100 mv) in both flumes; while the range of soil pH variation was from ~4.9 to 5.4 and from 5.7 to 6.1 in water samples. The range of the DP values was approximately the same for both flumes: 0.03-0.12 mg/L. The lowest DP value occurred when the soil was still aerobic, at the beginning of the experiment (Eh~ +150mv).

No DP significant differences were observed at the different sampling ports, indicating that DP did not move downward. As time progressed, the DP increased to a peak of DP=0.11 mg/L that occurred at about 80-90 hours of water flow. A similar trend occurred in a desorption analysis performed in soil samples taken in Fall 1999. At that time, the peak of DP=0.13 mg/L occurred during the 6th cycle and the lowest DP concentration was approximately equal to 0.04 mg/L.

Mixing layer.

DP concentrations in ports F, G, and H were very similar in both flumes. DP concentrations in port E show a clear P desorption trend as time and water flow progresses.

Water pathway: overland flow

Saturation Duration

The overflow experiments were carried out with water flowing on top of the flumes (A port) and retrieving samples progressively at the E, F, G, and H ports. These experiments were performed immediately after the subsurface flow experiments finished, which essentially increased the soil saturation period. Eh during these runs was always negative, from (-40 to – 240 mv). The lowest DP concentration was about 0.08 mg/L in both flumes (twice the lowest observed during the subsurface flow experiments). DP concentrations from Flume 1 (no P added) are at the threshold limit for eutrophication, even after all these many hours of water flowing. This illustrate that this soil is a constant source of DP to the Cascade Reservoir. The higher DP values were in samples colleted form the H port in Flume 2 (~0.20 mg/L during the entire run of 160 hrs). These samples were the last to be collected, which implies that the saturation period effectively could affect P release.

Mixing layer

DP concentrations in E showed again the DP desorption trend, as the continuation of the P flushing out effect observed during the subsurface flow experiments.

Data from Flow Path Along Ditches

In the experiment conducted during subsurface irrigation on September 7, 1999, we tracked DP and TP in paired locations along a short flow pathway in the irrigation ditch leading to Field 2, through Field 2, and on to the ditch leading away from Field 2 (Table 17). We found that the loading of DP consistently decreased in the ditches and increased in Field 2. Total P increased in the first ditch and decreased in Field 2 and the second ditch. A mass balance on these data could not be performed because the flow rate data were not consistent. The flow rate reading for location #3 appears erroneous while at locations #5 and #6 additional water from an adjacent field entered the irrigation ditch. Further data collection in ditches is strongly recommended.

Table 17. Measurements of flow rate, DP and TP concentrations, and calculated loading for six locations following the inlet ditch to field 2, through field 2 and a ditch leaving field 2.

	Average Flow Rate (L/s)	Average DP (mg/L)	Average TP (mg/L)	DP loading (g/d)	TP loading (g/d)	DP loading in 5 days (Kg)	TP loading in 5 days (Kg)
Location #1							
morning	18.2	0.010	0.016	15.7	25.2	0.079	0.126
afternoon	16.3	0.012	0.053	16.9	74.8	0.085	0.374
Location #2							
morning	14.9	0.010	0.066	12.9	84.9	0.064	0.424
afternoon	12.6	0.015	0.036	16.4	39.3	0.082	0.197
Location #3							
flume data	34.1	0.023	0.034	67.8	100.2	0.339	0.501
Location #4							
flume data	6.5	0.060	0.143	33.4	80.0	0.167	0.400
flume data	6.5	0.051	0.049	28.6	27.5	0.143	0.138
Location #5[1]							
morning	80.1	0.044	0.042	304.6	290.8	1.523	1.454
afternoon	59.5	0.046	0.055	236.3	282.6	1.182	1.413
Location #6[1]							
morning	65.0	0.051	0.072	286.4	404.4	1.432	2.022
afternoon	65.0	0.044	0.197	247.1	1106.4	1.236	5.532

[1] note: at the outlet of field 2, water from an adjacent field is added causing the increased flow rates.

DISCUSSION

Several results from the field study are highlighted in this section. The results from the flume study are summarized in the last paragraph of this section.

Soil P Levels

Soil P levels in the pasture fields can be considered very high, especially in the absence of fertilizers or feed. According to Parker (1946), who presented a map of soil P levels across the United States, P levels can be naturally high in the Pacific Northwest, including our study area. It is unlikely that the practice of flood irrigation is responsible for the high P levels in soils for two reasons. First, the overall addition of P in irrigation waters was approximately 0.25 kg P/ha/yr with a much smaller amount entering as subsurface water. It would have taken on the order of thousands of years to establish the soil P levels measured today. Second, given that surface water P inputs are greater than subsurface inputs, one would expect higher soil P levels near the surface. Our measurements indicate that soil P levels drop off only after 60 cm and remain relatively high up to at least 100 cm.

P Concentrations

P concentrations in groundwater (Figure 4) and surface water (Tables 10 and 11) were highest in April,1999 after prolonged saturation and the presence of a frozen soil layer prior to Spring snow melt. As a result, P loading from the pasture fields was the highest observed during the study period. Flooding of soils is known to increase soil reduction (i.e., anaerobic conditions) which can increase P solubility and increase or decrease P sorption capacity (Vadas and Sims, 1999; Sah and Mikkelsen, 1989). In this study, P clearly was released into solution of low P concentrations. These findings are confirm the suggestion by Vadas and Sims (1999) that flooded soils may increase the potential for P loss from soils through both a decrease in soil P sorption capacity and an increase in solution P concentrations in topsoils.

Clearly, the prolonged saturation prior to snow melt in 2000 and 2001 did not increase P concentrations as much as during 1999. SRP concentrations in groundwater (Figure 7) and SRP and TP concentrations in surface water (Tables 10 and 11) were higher during irrigation events than during snow melt events in 2000 and 2001. Three reasons may explain why. First, the flooding periods during snow melt events in 2000 and 2001 were relatively short (on the order of 30 days), and compared more closely with flood irrigation events of 5 to 7 days. Note in this respect that soil flooding as short as 2 to 4 days can affect the soil P sorptivity (Willet, 1982). Second, temperature effects on P release may have been more important than flood duration. Hence, the P release during a longer flood period at low soil temperatures in Spring may be lower than P release during shorter flood periods at high soil temperatures in Summer. Third, there may be some effect of animal activity during summer causing fresh release of P from manure.

P Loading

P loading estimates show that, on average, the study site acted as a source for SRP and TP (Table 13), and a sink for PP. While approximately 20% of TP loading at the inlet consisted of SRP and 80% of PP, at the outlet 75% of TP loading at the outlet consisted of SRP, and 25% consisted of PP, regardless of season. Collectively, these findings show that flood irrigation added high amounts of particulates which were filtered out before water reached the end of the field. Moreover, these pasture fields generated little overall erosion.

Yearly and seasonal P loading estimates show variation in P source/sink behavior reflecting the combined effects of factors such as hydrology (e.g., discharge rates at inlet versus outlet), P fluxes (e.g., inlet concentrations versus outlet concentrations) and P dynamics (e.g., P sorption and desorption). The effects of individual factors on P source/sink behavior are difficult to discern. For example, water volumes during flood irrigation (Table 10) increased each year reflecting the change from a relatively high water year in 1999 to a relatively low water year in 2001. The effect of these increased inlet volumes alone would tend towards sink behavior of the pasture fields. However, the particulate P load in the water in 1999 overshadows this effect causing the most pronounced P sink behavior in that year. Similarly, effects of outlet flow volumes on P source behavior appear overshadowed by the P sorption/desorption behavior in 1999 (Table 10, 11 and 12).

Regardless of sink/source behavior of the fields, agricultural fields where flood irrigation is used contribute P to surface waters. In this study, the contribution decreased from the highest water year (1999) to the lowest water year (2001) (see Table 12). Average P loading of SRP and TP to surface water for both fields combined was 0.22 kg/ha and 0.29 kg/ha, respectively (Table 14). These P loading estimates cannot easily be extrapolated to export coefficients (Mattikalli and Richards, 1996; Johnes, 1996) because P dynamics in ditches and streams can change the load, or water can be re-used on other fields during the irrigation season (McDowell et al., 2001; Sallade and Sims, 1997). Export coefficients used to estimate P loading to Cascade Reservoir from irrigated pasture was 0.66 kg/ha/yr (Anonymous, 1991). The highest TP load observed in this study was 0.67 kg/ha in 1999 in Field 1, while the lowest was 0.03 kg/ha in Field 2 (Table 12). Thus, average or yearly estimates may not be constructive for the development of management plans in a system with strong differences in yearly and seasonal contributions.

This study showed that when the fields acted as sources for both SRP and TP, an average of 71% of the P transported out of the fields was in the soluble form. Edwards et al. (1996) and Edwards and Daniel (1994) reported an average of 86% for pasture fields. In other words, a relatively high fraction of the P load transported away from these fields is immediately available for accelerated eutrophication.

Comparison of P Transport Relationships

The range of ER values (1.5-31.1) in this study is comparable to that reported by Edwards et al. (1996) (1.5-40). Massey and Jackson (1952) observed a marked increase in ER with a decrease in the runoff sediment concentration. In this study, both the snowmelt events and the irrigation events can be characterized as overland flow, in which the degree of surface soil disturbance was minimal (Sharpley, 1980). ER and TSS followed an inverse relationship (Edwards et al., 1996), exemplified by the lower TSS concentrations during snowmelt events, with the consequent higher ER values. It is interesting to note, however, that although ER and TSS as a concentration (mg/L) showed an inverse relationship, ER and TSS as a load (kg/ha) did not show correlation, likely because of the significant flow differences between seasons.

Based on data from a variety of soils and cover conditions, Menzel (1980) obtained values of a_o equal to 2.0 and a_1 equal to –0.2, and Sharpley (1980) obtained a_o equal to 2.48 and a_1 equal to –0.27. For pasture fields in northwestern Arkansas, Edwards (1996) found a_o equal to 2.4 and a_1 equal to –0.46. Not considering the events in 2001 because of the low flow conditions, the averaged a_0 and a_1 values for the irrigation seasons ($a_0 = 2.0$, and $a_1 = -0.49$) compared better to the reported values obtained in the east than the averaged values obtained for Spring snow melt ($a_0 = 3.2$, and $a_1 = -0.57$).

The range of coefficients of determination for regression (r^2) in Table 15 for the period 1999-2000 also is comparable to the range of 0.16-0.54 reported by Edwards et al. (1996). In 2001, the poor correlation between *Ln(ER)* and *Ln(TSS)* likely can be explained by the combination of low flow at the outlets and high *TSS* concentrations, which caused a low *ER* in Spring 2001 and low *TSS* load in Summer 2001. At low *TSS* load, the estimation of ER using a logarithmic relationship is very sensitive. Edwards et al. (1996) suggested that Equation 1 might be modified for low event sediment yields (<10 kg/ha). Similarly, Sharpley et al. (1988) indicated that both Equations 1 and 3 provided less accurate predictions for low sediment yield (<10 kg/ha).

In general, Equation 1, $PP_t = TSS_t \times TP_{soil} \times ER$, is used to predict event particulate load after obtaining ER from the logarithmic relationship $Ln\ ER = a_o + a_1 Ln\ (TSS)$. In this study, when an average value of ER for the entire study period was used for the prediction of PP, comparison of predicted PP load versus observed PP load showed a regression coefficient of 0.281. When different ER values were used for the snow melt season and the irrigation season, this correlation coefficient improved to 0.328. When ER values were changed for each snow melt season in each year, and for each irrigation season in each year, the correlation coefficient increased to 0.436. The improvement in predicted versus observed PP load shown here suggests that ER may be dependent on the season and on the hydrologic year (Miller et al, 1984).

The default value 0.0057 used in the runoff P transport model EPIC (Sharpley and Williams, 1990) is comparable with XC from this study in Summer 1999, 2000 and Spring 2000 (Table 16). XC values appear in the same range as unmanured fields as reported by Edwards et al. (1996). The XC values for Spring 1999 and Summer 2001 are more than two times greater than the default value in EPIC. The value in Spring 1999 was higher because of high overall SRP loading, while the Summer 2001 value was high because of low overall runoff depth. These findings suggest that seasonal and 'water year' hydrologic effects should be considered in the prediction process using Equation 2.

Influence of Grazing Animals on P Loading

Shewmaker (1998) stated that effects of livestock grazing on nutrient loading are reported with mixed conclusions. While some have shown the presence of grazing animals to result in increased nutrient loading in return flows (Jawson et al., 1982), others have reported no effect on nutrient loading (Darling and Coltharp, 1973; Miller et al., 1984; Shewmaker, 1998). Data from this study showed that cattle exported 2.4 kg P/ha/yr, one order of magnitude larger than export of P through surface water. Obviously, proper grazing management is essential to reducing nutrient loading to streams. Cattle in our pasture fields did not have access to the ditches, nor did they receive P through feed (i.e., no feed was provided). In the absence of a control field without cattle, we cannot evaluate other effects of grazing such as the cycling of organic P from the subsurface and plants to other P forms in manure deposited on the surface.

Implications for Management

While the greatest P loading was contributed during the Spring snow melt period, management for the most part can influence loading contributions during the irrigation period. Irrigation management may have some effect on the moisture status prior to snow melt events, and thus reduce runoff, but this effect may be small. Thus, unless Soil P is reduced, snow melting events will continue to contribute P to surface waters.

A change from flood-irrigation to sprinkler irrigation will enhance infiltration and reduce overland flow and erosion. Hence, loading will shift from surface loading to subsurface loading via groundwater. Proper use of sprinkler irrigation also may promote lower groundwater table levels which can reduce surface runoff during Spring snow melt. Some of these effects were visible after use of pivot irrigation in Field 2 in 2001. Effects on subsurface contributions following the use of sprinkler irrigation, however should be investigated further considering hydrology and P dynamics.

Main Findings from the Flume Study

Two main findings characterize the results from the flume study: 1. at 25 °C, the SRP release was much higher than at 6 °C; and 2. SRP release was greatest when water traversed the mixing layer in the upward direction followed by the path when water flowed over the surface. SRP release was the lowest when water exited the flumes as subsurface flow. It is important to note that these results were obtained at anaerobic conditions, so that biochemical effects on SRP release were minimized. The first finding suggests that SRP release during Summer flows can be more significant than during Spring flows under the same biochemical conditions. As discussed above for the field study in 2000 and 2001, the P concentrations in Summer were nearly the same as during Spring. In the field situation, biochemical differences likely played a role. The second finding has implications for irrigation management. It supports the conversion from flood irrigation to sprinkler irrigation because this conversion would promote subsurface flow. Also, if irrigation (both flood and sprinkler) can be managed such that the ground water table does not rise to the mixing layer (the sod layer), phosphorus export may be reduced.

CONCLUSIONS

Results of this three year study showed that P source/sink behavior is season dependent. While the fields were sources of P during the Spring snow melt, they were sinks of TP and PP in most years during the irrigation season. The P source/sink behavior reflected the combined effects of factors such as hydrology, P fluxes, and P dynamics. The highest P concentrations and subsequent P loading were observed in spring of 1999, when anaerobic conditions prevailed prior to snow melt. An annual P mass balance showed that both fields have a large TP pool stored in the soil, and that in the absence of fertilizer and feed, cattle (with proper management) remove a significant amount of total P. Average *ER* and *XC* values compared well with values listed in the literature, indicating that ER and XC values from this study can be used to predict event P transport from western agricultural watersheds. A modification to the transport equations might be necessary for low event suspended solid yields (<10 kg/ha). Our findings suggest, however, that seasonal differences in hydrology and P sorption/desorption dynamics caused large variation in *ER* and *XC*. The laboratory experiments performed showed two combined effects (1) the effect of temperature on SRP release, and (2) the role of the water traversing the saturated P-enriched mixing layer on P release. Results from the measurements beyond the pasture fields were inconclusive and require further investigation.

Descriptors: ?

Articles in Refereed Scientific Journals: 3 are being prepared for submission

Book Chapters: none

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Conference Proceedings:

Boll, J., M. Sanchez, D. Davidson, and S.M. McGeehan. 2002. Phosphorous Transport in Cascade Reservoir Watershed. Presented at the 12th Nonpoint Source Water Quality Monitoring Results Workshop, Jan 8-10, Boise, ID. (Oral presentation)

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Other Publications:
Article in Long Valley Advocate, September 30, 1998.

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