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Sediment and Phosphorus Transport in Irrigation Furrows

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ABSTRACT

Sediment and phosphorus (P) in agricultural runoff can impair water quality in streams, lakes, and rivers. We studied the factors affecting P transfer and transport in irrigated furrows in six freshly tilled fallow fields, 110 to 180 m long with 0.007 to 0.012 m m^{-1} slopes without the interference of raindrops or sheet flow that occur during natural or simulated rain. The soil on all fields was Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids). Flow rate, sediment concentration, and P concentrations were monitored at four, equally spaced locations in each furrow. Flow rate decreased with distance down the furrow as water infiltrated. Sediment concentration varied with distance and time with no set pattern. Total P concentrations related directly to sediment concentrations (r^2 = 0.75) because typically >90% of the transported P was particulate P, emphasizing the need to control erosion to reduce P loss. Dissolved reactive phosphorus (DRP) concentrations decreased with time at a specific furrow site but increased with distance down the furrow as contact time with soil and suspended sediment increased. The DRP concentration correlated better with sediment concentration than extractable furrow soil P concentration. However, suspended sediment concentration tended to not affect DRP concentration later in the irrigation (>2 h). These results indicate that the effects of soil P can be overshadowed by differences in flow hydraulics, suspended sediment loads, and non-equilibrium conditions.

PHOSPHORUS is an essential nutrient for crop growth. Phosphorus can also accelerate algae and aquatic plant growth in surface water bodies, causing low oxygen conditions and a poor environment for fish (Correll, 1998; Daniel et al., 1998; Sharpley et al., 1994). Normal crop growth typically requires 0.2 to 0.3 mg L^{-1} inorganic P in soil solution (Barber, 1995), but total P concentrations as low as 0.02 mg L^{-1} can cause eutrophication in surface water (USEPA, 1996). Runoff from agricultural land is the main source of nutrients that impair stream water quality in the United States (USEPA, 2000).

Forty-four percent of the irrigated land in the United States is surface irrigated with 51% (4.75 million hectares) of that irrigated with furrows (USDA, 2004). While farmers try to control runoff from rain or sprinkler irrigation, runoff is often necessary to achieve acceptable uniformity during furrow irrigation and in many cases, it is impractical to contain runoff on sloping fields (i.e., >1%). Field runoff not re-used on farm or within an irrigation tract, along with associated sediment and nutrients, is discharged to rivers, lakes, or other water bodies (Bjorneberg et al., 2002).

The mechanics of erosion can be divided into three components: detachment, transport, and deposition. Water flowing in irrigation furrows detaches and transports sediment. Deposition occurs when flowing water can no longer transport the sediment. Some particles may be deposited within a few meters while others are transported off the field with runoff water. Most sediment detachment occurs on the inflow end of furrow irrigated fields with uniform slope (Trout, 1996) because flow rate is the greatest and sediment load is the least when water enters a field. Sediment transport and deposition are the dominant components on the lower end of a field because furrow flow rate decreases with distance as water infiltrates. Greater than 50% of the detached sediment can be deposited on the lower end of a field (Trout, 1996).

Flowing water also transports P, either dissolved in water or sorbed to or part of sediment. Sediment-bound P is directly related to soil erosion (Sharpley et al., 1994; Aase et al., 2001; Westermann et al., 2001). Typically more than 90% of the P transported from furrow irrigated row crop fields is associated with detached sediment (Berg and Carter, 1980). Runoff from fields of grass, hay, or pasture contains minimal sediment so soluble P is a greater percentage of the total P loss (Berg and Carter, 1980; Sharpley et al., 1994). Phosphorus may also desorb as runoff water interacts with a thin layer of surface soil in the furrow (Ahuja et al., 1981; Sharpley, 1985). Soluble P concentration in runoff typically increases as the extractable P in surface soil increases (Pote et al., 1996, 1999; Sharpley et al., 1981a; Turner et al., 2004; Westermann et al., 2001). Suspended sediment may also be a sink for soluble P (Sharpley et al., 1981b).

Phosphorus transport research is traditionally conducted under simulated or natural rainfall by measuring P concentrations at the end of a plot, field, or watershed. During rainfall, water flow rate tends to increase down slope as additional sheet and rill flow combine. Furrow irrigation differs from rainfall because water flows in controlled channels or rills that are not affected by rain drops or sheet flow. Furthermore, furrows are formed mechanically before irrigation while rills are formed by runoff. Sediment and P transport in furrows is a dynamic physical and chemical system with many processes interacting temporally and spatially. These processes occur during the relatively short time (10–30 min) that water flows down the field in a furrow. Furrow irrigation erosion resembles rill erosion initially, but begins to exhibit characteristics of an ephemeral stream or gulley after several hours of water flowing in the furrow. Water at the

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Abbreviations: DRP, dissolved reactive phosphorus.

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Table 1. Field and irrigation characteristics.

					Soil test P†			
Irrigation	**Date**	**Furrows**	**Field length**	**Field slope**	**Olsen**	**$CaCl_2$**	**Inflow rate**	**Advance time‡**
			m	m m^{-1}	—— mg kg^{-1} ——		L min^{-1}	min
1	5 Aug. 1998	3	110	0.010	33	2.6	30	260
2	10 June 1999	2	172	0.007	18	1.3	38	75
3	17 Aug. 1999	3	172	0.007	19	1.6	40	56
4	21 Sept. 2000	9	180	0.012	37	3.1	22/28/34	77/48/51§
5	27 June 2001	6	180	0.012	33	2.2	25	68
6	15 Aug. 2002	6	152	0.012	25	2.2	20	150

† Bicarbonate-extractable P (Olsen et al., 1954) and 0.01 *M* $CaCl_2$–extractable P (Pote et al., 1996) in furrow surface soil.
‡ Time for water to advance to the end of the field.
§ Advance time for low, medium, and high inflow rate, respectively.

advance front is cloudy due to high sediment concentration from the rapid breakdown of aggregates as the dry soil is instantaneously wetted. Soluble and particulate P enter flowing water as dry soil is rapidly saturated. With time, sediment concentration decreases and sediment deposition forms a surface seal on the bottom of the furrow (Segeren and Trout, 1991).

Irrigation furrows provide a unique opportunity to measure P transport changes with time and distance in a field without the interference of rain drops and sheet flow because P and sediment are detached and transported by only flowing water. We measured sediment and P transport during furrow irrigation to better understand the interactions between sediment detachment and deposition, and P sorption and desorption. Our objective was to identify factors affecting P transport during furrow irrigation.

MATERIALS AND METHODS

We measured sediment and P transport during six irrigations conducted over five years using the same general procedures (Table 1). All irrigations were performed on freshly tilled, fallow fields, 110 to 180 m long with 0.007 to 0.012 m m^{-1} slopes, with Portneuf silt loam at the Northwest Irrigation and Soils Research Laboratory (Table 1). Any surface residue remaining from the previous crop was tilled into the soil several months before any irrigation. Two to nine furrows were monitored during each irrigation. Each monitored furrow was wheel compacted when furrows were formed.

Furrow Flow Sampling and Analysis

The irrigation water source was the Snake River (typical chemical analysis: pH = 8.2, electrical conductivity = 0.5 dS m^{-1}, sodium adsorption ratio = 0.7 [Lentz et al., 1996], sediment < 10 mg L^{-1}, total P < 0.10 mg L^{-1}, DRP < 0.01 mg L^{-1}). Furrow inflow rate was controlled by spigot valves on gated pipe for all irrigations except Irrigation 2, which used siphon tubes from a concrete-lined ditch. Inflow rates were typical or slightly greater than normal for production fields to ensure that water advanced across the field in a reasonable time (1 to 3 h) without causing unrealistically high erosion rates (Table 1). Inflow rates were measured by flumes or by the time required to fill a known volume. Inflow rates were set the same for each furrow during an irrigation except during Irrigation 4, which had three different inflow rates to give a greater range of sediment and P transport.

Furrows were monitored at four, equally spaced locations in each furrow (Fig. 1). Small trapezoidal flumes were installed at each monitoring station for measuring water flow rate. Collecting water samples from these flumes could be difficult when the bottom of the flume was below the furrow soil surface, which sometimes occurred when flumes were installed at the proper depth to avoid water backing-up upstream of the flume. (Flumes have a unique relationship between flow rate and flow depth.) Newly designed flumes with a wider throat (Clemmens and Bjorneberg, 2005), which made sample collection easier when installed at the proper depth, were used for Irrigations 5 and 6. Water samples were collected from flume outflow to determine transported sediment and P concentrations. Sediment concentration was estimated by pouring a 1-L sample into an Imhoff cone and reading the settled volume after 30 min (Sojka et al., 1992). The term "sediment" as used in this paper is the soil particles being transported by the water flow, including bedload. Two, 50-mL water samples were collected from flume outflow to determine total P and DRP concentrations. Unfiltered samples were collected for total P

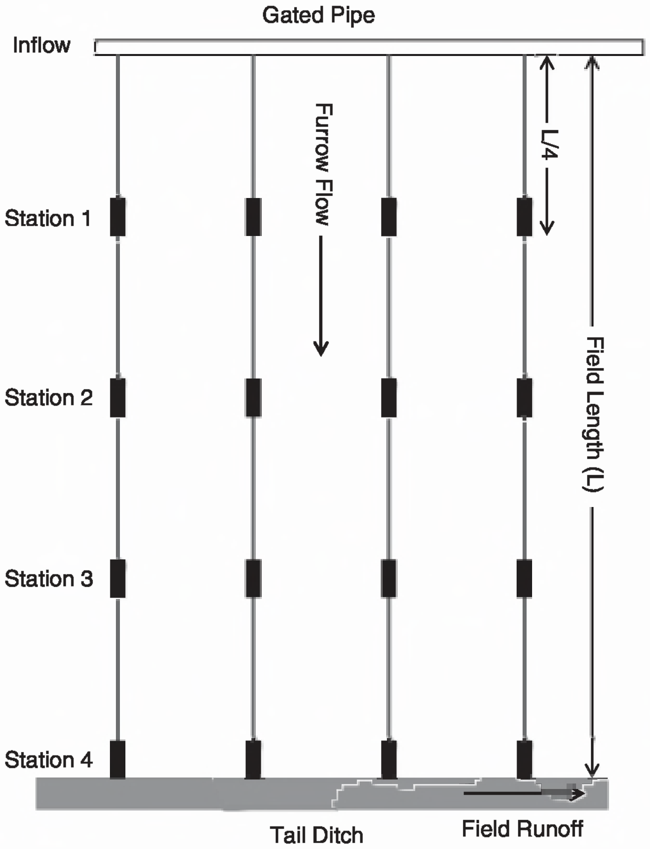

Fig. 1. Schematic diagram showing location of monitoring stations, inflow, and tail ditch for four furrows.

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analysis (persulfate digestion; American Public Health Association, 1992). The second sample was filtered (0.45 mm) in the field within 15 min of collection, stabilized with 0.5 mL of saturated H_3BO_3, and analyzed for DRP (Murphy and Riley, 1962).

Water samples were collected 5, 15, 45, 75, and 135 min after water advanced past a flume (5-, 10-, 30-, 30-, and 60-min intervals). Two or three additional samples were simultaneously collected from all stations at 1- to 2-h intervals for the remainder of the irrigation. An additional water sample was collected 1 min after advance for P analysis, except during Irrigation 1. Sediment samples were not collected at 1 min (and 5 min for Irrigation 1) because the flow rate was too low (<0.5 L min^{-1}) to fill the 1-L Imhoff cone in a reasonable time. Inflow water samples were also collected at the same time intervals from the gated pipe or siphon tubes. Total irrigation time was 6 to 7 h.

Before collecting the last flow samples, furrow top-width and depth were measured at six locations in each quarter-furrow segment. These measurements were used to calculate furrow wetted perimeter and cross-sectional flow area assuming a parabolic-shaped furrow. Flow velocity was calculated by dividing flow rate by average cross-sectional flow area.

Infiltration rate was calculated by subtracting flow rate at the downstream station from flow rate at the upstream station for each sample interval on a quarter-furrow segment. Flow rate at the upstream station was interpolated to match the sampling times at the downstream station. Inflow, infiltration, and furrow flow rates were integrated with time to calculate flow volume between sample intervals. Sediment and P loads were calculated by multiplying flow volume by sediment and P concentrations, respectively. The sum of the loads for each sample interval equals the total mass transported past a monitoring station. Flow-weighted average concentrations for an irrigation were calculated by dividing the total mass by the total flow volume. Runoff and infiltration depths were calculated by dividing the volume by furrow segment length and spacing. Similarly, sediment and P losses per unit area were calculated by dividing the mass by furrow segment length and spacing. Reported values are averages per furrow. Correlation coefficients, probabilities, and standard deviations were calculated with Microsoft Excel.

Soil Sampling and Analysis

Surface soil (0–30 mm) samples from 10 to 12 points along the furrow bottom on each quarter segment were composited immediately before each irrigation (<1 h). Soil P should be relatively uniform in this surface layer because the field was tilled and furrows formed 1 or 2 d before irrigation, and P fertilizer had not been recently applied. The soil samples were analyzed for both bicarbonate-extractable P (Olsen et al., 1954) and calcium chloride–extractable P (0.01 *M* $CaCl_2$) as an indication of water-soluble P (Pote et al., 1996). Soil samples were also collected from the furrow bottom after Irrigations 5 and 6, approximately 10 to 15 m from the inflow point and 10 to 15 m upstream from each flume location. Samples were collected 2 d after Irrigation 5 from the surface seal layer (0–5 mm) and immediately below the surface seal (about 5–20 mm). The surface seal was an easily defined consolidated soil layer 3 to 5 mm thick. Soil beneath the surface seal could have been undisturbed, deposited, or redistributed during irrigation. Samples were collected 1 d after Irrigation 6 from three depths (surface seal [0–5 mm], disturbed or deposited layer [5–10 mm], and undisturbed soil [10–30 mm]) to get more information about soil P change with depth. Post-irrigation soil samples were stored in sealed plastic bags at 5°C, and a subsample air dried and analyzed for 0.01 *M* $CaCl_2$–extractable P (Pote et al., 1996).

RESULTS AND DISCUSSION

Typical Furrow Flow, Sediment, and Phosphorus Trends

Data from one furrow from Irrigation 6 are shown in Fig. 2 as an example of typical flow, sediment, and P trends. Flow rate increased rapidly with time after water advanced past a monitoring station and then remained relatively constant (Fig. 2a). Flow also decreased between each monitoring station as water infiltrated. The DRP concentration at each station decreased rapidly with time until reaching a quasi-steady state concentration (Fig. 2b), a trend noted in previous runoff studies (Barlow et al., 2003; Turner et al., 2004). The quasi-steady state concentrations were greater than the inflow DRP concentrations, which was typical for all irrigations. Only 31 of the 805 furrow flow samples had DRP concentrations less than the inflow DRP concentration, indicating that DRP was not removed from flow in these furrows. At any given time during the irrigation, DRP concentration generally increased with distance down the furrow. However, the DRP concentration 1 min after water advanced past a flume (first sample) was similar among the four stations.

Sediment concentrations can be quite variable with time and distance during an irrigation (Fig. 2c). Sediment concentration at Station 3, for example, continued to increase during the last 4 h of the irrigation while concentrations at Stations 1 and 2 were lower and relatively constant. Sediment concentrations can be very erratic as sediment is added to the flow from headcuts (10- to 20-mm step changes in furrow bed) or other local scour in the furrow bed or sides. Headcuts were frequently noted in furrows during all irrigations. A thorough evaluation was not conducted, although a quick visual survey during Irrigation 6 noted more than 10 headcuts in each furrow. The headcuts varied in size and advance rate, and appeared to occur randomly, varying from 0 to 5 headcuts on a quarter-furrow segment.

Sediment and total P concentrations followed similar trends during an irrigation (Fig. 2c and 2d) because most of the total P was associated with particulates. Total P concentration, for example, increased at Stations 3 and 4 as sediment concentration increased. Dissolved reactive P concentrations, however, remained relatively constant, indicating that the additional sediment was not a net source or sink for DRP.

Water Flow and Sediment Transport in Furrows

Although all irrigations were conducted on the same soil with similar surface conditions (fallow, recently tilled, no surface residue), soil and P losses were quite variable. Infiltration was much greater during Irrigation 1 than for all other irrigations (Table 2), possibly because this field was moldboard plowed in the spring after being planted to grass for 8 yr before this study. The high infiltration rate caused a slow advance rate, little runoff, and small sediment and P losses. Erosion was minimal during Irrigation 1, with 36% of the samples having sediment concentrations below the lower

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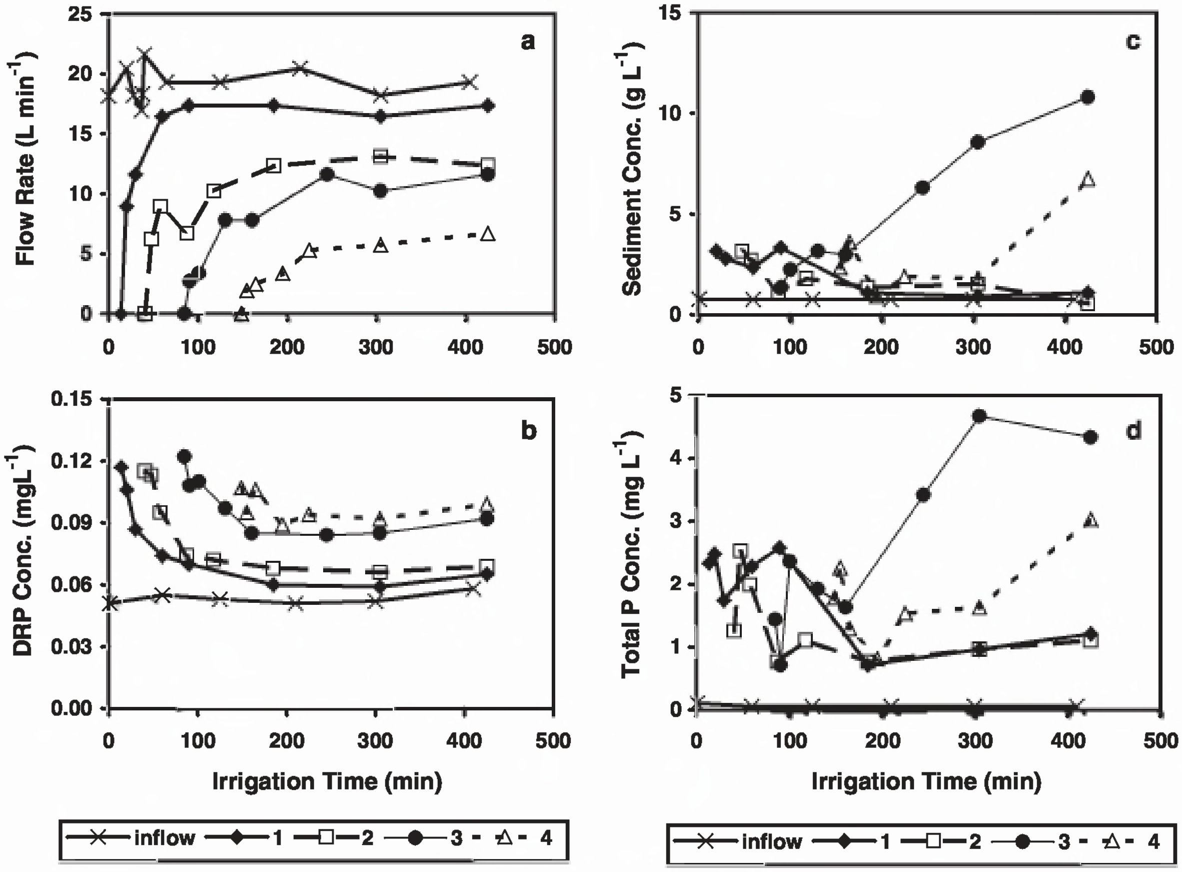

Fig. 2. Flow rate (a) and dissolved reactive phosphorus (b), sediment (c), and total P (d) concentrations for a typical furrow during Irrigation 6 at the inflow point and Stations 1, 2, 3, and 4.

detection limit for the Imhoff cone (<100 mg L^{-1}). Irrigation 5 had the greatest soil loss even though runoff volume was less than Irrigations 2, 3, and 4 (Table 2).

The decreases in flow rate and flow volume with distance were approximately linear for all irrigations, which indicates uniform infiltration down the furrows (Fig. 3a and 4a). Flow-weighted sediment concentration (Fig. 3b) always increased from inflow to Station 1 because inflow water contained little sediment and the furrow flow was most erosive on the upper end of the field where flow rate was greatest (Fig. 3a). As water continued to flow down the furrow, sediment concentration increased, decreased, or remained unchanged depending on flow rate, soil erodibility, and possibly other undefined characteristics. Sediment load (Fig. 4b) decreased between stations when sediment concentration was constant or decreased (Fig. 3b), because flow rate always decreased with distance (Fig. 3a). Sediment was deposited between Stations 3 and 4 for all irrigations but Irrigation 5 (Fig. 4b). Suspended sediment usually deposits on the lower end of a field as furrow flow rate decreases when water infiltrates (Trout, 1996).

Total Phosphorus in Furrow Flow

Changes in flow-weighted total P concentration with distance down a furrow during an irrigation were almost parallel to changes in sediment concentration (Fig. 3b

Table 2. Average flow, sediment, and P losses and concentrations at the end of the field.

Irrigation	Runoff	Infiltration	Soil Loss	Soil Concentration	Total P Loss	Total P Concentration	DRP† Loss	DRP† Concentration
	mm	mm	kg ha^{-1}	mg L^{-1}	g ha^{-1}	mg L^{-1}	g ha^{-1}	mg L^{-1}
1	6	107	12	203	17	0.3	5	0.079
2	46	41	502	1080	459	1.0	18	0.040
3	50	30	1620	3260	1300	2.6	43	0.086
4 Low‡	23	33	394	1740	596	2.6	16	0.070
4 Medium	36	34	1280	3560	1430	4.0	25	0.070
4 High	43	41	2400	5540	2240	5.2	33	0.077
5	17	29	3390	19700	2150	12.5	17	0.097
6	10	37	278	2710	226	2.2	9	0.086

† Dissolved reactive phosphorus.
‡ Low, medium, and high refer to the three inflow rates used for Irrigation 4.

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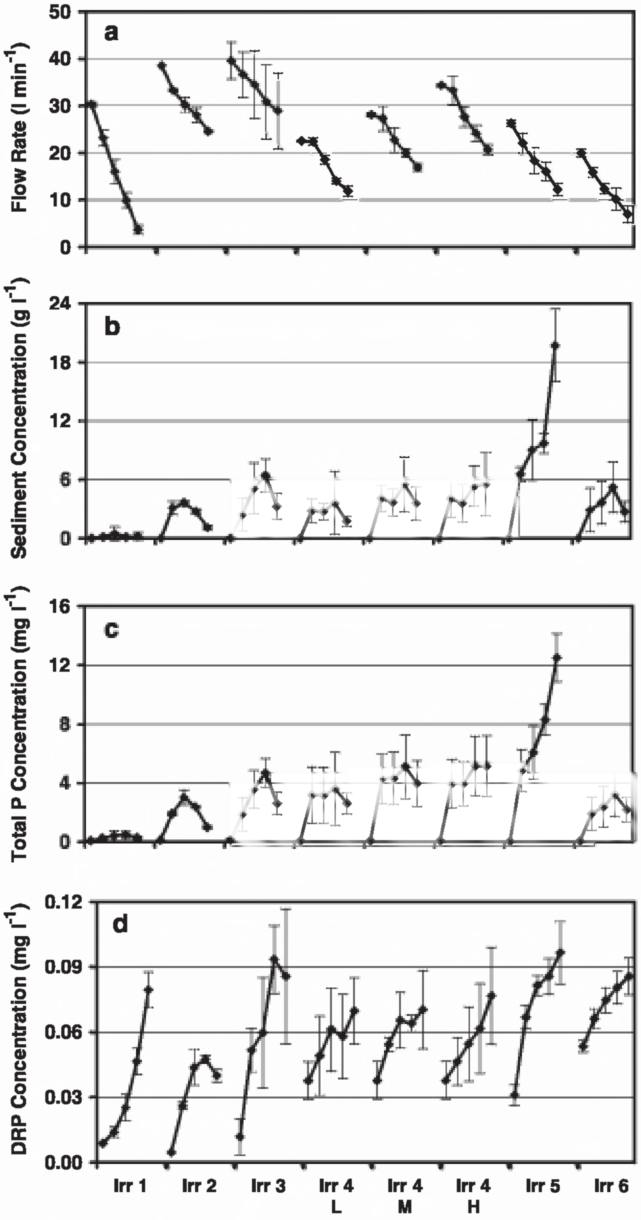

Fig. 3. Average flow rate (a) and flow-weighted sediment (b), total P (c), and dissolved reactive phosphorus (DRP) (d) concentrations for each irrigation. Data points are monitoring stations within furrows (inflow and Stations 1, 2, 3, and 4). Bars show one standard deviation.

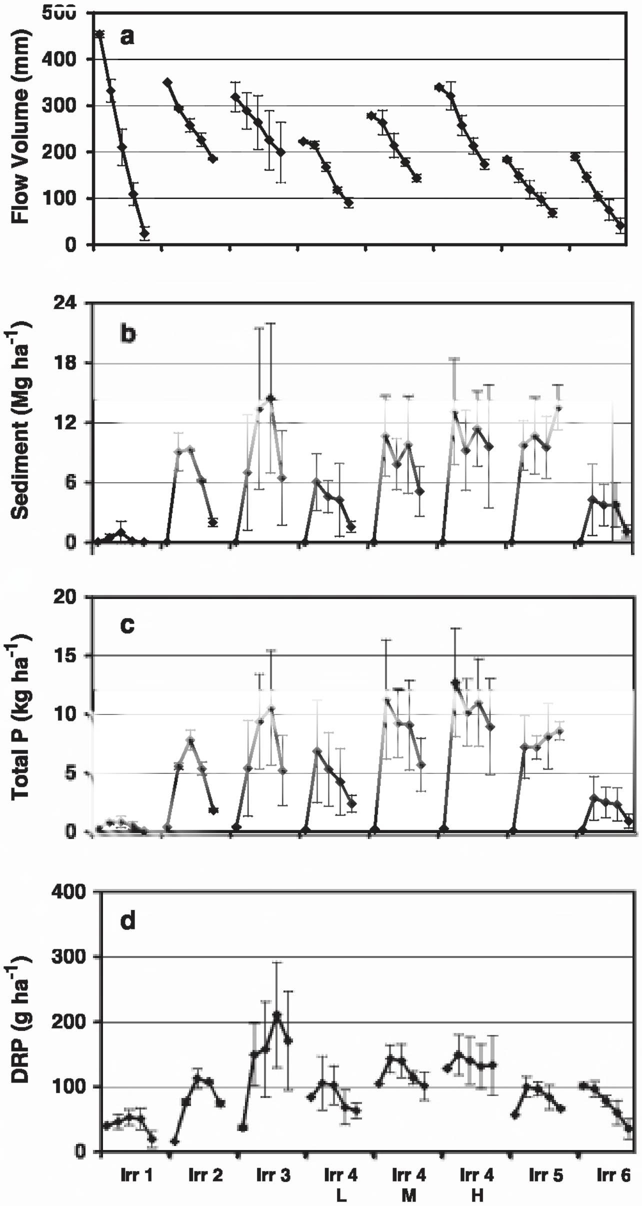

Fig. 4. Average flow volume (a) and mass of sediment (b), total P (c), and dissolved reactive phosphorus (DRP) (d) transported per furrow during each irrigation. Data points are monitoring stations within furrows (inflow and Stations 1, 2, 3, and 4). Bars show one standard deviation.

and 3c), because total P was directly related to sediment concentration ($r^2 = 0.75$). Thus, total P load increased as sediment was detached and decreased as sediment was deposited (Fig. 4b and 4c). This emphasizes the importance of controlling erosion to control total P loss. Furthermore, total P can be reduced in furrow irrigation runoff by removing sediment with settling ponds or similar practices (Bjorneberg and Lentz, 2005).

Total P concentration was directly related to sediment concentration because the majority of the total P was associated with particulates, which is typical for clean-tilled irrigation furrows (Berg and Carter, 1980). Nearly 80% of the of the water samples collected during the six irrigations had greater than 95% particulate P; 92% of the samples had greater than 90% particulate P. More than 95% of the total P was particulate P when sediment concentration was >2500 mg L^{-1} (data not shown).

The linear relationship between total P and sediment concentrations did not change noticeably with time during irrigation or distance down the furrow. Sediment, total P, and DRP mass losses increased linearly with the three inflow rates used for Irrigation 4 because runoff volume increased with inflow rate (Table 2). Sediment and total P concentrations also increased with inflow rate during Irrigation 4, but DRP concentrations were similar for all three inflow rates (Table 2). There was not an overall trend between inflow rate and sediment and total P losses among irrigations. Irrigation 3, for example, had the highest inflow rate (Table 1) but Irrigation 5 and the high inflow rate on Irrigation 4 had greater sediment and total P losses (Table 2). Field- and irrigation-specific characteristics are import factors affecting erosion and total P transport.

Dissolved Reactive Phosphorus in Furrow Flow

The DRP concentrations were greatest in the first samples collected from each station, when the advance front was about 1 to 5 m past the flumes. Since the infiltration rate is highest at the advancing water front, most water with the greatest DRP concentration infiltrates into the soil until the advance front reaches the end of the furrow.

Flow-weighted DRP concentration typically increased with distance down a furrow (Fig. 3d), indicating that P continued to desorb as water flowed down the furrow even if sediment and total P concentrations decreased. Although DRP concentration increased with distance, DRP load often decreased on the fourth and sometimes on the third segment of the furrow (Fig. 4d) because the mass of soluble P that infiltrated with irrigation water or re-sorbed to suspended sediment or furrow soil exceeded the mass of P desorbed. Most of the DRP load was supplied by inflow, with the exception of Irrigations 2 and 3 (Fig. 4d), despite the fact that DRP concentration increased as water flowed down the field (Fig. 3d).

As discussed in the previous section, DRP concentration was a small proportion of the total P, except for a few samples during Irrigation 6 when sediment concentration was low (<2000 mg L^{-1}) and during Irrigation 1, which had much lower sediment concentrations than the other five irrigations (Fig. 3b). With the slower advance rate during Irrigation 1 (Table 1), flowing water was in contact with the furrow soil and suspended sediment for a longer time, allowing more time for P dissolution and/or desorption. Average flow-weighted DRP concentrations for Irrigation 1 were 6, 11, 22, and 36% of the total P concentrations at Stations 1, 2, 3, and 4, respectively. The relative amount of DRP increased with distance down the furrow because DRP concentration increased and total P concentration decreased with distance. Sediment and total P transport rates for Irrigation 1 were almost the same at the inflow and outflow ends of the field, resulting in almost no net loss of sediment and total P (Fig. 4b and 4c). Irrigation 1 demonstrates that even if sediment loss is minimal, DRP will still be transported in furrow irrigation runoff.

Flow-weighted DRP concentration at the field end for Irrigation 1 was nearly as great as other irrigations with similar or lower soil test P concentrations and much greater sediment and total P concentrations. Irrigation 6, for example, had 15% lower $CaCl_2$–extractable P concentration (Table 1), 13-fold greater sediment concentration, and 7-fold greater total P concentration at Station 4 than Irrigation 1, but had almost the same DRP concentration (Fig. 3). Irrigation 5 had 15% lower $CaCl_2$–extractable P (Table 1) and only 20% greater DRP concentration than Irrigation 1 at Station 4 even though sediment and total P concentrations were 100- and 40-fold greater, respectively (Fig. 3). Irrigation 1 demonstrates the importance of contact time with furrow soil and suspended sediment on DRP concentrations in furrow flow. Conversely, Irrigation 6 indicates that greater sediment concentration can compensate for lower soil P concentration and shorter contact time in contributing DRP to furrow flow.

Soil Phosphorus versus Dissolved Reactive Phosphorus Relationships

Correlations between furrow surface soil P concentrations and furrow flow DRP concentrations were conducted with only 0.01 M $CaCl_2$–extractable P because bicarbonate and $CaCl_2$–extractable P tests are directly related (bicarb = $9.6[CaCl_2] + 13$, $r^2 = 0.63$, $n = 116$). Furrow soil-extractable P (0.01 M $CaCl_2$) did not correlate with flow-weighted average DRP concentration in furrow flow for Irrigations 1–5 (Table 3). The overall correlation coefficient (r) between extractable furrow soil P and average furrow flow DRP concentration from all irrigations and locations was -0.04 ($P = 0.64$). Extractable soil P was 1.0 to 5.0 mg kg^{-1} with an average concentration of 2.4 mg kg^{-1} for the 116 samples of furrow soil. The correlation was significant ($P = 0.01$) when extractable soil P was compared against DRP concentration in the first runoff sample collected at all stations (1 or 5 min), although the correlation coefficient was only 0.23 (Table 3). Within irrigations, using DRP concentrations from the initial furrow flow samples improved correlations with extractable furrow soil P, but linear relationships were only significant ($P < 0.05$) for two of the six irrigations (Table 3). The correlation further improved by using the first sample from only Station 1 for all six irrigations (data not shown; $r = 0.40$, $P = 0.03$, $n = 29$). Correlations between extractable soil P and furrow flow DRP were not significant after the first sample at Station 1, with correlation coefficients varying from -0.02 to -0.30 (data not shown). These

Table 3. Correlation coefficients (r) between furrow soil-extractable P (0.01 M $CaCl_2$) or suspended sediment concentration and dissolved reactive phosphorus (DRP) concentration in furrow flow.

	Extractable soil P vs.			Sediment concentration vs. DRP			
	Mean DRP		First sample DRP†	At Station 1‡		At all stations§	
Irrigation	n	r	r	n	r	n	r
1	12	0.14	0.53	18	0.74*	66	−0.03
2	8	−0.11	0.67	16	0.41	62	0.12
3	12	−0.27	−0.35	21	0.68*	83	0.35*
4	36	0.13	0.42*	63	0.60*	252	0.55*
5	24	0.16	0.22	42	0.60*	168	0.42*
6	24	0.75*	0.37*	42	0.43*	162	0.12
All	116	−0.04	0.23*	202	0.62*	793	0.42*

* Significant at the 0.05 probability level.

† First sample was collected 1 min after flow advanced to a station except for Irrigation 1, which was 5 min.

‡ Station 1 data are from the first quarter segment of the furrow and all sampling times.

§ All stations are data from all four furrow segments and all sampling times.

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correlations indicate that soil P does affect DRP in furrow flow, but furrow flow hydraulics and interactions with transported sediment likely confound these relationships.

The poor correlation between soil P concentration and DRP concentration in furrow flow tends to contradict previous studies where soil P correlated with runoff DRP concentration (Aase et al., 2001; Pote et al., 1996, 1999; Sharpley et al., 1981a; McDowell and Sharpley, 2001; Turner et al., 2004; Westermann et al., 2001). All of these studies but Westermann et al. (2001), however, were rainfall simulations on small plots or soil boxes where sediment deposition and interaction within the runoff area were probably minimal due to short runoff duration (30 min or less), steeper plot/box slopes (2.4 to 8%), and shorter plot/box lengths (1 to 6 m). Furthermore, the 28 L min^{-1} inflow rate used by Westermann et al. (2001) on 18-m-long furrows probably resulted in little or no sediment deposition and re-detachment, similar to Station 1 in this study. Plus, flow conditions were similar among furrows with different soil P concentrations.

The limited range of soil P concentrations among irrigations and field segments within each irrigation likely contributed to the lack of significant correlations between DRP concentration and furrow soil P concentration. The ratio of maximum to minimum soil P ranged from 1.6 to 2.9 for the six irrigations in this study, with the largest ratios occurring in Irrigations 4 (2.8) and 6 (2.9), which had significant correlations (Table 3). Previously referenced studies showing good correlation between runoff DRP concentration and soil test P concentration had soil P concentrations that increased between 2- and 20-fold, and maximum soil P concentrations of >100 mg kg^{-1} Olsen P. The range of soil test P (10 to 125 mg kg^{-1} Olsen P) on the one furrow irrigated field used by Westermann et al. (2001) was also much larger than occurred on the fields used in this study.

Suspended Sediment and Soil Phosphorus versus Dissolved Reactive Phosphorus Relationships

The DRP concentration in furrow flow correlated better with sediment concentration than furrow soil-extractable P (0.01 *M* CaCl_2) concentration, especially on the first quarter segment of the field, at Station 1 (Table 3). Sediment concentration predicted 18 to 55% of the variability in DRP concentration at Station 1. Correlation coefficients between sediment and DRP concentrations ranged from 0.41 to 0.69 ($P < 0.03$) for all sampling times at Stations 1 and 2 (data not shown). Correlations were more erratic at Stations 3 and 4. The DRP concentrations down the furrow, especially at Stations 3 and 4, were affected by concentrations transported from upper furrow segments as well as sediment dynamics on these furrow segments.

We further explored relationships among furrow soil-extractable P, sediment concentration, and DRP concentration using multiple linear regression analyses. Sediment concentration and log(irrigation time) were consistently significant factors for various analyses across irrigation and furrow station, while extractable furrow soil P often was not significant ($P > 0.05$, data not shown). Multiple linear regression of time, sediment concentration, and furrow soil-extractable P concentration versus DRP concentration for all data from the six irrigations ($n = 792$) gave a significant relation ($r = 0.70$), which is understandable given the large number of observations. However, the soil P coefficient was negative and not significant ($P = 0.22$). Using furrow soil P with sediment and DRP concentrations from only the first sample (5 or 15 min) at Station 1 from all irrigations ($n = 28$) gave a similar correlation ($r = 0.64$). Both sediment and soil P were significant ($P < 0.05$), but the soil P coefficient was negative again. A negative coefficient for furrow soil-extractable P is not realistic. Hydraulic differences (i.e., flow velocity, infiltration) among irrigations combined with sediment detachment and deposition dynamics likely confound these correlations. The main conclusion of the regression analyses is that DRP concentration is a factor of time, sediment concentration, and soil P concentration, but other interacting factors (e.g., sediment deposition and re-detachment) have as much or more influence on DRP concentration in furrow flow than furrow soil-extractable P concentration. Dissolved reactive P loss, for example, was greatest during Irrigation 3 (Fig. 4d, Table 2) even though the furrow soil P before irrigation was less than all other irrigations except Irrigation 2 (Table 1).

In theory, any detached sediment is a source or sink for DRP. In general, DRP concentration tended to increase as sediment concentration increased as shown by the correlation between DRP and sediment concentration (Table 3). However, increasing sediment concentration later in an irrigation often had little or no impact on DRP concentrations in furrows (e.g., Fig. 2). A change in sediment concentration without affecting DRP concentration suggests that the time when sediment is first detached affects DRP concentrations in furrow irrigation flows. We plotted sediment concentration change versus DRP concentration change between sampling intervals (Fig. 5) to illustrate the temporal effects of suspended sediment. Only data from Irrigations 4, 5, and 6 were included to reduce the number of data points. The DRP concentrations tended to increase or decrease as sediment concentrations increased or decreased, respectively, between Samples 1 (5 min) and 2 (15 min) (Fig. 5a), while sediment concentration changes between Samples 5 (approximately 120 min) and 6 (approximately 240 min) caused little change in DRP concentration (Fig. 5b). This trend could be coincidental, but it does support the hypothesis that DRP concentration is affected less by changes in sediment concentration later in an irrigation, possibly because this sediment has already lost most of the P susceptible to desorption/dissolution when the sediment was previously transported. Although conditions are different under rainfall, DRP concentration in runoff also decreases with successive runoff events (Sharpley, 1995). The role of resuspended sediment as a source or sink of DRP depends on the equilibrium P concentration (EP_∞), which is dependent on the physical and chemical properties of the solution and suspended sediment

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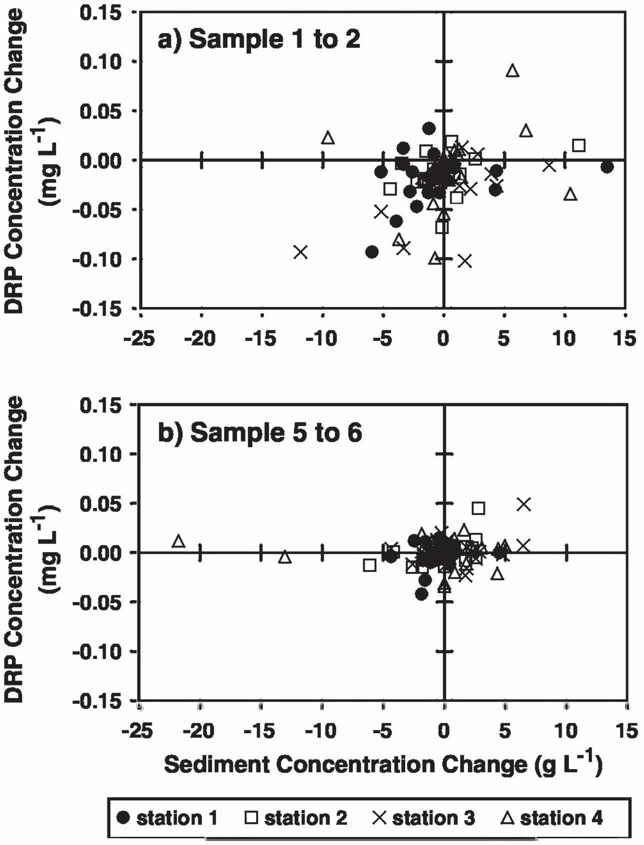

Fig. 5. Sediment and dissolved reactive phosphorus (DRP) concentration changes between Samples 1 and 2 (a) and 5 and 6 (b) for Irrigations 4, 5, and 6.

(Koski-Vähälä and Hartikainen, 2001; McDowell and Sharpley, 2003).

Furrow Soil-Extractable Phosphorus Changes

The furrow surface seal soil samples (0–5 mm) had 5 to 40% lower extractable P (0.01 *M* $CaCl_2$) concentrations than the soil before irrigation (Table 4). Although sampling depths were different, the soil was thoroughly mixed to at least 80 mm by tillage before irrigation. Surface seals form as aggregates disintegrate and as fine sediment deposits on the furrow wetted perimeter when sediment laden water infiltrates. Phosphorus probably desorbed from this soil as the aggregates broke apart during the initial wetting, as the sediment was transported with furrow flow before deposition, and as water infiltrated through the seal during irrigation. Phosphorus desorbed from the surface seal layer during infiltration may not contribute to DRP transport, but move downward with the infiltrating water. If soil in the surface seal layer is detached again and transported in furrow flow, less P would likely desorb from this sediment than when it was initially detached.

Table 4. Average furrow soil-extractable P (0.01 *M* $CaCl_2$) from samples collected before and after Irrigations 5 and 6.

	Irrigation 5			Irrigation 6			
	Before	After		Before	After		
Furrow location	0–30 mm	0–5 mm	5–20 mm	0–30 mm	0–5 mm	5–10 mm	10–30 mm
	mg kg^{-1}						
Inflow	–	1.98	2.21	1.77	1.45*	1.67	1.67*
1/4	2.01	1.66*	2.12	1.31	1.25	1.44	1.44*
1/2	2.07	1.72*	2.36*	2.34	1.60*	1.89*	1.89
3/4	2.47	1.80*	2.06*	2.40	1.69*	1.89*	1.89
End	2.14	1.90*	2.18	2.65	1.68*	1.87*	1.87

*** Denotes significant difference from sample collected before irrigation based on *t* test with $P < 0.05$.**

The amount, duration, and timing of transported sediment are critical components affecting DRP concentration in furrow flow, as well as the mass of DRP being transported. Initial extractable soil P concentration also affects the DRP concentration but is masked by furrow flow hydraulics, suspended sediment loads, and nonequilibrium conditions. Dougherty et al. (2004) also hypothesized that DRP concentrations are associated with increased sediment loads. Conversely, suspended sediment can be a P sink since DRP concentrations decreased when suspended sediment increased in runoff from grass and cropped watersheds (Sharpley et al., 1981b) and in runoff in earthen drains (Barlow et al., 2003).

As described earlier, infiltration is assumed to transport a mass of P into the soil in proportion to its DRP concentration, since the hydraulic gradient is downward. Therefore, if soil detachment or erosion is completely eliminated, then DRP concentrations in runoff should approximate inflow concentrations.

An additional often overlooked component that affects soil erodibility, and thus potentially affects P transport, in surface irrigation is the chemical makeup of the water used for irrigation and its interaction with the chemical properties of the soil. Increasing electrical conductivity decreased sediment concentrations, while increasing sodium adsorption ratio increased sediment concentrations in one surface irrigated study (Lentz et al., 1996). The quality of irrigation water will likely affect P dynamics also (Helyar et al., 1976; Yli-Halla and Hartikainen, 1996). Additional studies will be necessary to further identify and characterize the important contributing relationships before reliable P loss predictions can be made for surface irrigation.

CONCLUSIONS

Sediment and P transport in shallow ephemeral channels like irrigation furrows involve many interacting processes. Total P concentration was strongly correlated with sediment concentration on these tilled fallow fields with typically more than 90% of the total P associated with particulates. Thus, soil erosion must be controlled to reduce total P loss. The DRP concentration in furrow flow was also affected by sediment concentration along with the time that the water was in contact with soil and suspended sediment, furrow soil P concentration, and furrow hydraulic conditions. Results from this field study indicate that suspended sediment concentration has a greater influence on DRP concentration in furrow flow for whole fields than furrow soil P concentration. Sediment detachment, transport, and deposition

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in furrows must be understood to accurately predict both soluble and particulate P transport.

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