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ABSTRACT

Phosphorus was measured in irrigation and surface drainage waters for two large irrigation tracts, and inorganic, water-soluble $\text{PO}_4\text{-P}$ and total P inputs and outputs were computed. The present irrigation practices on both irrigation tracts conserve P by removing more P from the Snake River in irrigation water than is returned in drainage water. Even greater P conservation could be attained by implementing new practices. Approximately 90% of the P in waters diverted to irrigate the Northside Tract remained in the tract. About 50% of the amount diverted remained in the Twin Falls Tract. Particle size segregation takes place in some drainage streams and the finer sediments returning to the river contain higher total and NaHCO_3 -extractable P concentrations than the soils from which they were eroded. The importance of defining sampling methods and procedures for P analyses is illustrated by comparative data on irrigation and drainage waters. The $\text{PO}_4\text{-P}$ concentration in samples filtered through a $0.45 \mu\text{m}$ membrane filter was independent of the sediment concentration in waters, whereas the total P concentration of unfiltered samples was proportional to the sediment concentration.

Additional Index Words: phosphorus balances, water quality, total phosphorus, hydrolyzable phosphorus, organic phosphorus, water-soluble phosphorus.

Enormous quantities of P are carried by sediments washed into waterways of the United States each year (7, 11, 13, 16, 17). The possible stimulating effects of P on algal blooms and other aquatic plant growth has aroused the interest of many who are concerned with environmental quality. Several committees, task forces, and individuals have pointed out the need for information on the chemical behavior of P attached to sediment in relation to how much of it may solubilize and become available to algae and other aquatic plants (13, 14, 15, 16, 16). There are some who feel that limiting the P available in lakes is the single, most important step to be taken in eutrophication control (2).

Phosphorus is tightly held by most soils and sediments and the amount solubilizing, precipitating, or combining with the sediment depends upon the equilibrium condi-

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tions between the P in the ambient solution and that attached to or held by the sediment (4, 5, 9, 12, 15, 16, 17). Taylor and Kunishi (12) showed that sediments scavenge P from solution in the Mohantango watershed. Schuman, Spomer, and Piest (10) recently reported that sediments entering a stream from gully erosion of Missouri Valley loess removed P from solution. Latterell, Holt, and Timmons (9) found that sediments from the bottoms of three Minnesota lakes had a high capacity to remove soluble P from solution. Even though many sediments have a great capacity to absorb P under some conditions, they may also represent a vast reservoir of P that can maintain a low and nearly constant water-soluble P concentration in a lake or stream for a very long time under other conditions.

Information about solution to solid phase equilibria for phosphorus is very useful, but under many conditions, equilibria are not attained or factors influencing them may vary so that the equilibria are changed. For example, consider an irrigated tract of land for which water is diverted from a river, and where surface runoff returns via surface drains to the river. The irrigation water carries a sediment load that varies through the season. It carries P in solution and associated with the sediments. When this irrigation water is applied to lands supporting narrow crops such as alfalfa and grass, sediment will probably be deposited on land. In contrast, when the water is applied to recently cultivated row crops, erosion may occur, adding to the sediment load of the runoff water. Surface drainage waters from fields supporting all crops grown in the area, which are usually many in an irrigated area, enter surface drains and mix. In some cases, the flow velocities in drains are low and sediment settles. In other cases, velocities are high and no settling results until the water reaches the river or a major reservoir along the river. It is evident that many dynamic processes take place in irrigated agriculture and all of them can influence P equilibria. Almost nothing is known about the phosphorus inputs and outputs from such systems.

This paper reports P inputs and outputs for two large irrigated tracts, the P concentration in irrigation and surface drainage waters, and the total P and NaHCO_3 -extractable P for sediments from irrigation and surface drainage waters. The influence of physiography and management are also discussed.

MATERIALS AND METHODS

The study involved the Twin Falls and Northside Canal Company tracts previously described and was conducted simultaneously with an input-output sediment study (3). The sampling sites and frequency were the same as for the sediment study. Preliminary data were collected during the 1969 and 1970 irrigation seasons during which methods were calibrated and evaluated. The data reported are for the 1971 irrigation season.

At each site, three samples were collected usually at about 2-week intervals during the season. One was a 200-ml sample filtered through a $0.45 \mu\text{m}$ membrane filter at the site. The second was an unfiltered 200-ml sample, and the third was an unfiltered 10-liter sample. Forty mg HgCl_2 /liter were added to all samples upon collection to stop biological activity, and the 200-ml samples were refrigerated at 4C until analyzed. The 10-liter samples were allowed to stand undisturbed for 1 week in the laboratory (3), and then the clear, supernatant solution was siphoned off. The sediment and a small amount of solution were then transferred into small con-

tainers, dried at 50C, weighed, and retained for chemical analyses. All samples were collected at a drop structure, culvert, or turbulent zone to assure that samples were representative of the stream and its sediment load. At some sites a fractional water-sediment sampler was used (8) to assure representative samples.

Analytical methods of progressively greater chemical attack were employed to determine concentrations of various P fractions and finally the total P concentration in samples (6, 1). The $\text{PO}_4\text{-P}$ was determined by the ascorbic acid method (18) without pretreatment except to adjust pH by adding 0.5 ml 4N HCl to each 40-ml sample in 50-ml volumetric flasks, adding 1 drop of phenolphthalein, adjusting to a faint pink color by adding 30 to 35% NaOH solution dropwise, and then removing the pink color with 4N HCl. Then 8 ml of the ascorbic acid-ammonium molybdate solution (18) were added and the total volume diluted to 50 ml. Hydrolyzable P was determined by adding 1.0 ml of a strong acid solution containing 300 ml concentrated H_2SO_4 plus 4 ml concentrated HNO_3 /liter to each 40-ml sample, autoclaving at a total pressure of 1.9 to 2.2 bars (15 to 20 psi gauge pressure) for 30 min, cooling, adding 1 drop of phenolphthalein, adjusting to a faint pink color with NaOH, removing the pink color with 4N HCl, adding 8 ml ascorbic acid-ammonium molybdate solution (18), and diluting to 50-ml. The $\text{PO}_4\text{-P}$, as determined above, was subtracted from the concentration obtained by this latter procedure to give hydrolyzable P. Total P was determined by adding 1.0 ml of approximately $0.43\text{N K}_2\text{S}_2\text{O}_8$ to each 40 ml sample, then autoclaving, adjusting pH, and adding the color developing reagents as described for hydrolyzable P. This method is known as the persulfate digestion method, and it was compared with the nitric-perchloric acid digestion and Na_2CO_3 fusion methods for total P before adopting the method. The persulfate digestion method was more precise and consistently gave total P values as high as or slightly higher than the other methods. However, care must be exercised to assure that the autoclave pressure or temperature is sufficient for the full 30 min specified in the procedure or incomplete digestion may result. Organic P was calculated by subtracting $\text{PO}_4\text{-P}$ and hydrolyzable P from total P.

Both filtered and unfiltered samples were analyzed for all P fractions as described above so that comparisons could be made and techniques evaluated. All unfiltered samples were shaken before taking aliquots for analyses to assure representative samples. The $\text{PO}_4\text{-P}$ in filtered samples was assumed to be the inorganic, water soluble $\text{PO}_4\text{-P}$ fraction. The $\text{PO}_4\text{-P}$ determined directly on unfiltered samples includes the inorganic, water soluble $\text{PO}_4\text{-P}$ plus any P extracted from sediment and converted to $\text{PO}_4\text{-P}$ during the analyses. Hydrolyzable P in unfiltered samples would similarly include hydrolyzable P in filtered samples plus the P extracted from sediment and converted to $\text{PO}_4\text{-P}$ during the hydrolysis. Total P includes all P both in the solution and the sediment.

Total P and $\text{PO}_4\text{-P}$ inputs and outputs were computed for the two irrigation tracts based on the $\text{PO}_4\text{-P}$ concentration in filtered samples, and the total P concentration in unfiltered samples of the irrigation and the surface runoff water and the volumes of these waters for the season on the two tracts. These results were combined with input-output sediment results (3), and P associated with input and output sediment was calculated.

The sediments collected from the 10-liter samples were analyzed for NaHCO_3 -extractable and total P by slightly adapting published methods (6, 1, 18). Where only small sediment samples were obtained, 0.5-g samples were extracted with 10 ml 0.5M NaHCO_3 solution instead of the usual 5 g with 100 ml. Following the extraction, 5-ml aliquots were taken from the supernatant and placed into 50-ml volumetric flasks. Five ml of 4N HCl were added slowly to each sample and the samples were allowed to boil slowly for approximately 1 min to remove carbonates. After cooling, the pH was adjusted and color developed as described for water samples. Total P on sediments was determined by placing 0.1 g of sediment in 40 ml of H_2O in a 50-ml volumetric flask and analyzing as described for total P in water samples.

To evaluate the relationship of P concentration to particle size, soil samples from subbasins drained by certain surface drains were placed in irrigation water and mixed without the aid of dispersing agents and allowed to settle for time periods that gave an aggregate or particle size fractionation into sand, silt, and clay sizes. This separation was assumed to simulate the processes taking place in

streams as eroded soil enters and subsequently settles when the flow velocity slows. Complete dispersion is not expected under these conditions, and the settling of some aggregates containing clay would be expected in the sand and silt size fractions. These size fractions were analyzed for total and NaHCO_3 -extractable P. Soil samples from the surface 15 cm were collected from both tracts on a grid and analyzed for NaHCO_3 -extractable and total P so that results could be compared with those from the sediments collected from surface drainage streams. Forty-four samples were from the Northside tract and 48 samples from the Twin Falls tract.

RESULTS AND DISCUSSION

P Concentrations in Waters

Concentrations of P in the four fractions measured are presented for three sampling dates for the canal waters and for three surface drainage waters from each tract to represent the results. The J-8, N-32 and W drains, representing drainage waters with the highest, near average and lowest sediment concentrations, respectively, were selected for the Northside tract. The Filer, Rock Creek and Deep Creek drains, containing the highest, near average and lowest sediment concentrations, respectively, for the Twin Falls tract were similarly selected.

The $\text{PO}_4\text{-P}$ concentrations were lower in filtered irrigation water than in filtered surface drainage water with a few exceptions (Table 1). Concentrations were generally below 100 $\mu\text{g/liter}$, and independent of the sediment load in the stream, but were generally higher than the 10 $\mu\text{g/liter}$ often associated with waters called eutrophic. Unfiltered samples similarly contained higher $\text{PO}_4\text{-P}$ concentrations than did filtered samples, and concentrations in drainage waters were higher than in irrigation waters. Differences between $\text{PO}_4\text{-P}$ concentrations in unfiltered and filtered samples were greater in drainage waters, and the magnitude of the difference was greater at higher sediment concentrations. These data show that the acid added for $\text{PO}_4\text{-P}$ analysis extracted $\text{PO}_4\text{-P}$ from the sediment and perhaps converted some other P forms extracted to the PO_4^{3-} form. Therefore, the greater the sediment concentration, the greater was the difference between the $\text{PO}_4\text{-P}$ concentration measured in the unfiltered and filtered samples. The $\text{PO}_4\text{-P}$ measured in unfiltered samples, even at very low sediment concentrations, includes more P than the inorganic, water-soluble $\text{PO}_4\text{-P}$. Carter et al. (4, 5) reported earlier that no significant difference in $\text{PO}_4\text{-P}$ concentrations was observed between irrigation and drainage waters. Their samples were not filtered, but the supernatant was sampled for analyses after sediments had settled.

Total P concentrations in unfiltered samples were markedly higher than in filtered samples of both irrigation and drainage waters, and were proportional to the sediment concentration in most drains. This was particularly true when the sediment concentration differences between irrigation and drainage waters were large as was the case for the Filer drain (Table 1). Surface drainage waters generally contained higher total P concentrations than found in irrigation waters. Where differences in sediment concentrations were great, so were differences in total P concentrations. Total P concentrations were greater than $\text{PO}_4\text{-P}$ concentrations in filtered samples which points out

Table 1—Concentration of sediment and different P fractions in irrigation and representative surface drainage waters for two large irrigated tracts for three sampling dates during the 1971 irrigation season

Sampling dates	Northside Tract Canal			Twin Falls Tract Canal		
	6/28	8/3	10/5	7/6	8/17	10/5
Sediment, mg/liter	30	40	30	40	40	30
P, $\mu\text{g/liter}^*$						
$\text{PO}_4\text{-P}$ (F)	17	33	13	21	29	10
(UF)	33	66	66	66	62	50
Hydro (F)	4	3	4	8	7	7
(UF)	33	24	24	24	61	24
Organic (F)	8	14	4	7	3	4
(UF)	28	21	25	45	0	32
Total (F)	29	50	21	36	39	21
(UF)	94	111	115	195	123	106

Sampling dates	J-8 Drain			N-32 Drain			W Drain		
	6/15	7/26	9/28	6/15	7/26	9/28	6/15	7/26	9/28
Sediment, mg/liter	660	170	110	90	180	50	40	30	40
P, $\mu\text{g/liter}$									
$\text{PO}_4\text{-P}$ (F)	25	58	39	36	115	58	3	86	17
(UF)	131	245	139	84	333	131	36	139	74
Hydro (F)	8	4	7	7	16	8	14	12	12
(UF)	96	38	61	55	30	42	38	21	41
Organic (F)	13	4	4	15	4	8	12	4	4
(UF)	76	40	36	79	44	36	26	22	24
Total (F)	46	66	50	58	135	74	29	102	33
(UF)	303	323	236	218	407	209	100	182	139

Sampling dates	Filer Drain			Rock Creek Drain			Deep Creek Drain		
	6/15	7/26	9/28	6/15	7/26	9/28	6/15	7/26	9/28
Sediment, mg/liter	210	2,210	290	140	320	150	70	70	90
P, $\mu\text{g/liter}$									
$\text{PO}_4\text{-P}$ (F)	6	86	33	6	94	66	21	74	58
(UF)	120	1,152	273	74	407	164	58	139	123
Hydro (F)	19	0	6	27	21	8	8	16	16
(UF)	72	80	100	73	37	63	32	25	24
Organic (F)	18	55	7	45	0	24	22	4	8
(UF)	26	140	46	103	21	46	53	0	17
Total (F)	43	141	46	78	115	98	52	94	82
(UF)	218	1,372	419	250	465	273	139	164	164

* The four P fractions are $\text{PO}_4\text{-P}$ or ortho-P; hydro = H_2SO_4 hydrolyzable P excluding the $\text{PO}_4\text{-P}$; organic = organic P obtained by subtracting $\text{PO}_4\text{-P}$ and hydro-P from total P; and total P = persulfate digestible P.

† (F) means filtered through a 0.45 μm filter.

‡ (UF) means unfiltered.

that all the P in samples passing through a 0.45 μm membrane filter is not in the PO_4^{3-} form.

Hydrolyzable and organic P concentrations were generally very low in filtered samples of both irrigation and drainage waters, and they are probably of little significance. Higher concentrations of these two P fractions were found in unfiltered samples. Concentrations of these two P fractions are presented to indicate the proportions of the total P present in the fractions measured, and they are not discussed further in this paper.

The only seasonal trends in P concentrations paralleled those for sediment concentrations and were restricted to concentrations measured in the unfiltered samples.

P Inputs and Outputs for Two Tracts

Most of the $\text{PO}_4\text{-P}$ and total P entering the Northside tract in the irrigation water remained within the tract and did not return to the Snake River (Table 2). This was also true for the sediment, but the portion of the total P remaining in the tract was 90% compared to 80% of the sediment remaining. Only 6% of the diverted water returned as surface runoff from this tract. About 50% as much total P leaves the Twin Falls tract in drainage water as enters in the irrigation water (Table 2), even though there was a net sediment output (3). About 90% as much $\text{PO}_4\text{-P}$ leaves as enters based upon the approach used in this study. Limiting surface runoff has a very favorable effect on sediment and P retention. The difference be-

Table 2—Water, sediment, PO₄-P and total P inputs and total P outputs for two large tracts for the 1971 irrigation season

Source	Water		Sediment		PO ₄ -P		Total P	
	input	output	input	output	input	output	input	output
	10 ⁴ m ³				metric tons			
Northside Tract, 65,350 ha								
Diverted from Snake River	150,631	--	57,250	--	34.38	--	159.39	--
Surface drains, total returned to River	--	9,037	--	12,080	--	4.67	--	19.31
K	--	1,410	--	1,300	--	1.28	--	3.75
N-32	--	2,478	--	2,160	--	1.84	--	5.71
J-8	--	622	--	3,550	--	0.25	--	1.42
S	--	1,780	--	3,440	--	0.60	--	2.97
W-26	--	1,787	--	1,280	--	0.25	--	1.19
W	--	960	--	350	--	0.45	--	4.28
Net input or output	141,594	--	45,170	--	29.97	--	140.08	--
Twin Falls Tract, 82,030 ha								
Diverted from Snake River	138,310	--	75,820	--	28.57	--	189.00	--
Surface drains, total returned to River*	--	37,424	--	113,610	--	25.75	--	94.83
Rock Creek	--	13,930	--	43,090	--	12.11	--	34.84
Cedar Draw	--	4,144	--	8,750	--	2.82	--	11.16
Filer Drain	--	1,084	--	11,280	--	1.13	--	10.16
Mud Creek	--	7,239	--	13,820	--	5.64	--	16.47
Deep Creek	--	4,732	--	5,630	--	1.74	--	7.14
Thirteen small drains	--	6,295	--	31,040	--	2.31	--	15.06
Net input or output	100,886	--	--	37,790	2.82	--	94.17	--

* Includes flow from subsurface drainage tunnels that enter the listed streams as well as water pumped from wells for industrial purposes.

tween the total P and the PO₄-P represents the fraction of the P associated with sediments. The data show that where the sediment load is great, the inorganic, water-soluble PO₄-P represents only a small fraction of the total P. Therefore, limiting the amount of sediment returning to the river also limits the P returning.

The P inputs and outputs shown in Table 2 do not include all P in subsurface drainage water. Previous work has shown that the PO₄-P concentration in subsurface drainage water is very low, and the total amount from the Twin Falls tract would be small relative to the input. No such information is available for the Northside tract, but results should be similar.

Some factors that influence P outputs measured for the Twin Falls tract have no bearing on P outputs from the Northside tract, and they account for the difference observed between the two tracts. One factor is that subsurface drainage water containing only 12 µg PO₄-P/liter (4, 5) enters the surface drains on the Twin Falls tract. This dilutes the PO₄-P concentration in the combined water in the surface drains, but the P in the subsurface drainage waters contribute to the total P output measured in this study. About 14% of the input water leaves the Twin Falls tract as surface runoff (4, 5), but the 37,000 × 10⁴ m³ shown in Table 2 represents a volume approximately 27% of the water diverted onto the tract. Therefore, nearly half of the total outflow measured comes from subsurface sources including drains, tunnels, and water pumped from wells for industrial purposes.

A second factor is that effluents from several processing and industrial plants enter the surface drains listed, and undoubtedly considerable P comes from those sources. A third factor is that effluent from sewage systems and septic tanks enter some of these surface drains. Nevertheless, even with these confounding factors, results indicate that P is conserved. There was a net input of 50% of the total P and 10% of the PO₄-P.

The P inputs and outputs for the Twin Falls tract in this study are not to be confused with the agricultural P inputs and outputs reported earlier (4, 5). In that study, streams known to have P sources other than agricultural

were avoided. All surface runoff samples for determining PO₄-P concentration were collected from field runoff. In the present study, inputs and outputs were based on diverted water and water entering the river from surface runoff drains without avoiding nonagricultural P sources known to be present in some drains as discussed above.

The sediment and P inputs and outputs for the Northside tract are most meaningful from the agricultural and irrigation project viewpoint. However, inputs and outputs from both tracts are important when considering the total amounts of these components returning to the river relative to the amounts diverted from the river. Actually, P is conserved on both tracts, and this is very important because P is a limited, valuable natural resource important to all life.

P Concentrations in Sediments

The NaHCO₃-extractable and total P concentrations were higher for sediments collected from the Northside tract than for those from the Twin Falls tract (Table 3).

Table 3—NaHCO₃-extractable and total P concentrations in sediments collected from irrigation and surface drainage waters for two large irrigated tracts during the 1971 irrigation season

Source	NaHCO ₃ -extractable P					Total P				
	May	Jun	Jul	Aug	Sep	May	Jun	Jul	Aug	Sep
	mg/kg									
Northside Tract										
Diverted water	138	80	46	--	--	1,100	1,243	1,040	1,100	1,278
K	195	148	98	95	51	1,206	1,040	1,036	1,185	1,018
N-32	345	277	104	--	72	1,395	1,392	1,076	1,338	941
J-8	47	75	59	84	68	649	808	1,018	1,110	948
S	166	157	62	53	60	1,075	1,086	966	999	908
W-26	171	191	55	44	64	1,345	1,153	985	1,018	1,940
W	278	404	--	--	318	1,370	1,760	1,000	1,228	1,006
Twin Falls Tract										
Diverted water	133	--	66	37	63	1,160	1,600	1,040	1,025	1,047
Rock Creek	36	122	38	29	33	955	935	831	672	939
Cedar Draw	34	74	44	36	30	895	1,038	902	915	819
Filer Drain	21	52	33	29	31	895	1,006	842	940	952
Mud Creek	30	48	21	26	22	1,040	1,110	1,040	1,138	956
Deep Creek	66	96	20	28	38	912	1,070	602	840	870
Hansen Drain	39	95	32	28	41	882	1,040	870	970	988
Kimberly Drain	54	59	40	38	80	963	1,013	897	912	965

Table 4—Total and NaHCO₃-extractable P for various particle size fractions of surface soils collected from four subbasins, ppm

Drainage subbasin	Total P			NaHCO ₃ -extractable P		
	Sand	Silt	Clay	Sand	Silt	Clay
	ppm					
Kimberly	875	1,000	1,400	33	51	137
Filler	650	975	1,285	13	27	67
K	550	1,150	1,285	21	74	125
J-8	450	1,020	1,325	8	45	70

Table 5—NaHCO₃-extractable and total P concentration in soil samples collected from the surface 15 cm of fields in two large irrigation tracts, mg/kg

	No. of fields sampled	NaHCO ₃ Extractable P				Total P			
		Max.	Min.	Median	Mean	Max.	Min.	Median	Mean
		mg/kg							
Northside tract	44	64	4	22	24	885	488	763	722
Twin Falls tract	48	55	6	20	22	1,007	580	842	839

This is probably a result of the particle size segregation that takes place as water velocities vary. Drains on the Northside tract were constructed to grade and, therefore, have only a slight slope, and most of the larger sediment particles settle from the water before reaching the sampling site near the point where the water tumbles into the Snake River Canyon. The finer particles and aggregates contain higher P concentrations than do the larger ones. This is illustrated by the total and NaHCO₃-extractable P concentrations of the various particle and aggregate size fractions separated from soils of four subbasins in the tracts (Table 4). The NaHCO₃-extractable and total P concentrations are markedly higher for each successively smaller particle and aggregate size fraction.

Results from analyses of surface soil samples collected systematically across the two tracts show that both the NaHCO₃-extractable and total P concentrations are higher in sediments than in the soil from which the sediments were eroded (Tables 3 and 5). This illustrates that particle size segregation takes place in the drainage streams although it is realized that some P enrichment can be brought about through the selectivity of erosion and transport processes. The differences between sediment and soil values are greater for the Northside than for the Twin Falls tract again indicating that more particle size segregation takes place in the surface drains with low slope and subsequently lower flow velocities. The total P in Northside tract soils is lower than in soils from the Twin Falls tract because about one half of the soils on the Northside tract are sands or sandy loams which do not absorb as much P as do silts and clays.

The P concentrations on sediments separated from irrigation water were also high (Table 3) indicating that similar particle size segregation takes place in the river. This would be expected because the river water passes through several reservoirs before reaching the diversion point at Milner Dam.

CONCLUSIONS

The present management practices on both the Northside and Twin Falls irrigation tracts conserve P by remov-

ing much more P from the Snake River in irrigation water than is returned to the River in surface drainage water. This P conservation results from water management practices that limit the fraction of irrigation water that returns to the River, and because of a net sediment input onto the Northside tract. Greater P conservation could be attained by installing properly designed sediment retention ponds to remove more sediment from drainage waters, particularly on the Twin Falls tract. It should be possible to reduce the sediment concentration in drainage waters to or below that found in irrigation waters. Further reducing the surface drainage would also conserve more P and sediment.

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