July 2005

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0038-075X/05/17007-543–558
Soil Science

July 2005
Vol. 170, No. 7
Printed in U.S.A.

LOSS OF PHOSPHORUS BY RUNOFF FOR AGRICULTURAL WATERSHEDS

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The loss of nutrients in runoff from agricultural land is a major cause of poor surface water quality in the United State. Scientists (NRCS) developed a technique to estimate the impact of agricultural watersheds on natural water resources. The objectives of this study were to apply this technique on the Wagon Train (WT) watershed to predict (1) loss of water by surface runoff, (2) loss of phosphorus (P) from soils by runoff and P loading for WT reservoir. The annual loss of water by runoff was estimated at 4.32 million m^3. The USGS data for a 50-year period (1951 to 2000) indicated that the average annual inflow for WT reservoir was 4.25 million m^3. The predicted annual P loss by runoff was 844 kg and could be considered as the annual loading for WT reservoir. The predicted P concentration in the runoff water at field sites was 196 μg/L. Phosphorus concentration observed in major streams at the beginning of spring (March) ranged from 99 μg/L to 240 μg/L with an average of 162 μg/L (S.D.. = 40 μg/L), and the average P concentration in water samples taken from different locations in the reservoir was 140 μg/L. Phosphorus uptake by algae, weeds and aquatic plants, as well as high pH in the reservoir and streams might explain the slight drop of P concentration in waters. Further, the average P concentration observed in the main stream samples for the entire rainy season (March through October), ranged between 157 and 346 μg/L with an average of 267 μg/L (S.D. = 65 μg/L). Application of P fertilizers (April/May) for summer crops might explain the increase in P concentration. When factors affecting P concentration in streams are considered, the technique could provide a reasonable estimation of P concentration in stream water. (Soil Science 2005;170:543–558)

Key words: Agricultural watershed, anion exchange resin, phosphorus release characteristics, runoff phosphorus, runoff water.

WHEN phosphorus (P) applied to agricultural land by fertilizers and manure application exceeds P removal by harvested crops, repeated applications can lead to an accumulation in surface soils. Carpenter et al., (1998) reported that during the period of 1950 to 1995, an average P surplus of 26 kg/ha per year accumulated on agricultural soils in the United States.

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Received Dec. 9, 2004; accepted March 24, 2005.

DOI: 10.1097/01.ss.0000175340.84421.ec

The accumulation increases the potential for P movement from soils through runoff and leaching to pollute surface and ground waters. The downward transport of P through the vadose zone is limited because of the high sorption capacity for most acidic and alkaline soils (Lindsay, 1979). Except for sandy soils in high rainfall areas, leaching P from agricultural land plays an insignificant role in contaminating fresh waters (Elrashidi et al., 2001; Novak et al., 2000). On the other hand, surface runoff from agricultural land is considered a major nonpoint P source of pollution for many lakes, rivers, estuaries, and coastal oceans (Carpenter et al., 1998).

Phosphorus is lost from agricultural land to surface water bodies in sediment-bound and

dissolved forms. Sediment-bound P includes P associated with minerals and organic matter. Dissolved P constitutes 10 to 40% of the P transported from most cultivated soils to water bodies through runoff (Sharpley et al., 1992). Sharpley et al. (1992) reported that surface runoff from grassland, forest, and cultivated soils carries little sediment and carries dominantly dissolved forms of P. Unlike sediment-bound P, dissolved P is readily bioavailable and thus is the main cause of eutrophication.

Dissolved P concentration as low as 20 μg/L in water can cause eutrophication (Sharpley et al., 1999; USEPA, 1996). There is no regulatory threshold for P concentration in surface or ground waters. However, the USEPA (1986) recommended a limit of 50 μg/L for total P in streams that enter lakes and 100 μg/L for total P in flowing water to minimize the impact on freshwater bodies.

The transport of soil P from agricultural land to surface waters depends on many factors including climate, soil type and hydrology, soil P content, agronomic practices, and landscape (Lemunyon and Gilbert, 1993). Most of these factors were considered by the NRCS technique (Elrashidi et al., 2003) to estimate P release from soils by rainfall and quantify runoff P for agricultural land. A brief description of the technique is outlined in the Materials and Methods section.

Eutrophication of some freshwater bodies in Wagon Train (WT) watershed (Lancaster County, Nebraska) raised public concern of the role of agricultural land as nonpoint P source of contamination. The overall goal of the project was to apply the NRCS technique in evaluating the role of agricultural land and how it might affect surface water bodies in WT watershed. The objectives were to estimate (1) water loss from soils by runoff and (2) P loss from soils by runoff and loading in WT reservoir.

MATERIALS AND METHODS

Wagon Train Watershed

Wagon Train (WT) watershed lake is a 128-hectare (315-acre) reservoir located on the Hickman Branch of Salt Creek (Platte River Basin) in Lancaster County, Nebraska (Fig. 1). The reservoir was constructed primarily as a flood control structure by the U.S. Army Corps of Engineers in 1962. The total drainage area encompasses 9,984 acres (4042 hectare) of agricultural land. Most of the area (70%) is cultivated with crops [soybean (*glycine willd*), corn (*zea mays L.*), wheat (*triticum aestivum L.*), sunflower (*helianthus L.*), and alfalfa (*medicago sativa L.*)]. The rest of the watershed is covered with grassland while forest land, wetland, and urban development account for small areas.

The watershed topography is moderately sloping and most soils are well drained. The land relief consists of uplands, stream terraces and bottom lands. There are 53 km (33 miles) of streams in the watershed and 40 ponds ranging in size from 0.3 to 6.5 acres (0.12 to 2.6 hectare). Overland flow enters the reservoir through intermittent tributaries. From the dam, the water flows into the Hickman Branch of Salt Creek, which flows west and north to Lincoln and eventually to the Platte River near Ashland.

The watershed has three major soil associations. The Wymore-Pawnee association soils are deep, nearly level to sloping soils, located on ridge tops and side slopes. The Pawnee-Burchard association soils are deep, gently to steeply sloping, loamy and clayey upland soils that developed in glacial till. The Kennebec-Nodaway-Zook association soils are deep, nearly level or gently sloping silty soils formed in alluvium on flood plains.

We used soil associations on the general soil map in the Soil Survey Report of Lancaster County, Nebraska (Brown et al., 1980), to determine the major soil series and phases in WT watershed. Nine soil series (Wymore, Pawnee, Nodaway, Sharpsburg, Mayberry, Colo, Judson, Burchard, and Kennebec; Table 1) account for 96.1% of the agricultural land. Nearly three-quarters of the watershed consist of Wymore and Pawnee soils.

Soil and Water Sampling

Soil sampling included each of three widely existent phases of Wymore (Wymore-WtB, -WtC2, and -WtD3), and two phases of Pawnee (Pawnee-PaC2 and -PaD2) along with the other seven soil series. This approach gave a total of 12 soil map units. Recently, updated soil survey activities have split Sharpsburg into three series (Tomek, Yutan, and Aksarben). The new classification, however, should not affect results given in this study.

To obtain representative soil samples, we divided the watershed area into six sections. For each of the 12 soil map units, one sample was

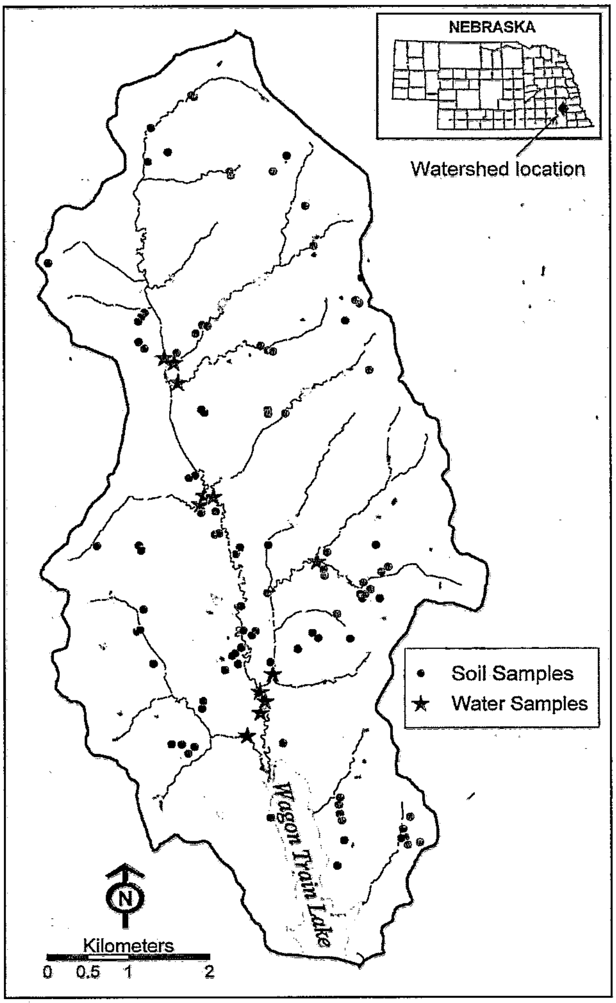

Fig. 1. Soil and water sampling locations in Wagon Train watershed, Lancaster County, Nebraska.

taken from cropland within each of the six sections of the watershed. For each soil map unit, however, only two grassland samples were collected because of the limited area covered with grass in the watershed. Thus, in total, 72 soil samples from cropland and 24 from grassland were collected. At the randomly selected sampling sites, three cores were taken from the top 30-cm soil layer and mixed thoroughly in a stainless steel tray. Approximately, a 2-kg composite sample was packed in a plastic bag and sealed. Sampling was completed during April of 2003 before fertilizer application for the summer crop.

Many small streams receive surface water runoff from the agricultural land in the watershed. Eventually, streams located northerly of the reservoir join in a single stream that runs southerly about 0.5 km before entering the reservoir near the north edge. Water samples taken along the main stream were assumed to represent the surface water runoff generated from the entire watershed.

Most of the surface water runoff from the agricultural land in WT watershed and water inflow for WT reservoir are expected during the rainy season in the spring, summer, and early fall (March through October). In the middle of March, water samples were collected at 12 locations for major streams in the watershed (Fig. 1). These samples include three locations along the main stream before entering the reservoir. Phosphorus analysis for major streams proved that samples taken from the main stream are good representative for runoff generated from the entire watershed. Accordingly, during

the period from April to October, monthly samples were collected only from the three locations along the main stream.

All water samples were taken from streams under base flow conditions to ensure a clear runoff with almost no suspended particulates. Samples were collected (grab) in midstream, by using 1-L polyethylene bottles that have been rinsed twice with stream water before sample collection. The water samples were taken immediately to the laboratory and refrigerated at 4 °C. The water analysis was completed within 1 week. The soil and water sampling locations are shown in Fig. 1.

Soil and Water Analysis

Soil samples were analyzed on air-dried <2-mm soil by methods described in Soil Survey Investigations Report (SSIR) No. 42 (USDA/NRCS, 1996). Alphanumeric codes in parentheses next to each method represent specific standard operating procedures. Particle-size analysis was performed by sieve and pipette method (3A1). Cation exchange capacity (CEC) was conducted by NH_4OAc buffered at pH 7.0 (5A8b). Total carbon (C) content was determined by dry combustion (6A2f), and $CaCO_3$ equivalent was estimated by electronic manometer method (6E1g). Organic C in soil was estimated from both the total-, and $CaCO_3$-C. Soil pH was measured in a 1:1 soil/water suspension (8C1f). Classification and selected properties for soils under crop and grass in WT watershed are given in Table 1.

Soil P was determined by Olsen (Olsen et al., 1954), Bray1 (Bray and Kurtz, 1945), and Mehlich3 (Mehlich, 1984) methods. Anion exchange resin (AER) extractable-P was determined by the Soil Survey Laboratory method (Elrashidi et al., 2003). Phosphorus measured by these methods (mg/kg soil) for soils under crop and grass in WT watershed are presented in Table 2.

TABLE 1

Classification and some properties for the 12 major soils under crop and grass cover in Wagon Train watershed, Lancaster County, Nebraska

Soil (map unit)	Classification	Land use	Clay (%)	OM (%)	CEC (Cmol/kg)	pH-water
Wymore (WtB)	Fine, smectitic,	Cropland	37.3	2.14	25.9	5.56
	mesic Aquertic Argiudolls	Grassland	32.9	2.44	25.7	5.90
Wymore (WtC2)	Fine, smectitic,	Cropland	37.9	2.23	26.5	5.70
	mesic Aquertic Argiudolls	Grassland	35.6	3.46	28.2	5.80
Wymore (WtD3)	Fine, smectitic,	Cropland	41.2	2.16	29.3	5.85
	mesic Aquertic Argiudolls	Grassland	34.2	2.78	28.9	6.40
Pawnee (PaC2)	Fine, smectitic, mesic	Cropland	35.2	1.94	24.9	5.64
	Oxyaquic Vertic Argiudolls	Grassland	29.3	2.38	21.7	5.55
Pawnee (PaD2)	Fine, smectitic, mesic	Cropland	34.9	1.85	24.5	5.79
	Oxyaquic Vertic Argiudolls	Grassland	34.7	2.39	25.5	6.10
Nodaway (No, Ns)	Fine-silty, mixed, superactive,	Cropland	29.4	2.08	24.4	6.58
	nonacid, mesic Mollic Udifluvents	Grassland	30.1	2.97	26.4	6.25
Sharpsburg	Fine, smectitic,	Cropland	39.7	1.94	27.6	5.70
(ShC, ShD, ShD2)	mesic Typic Argiudolls	Grassland	37.4	2.05	27.0	6.15
Mayberry	Fine, smectitic,	Cropland	31.8	1.96	22.8	5.99
(MeC2, MeD2, MhC3)	mesic Aquertic Argiudolls	Grassland	26.0	2.08	20.4	6.50
Colo (Co, Cp)	Fine-silty, mixed, superactive,	Cropland	32.1	2.13	25.0	6.30
	mesic Cumulic Endoaquolls	Grassland	29.0	2.95	26.1	6.10
Judson (JuC)	Fine-silty, mixed, superactive,	Cropland	32.0	2.26	24.8	6.05
	mesic Cumulic Hapludolls	Grassland	30.5	3.06	24.0	6.00
Burchard	Fine-loamy, mixed,	Cropland	29.8	1.89	21.7	5.96
(BpF, BrD, BrE)	superactive, mesic Typic Argiudolls	Grassland	30.1	2.99	23.1	7.00
Kennebec (Ke)	Fine-silty, mixed, superactive,	Cropland	27.6	1.94	20.7	5.95
	mesic Cumulic Hapludolls	Grassland	24.7	2.09	19.5	6.10
Average of all soils		Cropland	34.1	2.04	24.8	5.92
		Grassland	31.2	2.63	24.7	6.15

TABLE 2

Phosphorus extracted by the AER and four conventional soil tests (mg/kg soil) for 12 soils under crop and grass cover in Wagon Train watershed

Soil	AER-1h		AER-24h		Mehlich3		Bray1		Olsen	
	Cropland	Grassland	Cropland	Grassland	Cropland	Grassland	Cropland	Grassland	Cropland	Grassland
	(mg/kg soil)									
Wymore (WtB)	7.21	19.65	17.88	49.67	15.17	64.82	21.49	41.20	6.89	20.82
Wymore (WtC2)	8.70	8.23	20.81	19.43	17.84	6.91	14.71	7.50	8.41	3.01
Wymore (WtD3)	11.24	21.52	29.21	47.88	23.21	44.76	28.56	33.40	9.83	21.03
Pawnee (PaC2)	6.37	4.96	16.70	12.46	11.77	4.99	10.24	4.85	5.05	1.25
Pawnee (PaD2)	4.84	5.10	12.62	11.81	9.08	2.02	7.46	2.70	5.44	1.81
Nodaway (No, Ns)	42.35	15.63	80.81	33.47	73.05	24.88	54.08	21.20	31.21	7.95
Sharpsburg (ShC, ShD, ShD2)	17.24	7.25	43.52	14.58	50.52	7.08	32.88	7.90	16.26	4.17
Mayberry (MeC2, MeD2, MhC3)	13.70	7.33	31.07	16.02	35.65	9.81	23.08	10.25	12.42	5.59
Colo (Co, Cp)	30.85	34.88	54.35	72.59	78.95	81.62	49.74	56.15	27.21	33.23
Judson (JuC)	10.92	16.34	25.17	35.37	21.16	28.64	25.03	26.65	9.60	11.81
Burchard (BpF, BrD, BrE)	4.57	8.75	11.72	21.14	7.42	7.50	9.50	6.20	4.15	5.24
Kennebec (Ke)	14.14	7.32	31.26	15.47	38.10	9.03	24.29	8.75	16.12	5.11
Average of all soils	14.34	13.08	31.26	29.16	31.83	24.34	25.09	18.90	12.72	10.08

Stream-water samples were filtered by using a glass syringe equipped with Whatman 25-mm GD/X disposable nylon filter media (0.45 μm pore size). In the filtrate, pH was measured with a combination glass electrode and digital pH/ion meter (USDA/NRCS, 1996), and P concentration was determined by the modified phosphomolybdate/ascorbic acid method (Olsen and Sommers, 1982).

NRCS Technique

The NRCS technique (Elrashidi et al., 2003), applies the AER method and runoff model to estimate runoff P for agricultural watersheds, which can be outlined as follows (1) the AER method is used to determine phosphorus release characteristics (PRC) for soils, (2) the runoff model is applied to estimate runoff from soil by an annual rainfall, and (3) an energy conversion factor that relates soil:water suspension (AER method) to rainfall energy is used to estimate runoff P.

Phosphorus Release Characteristics

Implementing the linear relationship between P released from soil by AER (mg/kg soil) and the logarithm of extraction period (hour), two equations are developed to describe PRC for a soil. For the 1- to 48-hour extraction region, the regression equation could be written as follows.

$$P = I + S2 \times \text{Log } h \qquad (1)$$

where P = P released (mg/kg soil), I = intercept (mg P/kg soil), S2 = slope, and h = extraction period in hours.

For the 1- to 60-minute extraction region, the regression equation is written as follows:

$$P = I + (I \div 1.78) \times \text{Log } h \qquad (2)$$

where $(I \div 1.78)$ = slope (S1).

In our study, the AER method was applied to estimate the PRC for the 12 soils investigated. Parameters for the linear regression equations (1 and 2) developed to describe P released for the 1- to 60-minute and 1- to 48-hour extraction region are given in Table 3.

Estimation of Runoff Water

The Soil Conservation Service (USDA/SCS, 1991) developed the runoff equation to

TABLE 3

Linear regression equations* used to predict P released by AER (mg/kg soil) for the 1 to 60-minute and 1 to 48 hour extraction region as well as the AER-1h-P and AER-24h-P (kg/ha)† for 12 soils under crop and grass in Wagon Train watershed

Soil	Land use	Intercept (I) (mg P/kg)	Slope (S1) (mg P/min)	Slope (S2) (mg P/h)	AER-1h-P (kg/ha)†	AER-24h-P (kg/ha)†
Wymore-WtB	Cropland	7.21	4.05	7.73	27.69	68.66
Wymore-WtB	Grassland	19.65	11.05	21.75	75.46	190.73
Wymore-WtC2	Cropland	8.7	4.89	8.77	33.41	79.91
Wymore-WtC2	Grassland	8.23	4.63	8.11	31.60	74.61
Wymore-WtD3	Cropland	11.24	6.32	13.02	43.16	112.17
Wymore-WtD3	Grassland	21.52	12.1	19.1	82.64	183.86
Pawnee-PaC2	Cropland	6.37	3.58	7.48	24.46	64.13
Pawnee-PaC2	Grassland	4.96	2.79	5.43	19.05	47.85
Pawnee-PaD2	Cropland	4.84	2.72	5.64	18.59	48.46
Pawnee-PaD2	Grassland	5.1	2.87	4.86	19.58	45.35
Nodaway (No, Ns)	Cropland	42.35	23.82	27.87	162.62	310.31
Nodaway (No, Ns)	Grassland	15.63	8.79	12.93	60.02	128.52
Sharpsburg (ShC, ShD, ShD2)	Cropland	17.24	9.7	19.04	66.20	167.12
Sharpsburg (ShC, ShD, ShD2)	Grassland	7.25	4.08	5.31	27.84	55.99
Mayberry (MeC2, MeD2, MhC3)	Cropland	13.7	7.7	12.59	52.61	119.31
Mayberry (MeC2, MeD2, MhC3)	Grassland	7.33	4.12	6.3	28.15	61.52
Colo (Co, Cp)	Cropland	30.85	17.35	17.03	118.46	208.70
Colo (Co, Cp)	Grassland	34.88	19.62	27.32	133.94	278.75
Judson-JuC	Cropland	10.92	6.14	10.32	41.93	96.65
Judson-JuC	Grassland	16.34	9.19	13.79	62.75	135.82
Burchard (BpF, BrD, BrE)	Cropland	4.57	2.57	5.18	17.55	45.00
Burchard (BpF, BrD, BrE)	Grassland	8.75	4.92	8.98	33.60	81.18
Kennebec-Ke	Cropland	14.14	7.95	12.4	54.30	120.04
Kennebec-Ke	Grassland	7.32	4.12	5.9	28.11	59.40

*P = I + S1 × (Log h) for 1 to 60 minutes; P = I + S2 × (Log h) for 1 to 48-hour extraction region; where P = P released, I = intercept, S1 and S2 is slope, and h = extraction period (hour).

†The AER-extractable P is calculated for the top 0 to 30 cm soil in hectare. Correlation coefficient (r) between P and log h for all regression equations were >0.99.

estimate runoff water from small watersheds by rainfall. The runoff equation is

$$Q = R - [(200 - 2CN)/CN]^2 \div R + [(800 - 8CN)/CN] \quad (3)$$

where Q = runoff (inches), R = effective rainfall (inches), and CN = curve number which is dependent on both the hydrologic soil group and type of land cover (i.e., fallow, crop, or grass).

The annual rainfall for WT watershed (Lancaster County, NE) was taken from the U.S. National Water and Climate Center (NWCC, 2003). In Eq. (3), the effective rainfall (R) is the portion of annual rainfall that could generate runoff and it was assumed to be 20% of the annual rainfall (Elrashidi et al., 2003; Gilbert et al., 1987). The hydrologic group for soil and related CN numbers for various types of land cover are published in NRCS National Engineering Field Manual (USDA/SCS, 1991).

For agricultural land in the watershed, the effective rainfall (R) and the runoff curve numbers were determined then the runoff equation was applied to estimate the runoff water (Q) for soil under fallow, crop, and grass. The equation calculated runoff water in inches. Values were converted to millimeters for this study.

Estimation of Runoff P

Various forms of P such as moisture are held by soil particles at different energy levels. Kinetic energy exerted by raindrops on surface soil plays a major role in releasing P. The Soil Survey Laboratory developed the AER method to determine PRC for soils (Elrashidi et al., 2003). In this method, different levels of energy are applied by water on soil particles when soil suspension is shaken for various periods of time at a constant speed. Understanding the relationship between shaking and rainfall energy enabled the prediction of P released from surface soil by rainfall of known intensity and duration.

Assuming a rainfall intensity of 50 mm/h and that rain force affects the top 10-mm layer of soil, a conversion factor (shaking energy/rainfall energy) = 15 was calculated (Elrashidi et al., 2003). Under the experimental conditions, an energy applied by four minutes of shaking the soil suspension was equivalent to an hour of rainfall event of an intensity of 50 mm/h.

In this study, we used the conversion factor of 15 to calculate the shaking period (hour) equivalent to the annual rainfall. The log of the calculated shaking period was applied in the respective regression equation (1 or 2) (Table 3) to estimate the amount of P released from soil by the annual rainfall (mg/kg soil). The values of annual rainfall (mm), runoff water (mm), and the amount of P released (mg/kg soil) were used to estimate the portion of released P that was removed from surface soil by runoff water (runoff-P). With the knowledge of the soil bulk density and assumption that P was released from the top 10-mm of soil by the annual rainfall, P removed annually by runoff from a known area (i.e., hectare) could be estimated.

Observed Inflow for WT Reservoir

In 1962, the dam on a tributary of Salt Creek and construction of the Wagon Train reservoir were completed. However, the United States Geological Survey (USGS, 2001) has monitored the water flow in Salt Creek and streams in the Platte River basin long before the construction of WT reservoir. The Salt Creek gauge at Roca (USGS gauge # 06803000, hydrologic unit 10200203, Lancaster County, NE) with a period of record from 1951 to 2000 provided an average monthly water flow rate values for a drainage area of 43,286 hectares (106,880 acres) encompassing WT watershed (USGS, 2001). Recently, the Lower Platte South Natural Resources District (LPSNRD, 2004) used the ratio of the watershed to the Salt Creek drainage area (9.34%) to calculate the average monthly water flow rate values for WT watershed. In this study, we used these average monthly water flow rate values to calculate the observed inflow for WT reservoir.

Geographical Information Systems Digital Mapping

Digital maps for water and P losses from agricultural land in Wagon Train watershed, Lancaster County, Nebraska, were generated by Geographical Information Systems (GIS) software. The GIS software used was ArcView 8.3 (ESRI, 2003). The input required to generate the map included spatial data layers (soil series and land cover) and the tabular data from both the runoff model and AER method (water and P loss from soils and concentration in runoff water).

The principal spatial data layer used was the Soil Survey Geographic Database (SSURGO) (USDA/NRCS, 1999). Both the National Land Cover (NLCD, 1992) and National Agricultural Statistics Service (NASS, 2003) spatial layers were used to identify areas of cropland and grassland within the county. Other types of land cover, such as urban, forest, water, or marsh were not mapped for the watershed. The proposed technique calculated water and P losses and P concentration in runoff water for soils under different types of land cover (fallow, crop, and grass). Thus, GIS mapping of agricultural land in the county included data layers for soils and land cover as well as water or P.

RESULTS AND DISCUSSION

Runoff Water

The predicted loss of surface water by runoff (m^3/ha per year) for 12 soils under different land covers in WT watershed is given in Table 4. Fallow (till without planting) was rarely found in the watershed. However, it was included to provide a worst-case scenario if heavy storms and runoff events have occurred during crop field preparations or early growth stages for the summer crop (April to June). Accordingly, the area of cropped soils (70% of the watershed) was also used to predict the runoff water for fallow. Grass covered the remainder of the watershed.

Generally, the loss of water by runoff was slightly higher for fallow than cropland while grassland produced relatively lower values. The predicted average (area-weighted) of runoff water was 1242, 1122, and 939 m^3/ha per year

TABLE 4

Predicted loss of surface water by runoff* expressed as (m^3/ha/y) and (1000m^3/soil/y) for 12 soils under different land covers in Wagon Train watershed

Soil (map unit)	Area (ha)	Runoff water*			Runoff water*		
		Fallow	Cropland	Grassland	Fallow	Cropland	Grassland
		----------(m^3/ha/y)----------			-------(1000 m^3/soil/y)--------		
Wymore (WtB)	558	1280	1167	1000	500	456	167
Wymore (WtC2)	1815	1280	1167	1000	1626	1482	544
Wymore (WtD3)	177	1280	1167	1000	158	144	53
Pawnee (PaC2)	343	1280	1167	1000	307	280	103
Pawnee (PaD2)	77	1280	1167	1000	69	63	23
Nodaway (No, Ns)	203	1057	901	640	150	128	39
Sharpsburg (ShC, ShD, ShD2)	177	1057	901	640	131	111	34
Mayberry (MeC2, MeD2, MhC3)	157	1280	1167	1000	141	128	47
Colo (Co, Cp)	152	1195	1084	880	127	116	40
Judson (JuC)	101	1057	901	640	75	64	19
Burchard (BpF, BrD, BrE)	81	1057	901	640	60	51	16
Kennebec (Ke)	45	1057	901	640	33	28	9
Weighted Average		1242	1122	939			
Total	3885				3377	3051	1094

*USDA/SCS, 1991.

for fallow, cropland, and grassland, respectively. These results accounted for 17.0, 15.4, and 12.9% of the annual rainfall for fallow, cropland, and grassland, respectively. Similar values were reported for 13 United States soils of humid regions (rainfall >800 mm/y) where the average was 16% for fallow, 15% for cropland, and 12% for grassland (Elrashidi et al., 2003).

However, these values were relatively higher than those reported for Lancaster County, NE where WT watershed is located (Elrashidi et al., 2004). This could be attributed to the slow water infiltration rate (hydrologic group D) for the dominant soils (Wymore, Pawnee, and Mayberry) in the watershed. These three soils occupy approximately 80% of the agricultural land in the watershed. The map (Fig. 2), illustrating the water loss by runoff, indicates that these soils of poor hydrologic properties and high runoff potential (runoff >100 mm/y) are evenly distributed throughout the watershed.

Table 4 shows the total volume of water generated from each of the 12 major soils (m^3/soil per year) under different land covers in the watershed. The results indicated that Wymore-WtC2, irrespective of the land cover, produced the highest volume of runoff, mainly because of its abundance in the watershed. Expectedly, Kennebec soil, which had very limited area, generated the least amount of runoff water. The total annual loss of runoff water from the 12 major soils was 4.15 million m^3. Under the worst-case scenario, this value should increase (8%) to 4.47 million m^3. The area of the 12 major soils (3885 ha) cover about 96% of the entire watershed. Thus, when the entire watershed area (4042 ha) was considered the total annual runoff accounted for 4.31 million m^3 of water.

Table 5 and Fig. 3 show (1) the observed average monthly inflow for WT reservoir for a 50-year period between 1951 and 2000 (USGS, 2001), (2) the predicted surface water runoff for WT watershed, and (3) the historic monthly rainfall. The historic record of monthly rainfall for Lancaster County (NWCC, 2003) was used to predict the runoff water. The runoff model (USDA/SCS, 1991) appeared to underestimate the observed water flow to the reservoir for February and March while overestimating the inflow for August and September.

According to the historic record of Lancaster County (NWCC, 2003), a total of 607 mm (23.9 inches) of snow falls during the winter. Usually, a large portion of this snow remains on the ground because of the cold weather. The moderate temperature in early spring could melt much of the snow, which increases the water inflow for the reservoir. This snow melt might explain the underestimation of the inflow for February and March. During the hot summer period, crops such as corn and soybean are in full growth and have a high demand for water. Further, the high temperature and low relative humidity could dry the surface soil and increase evapotranspiration by plants. These combined factors could reduce the runoff and reservoir inflow

and thus explain the overestimation for August and September. The underestimation in early spring appeared to offset the summer's overestimation and kept the predicted annual runoff water (4.31 million m^3) in good agreement with the observed annual inflow (4.25 million m^3).

Phosphorus Released by Rainfall

Linear regression equations to predict P released by the AER technique for the 12 soils under different land covers are given in Table 3. The equations included both the 1- to 60-minute and 1- to 48-hour extraction regions which were used to predict P released from soils (mg/kg soil) by annual rainfall. The intercept at 1-hour extraction period reflects mainly the water soluble and adsorbed P for soil (Elrashidi et al., 2003). For the 12 soils, it varied widely between 4.57 and 42.4 mg/kg soil for cropland and from 4.96 to 34.9 mg/kg soil for grassland.

With the exception of Nodaway and Colo soils, the data in general indicated a low P concentration. The 24-hour extractable P was ranging between 11.7 and 80.8 mg/kg soil for cropland and from 11.8 to 72.6 mg/kg soil for grassland. No trend was observed for the effect of land cover on either 1-hour or 24-hour AER-extractable P. For 24 U.S. soils, the AER-h1-P ranged between 3.8 and 136 mg/kg soil and from 14.8 to 256 mg/kg soil for the AER-24h-P (Elrashidi et al., 2003). The authors suggested that the high P values were probably

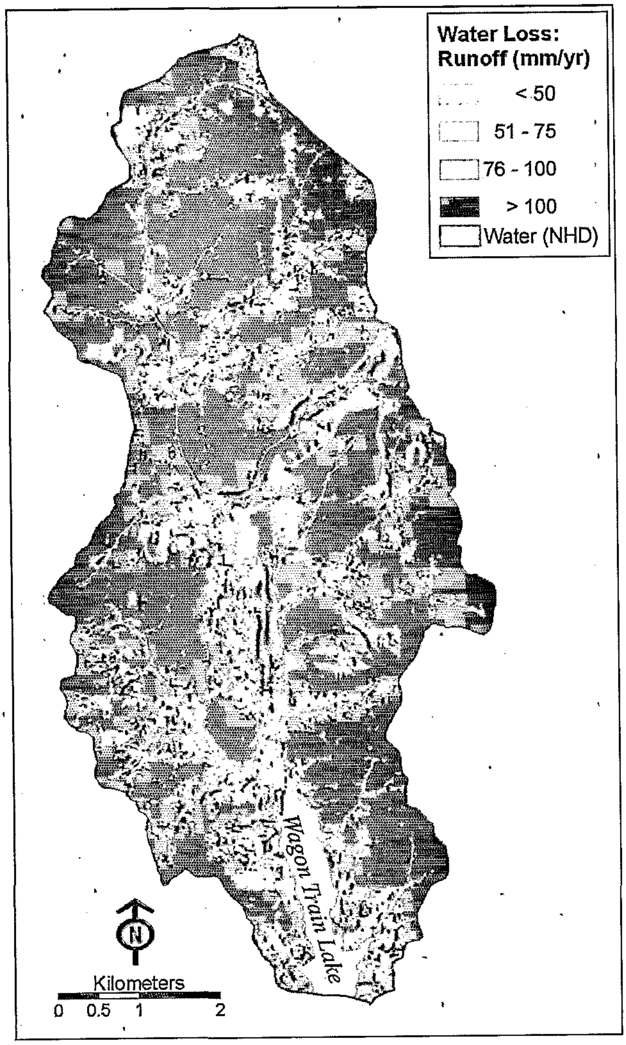

Fig. 2. Water loss by runoff for soils (mm/y) in Wagon Train watershed, Lancaster County, Nebraska.

TABLE 5
Average monthly rainfall (mm), observed inflow* (m^3) for Wagon Train (WT) reservoir, and predicted surface water runoff† for WT watershed

Month	Rainfall (mm)	Observed Inflow* (m^3)	Predicted runoff† (m^3)
January	15	133,860	91,704
February	18	244,371	108,241
March	55	610,517	327,729
April	75	475,674	446,493
May	99	653,013	583,297
June	102	620,296	602,841
July	78	574,396	461,526
August	89	221,684	524,667
September	86	161,071	508,130
October	55	289,677	323,219
November	35	146,678	205,958
December	23	117,571	135,301
Year	729	4,248,808	4,314,713

*USGS, 2001.
†USDA/SCS, 1991.

associated with soils treated with P fertilizers or manure.

Available P for Crops

The AER technique can be used to quantify the readily available P (AER-1h-P) and P supplying power (AER-24h-P) for soils. In their study on 24 U.S. soils, Elrashidi et al. (2003) reported that the AER-1h-P was mainly driven from water soluble and adsorbed forms. The authors also found that the AER-24h could remove all P forms dissolved by Bray1 and Olsen solution. Olsen and Khaswneh (1980) reported that the resin-extractable P is related to labile P and to Olsen's bicarbonate extraction. Therefore, the AER-24h could be considered a valid measure of the capacity factor for soils. Table 2 shows the amount of P extracted (mg/kg soil) by both the AER-1h and AER-24h as well as three conventional soil tests (Olsen, Bray1, and Mehlich3) for 12 soils under crop and grass in WT watershed.

The amount of P extracted by the AER-1h and Olsen test was very similar, and a highly significant correlation (r = 0.98) was obtained between the two methods for soils under crop and grass. Both Bray1 and Mehlich3 extracted relatively higher amount of P than the AER-1h. For Bray1, a highly significant correlation with the AER-1h was obtained for soils under crop (r = 0.95) and grass (r = 0.98). For Mehlich3, the corresponding correlation with the AER-1h was 0.94 and 0.99 for soils under crop and grass, respectively.

The AER-24h extracted more P than Olsen test but similar to that removed by either Bray1 or Mehlich3 test. Like the AER-1h, a highly significant correlation was also found between the AER-24h and each of the three soil tests (Olsen, Bray1, and Mehlich3) for soils under crop and grass.

Both the AER-1h-P, and AER-24h-P were calculated as kg/ha for the 0- to 30-cm root zone (Table 3). Most cropped soils had a readily available P below 100 kg/ha, indicating a need for P addition to sustain commercial crops such as corn or soybeans. Grass P requirements are known to be much lower than crops. However, even with the relatively low P concentrations found for most soils under grass, some grassland soils might need P fertilizers. On the other hand, the AER-24h-P ranged between 45 and 310 kg/ha, with an average of 120 kg/ha for cropped

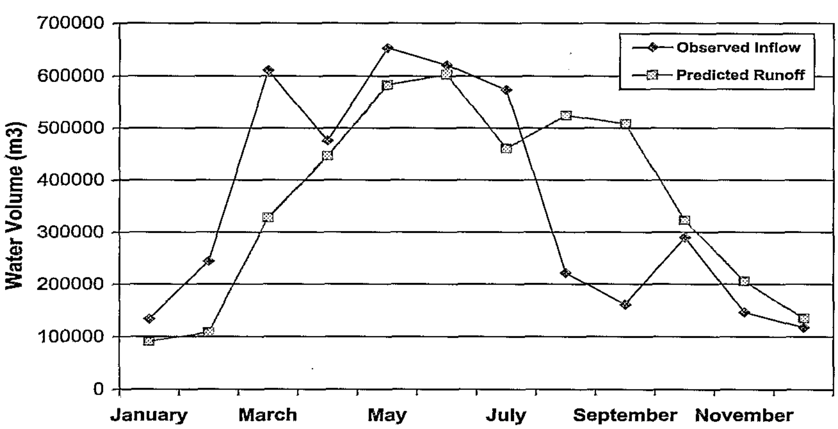

Fig. 3. Observed average monthly water inflow for Wagon Train (WT) reservoir (m^3), and predicted surface water runoff for WT watershed (m^3).

soils. For soils under grass, the range was 45 to 278 kg/ha, with an average of 112 kg/ha. It is unlikely that all P forms extracted by the AER-24h would be available for plant roots during an annual growth season. Accordingly, these data suggested a relatively low P capacity since most soils were below 150 kg/ha.

Runoff P

Land cover (i.e., crop, grass, etc.) could affect the amount of P released from surface soil by rainfall in two different ways: (1) it reduces the volume of surface water runoff generated by rainfall, and (2) it minimizes the area of surface soil exposed to direct rainfall energy. The results (Table 4) indicate that the average runoff water generated by annual rainfall was 1242 m^3/ha for bare soils (fallow), which was higher than that of either cropland (1122 m^3/ha) or grassland (939 m^3/ha). The reducing effect on surface water runoff was also observed for crop residue. Gilley et al. (1986a, 1986b) used a rainfall simulator to measure runoff from plots on which corn, sorghum, and soybean residues were added at rates ranging from 0 to 13.5 t/ha. The authors found that increased rate of surface cover resulted in reduced runoff.

The effectiveness of vegetation canopy in reducing the energy of rainfall striking the soil surface is dependent on the area covered by canopy. For permanent pasture or grass, the canopy covers an area relatively constant during the entire year in comparison to the wide range of coverage for most agronomic crops. It is difficult to estimate the magnitude of reduction in runoff P caused by different types of land cover. However, in comparison to cropland and grassland, fallow (bare soil) releases a higher amount of P in runoff water and represents the worst-case scenario.

The results in Table 6 indicate that the average annual runoff P was 243 g/ha for fallow, 217 g/ha for cropland, and 190 g/ha for grassland in the watershed. These values are on the low side but still within the range for 24 U.S. soils where the estimated average ranged between 0.09 and 8.3 (fallow), 0.06 and 7.5 (cropland), and 0.01 and 6.0 kg P/ha per year for grassland (Elrashidi et al., 2003). The authors reported that the high runoff P values were probably associated with soils treated with P fertilizer or manure. In a field experiment on an Iowa soil (fallow), Tabbara (2003) studied P loss to runoff water from a 90-minute rainfall event after application of manure or fertilizer. He found that the mean loss of dissolved P by runoff water ranged from 0.38 to 1.76 kg/ha.

No large livestock feedlots or intensive cattle grazing are currently present in WT watershed area. Phosphorus fertilizer (50 to 60

TABLE 6

Predicted P loss from soils by runoff expressed as (g/ha/y) and (kg/soil/y) as well as P concentration in runoff water (μg/L) generated from 12 soils under different land covers for Wagon Train watershed

Soil	P loss from soils by runoff water						P concentration in runoff water		
	Fallow	Cropland	Grassland	Fallow	Cropland	Grassland	Fallow	Cropland	Grassland
	(g/ha/y)			(kg/soil/y)			(μg/L)		
Wymore (WtB)	161	147	344	63	57	58	126	126	344
Wymore (WtC2)	194	177	144	247	225	78	152	152	144
Wymore (WtD3)	251	229	377	31	28	20	196	196	377
Pawnee (PaC2)	142	130	87	34	31	9	111	111	87
Pawnee (PaD2)	108	98	89	6	5	2	84	84	89
Nodaway (No, Ns)	781	665	174	111	94	11	738	738	272
Sharpsburg (ShC, ShD, ShD2)	318	271	81	39	33	4	301	301	126
Mayberry (MeC2, MeD2, MhC3)	306	279	128	34	31	6	239	239	128
Colo (Co, Cp)	643	583	533	68	62	24	538	538	605
Judson (JuC)	201	172	182	14	12	6	190	190	284
Burchard (BpF, BrD, BrE)	84	72	97	5	4	2	80	80	152
Kennebec (Ke)	261	222	81	8	7	1	247	247	127
Weighted average	243	217	190	660	591	221	195	194	202

kg P_2O_5/ha) is usually applied to cropped soils during the preparation for summer crop, whereas grassland soils receive smaller amounts and less frequent fertilizer application as well as occasional animal-waste additions. The fact that the soil sampling has been completed before fertilizer application might explain the relatively low P content found particularly for cropped soils and runoff waters. We found that five cropped soils (Wymore-WtB and Wymore-WtD3, Colo, Judson, and Burchard) were depleted of P by the previous year's cropping, with a runoff P lower than soils under grass. This might appear in contradiction with Sonzogoni et al., (1980) who stated that cropped soils, in general, generate higher P concentration in runoff water than grassland soils.

Phosphorus Loss and Loading

For the agricultural land in WT watershed, we assumed that most of the P loss from soils by runoff was transported eventually to WT reservoir. Table 6 shows the estimated P loss by runoff for the 12 soils under different land covers in the watershed. As mentioned, we included fallow in this study to estimate the worst-case scenario when all cropland areas could be considered as fallow due to heavy spring storms. Under the worst-case scenario, the annual P loss by runoff from soils would increase by 8.5% from 812 to 881 kg. As mentioned above (Table 4), the runoff water would increase by 8% from 4.15 to 4.47 million m^3. This change, however, would not have any significant effect on the average P concentration in runoff water generated from the entire watershed area.

Table 6 shows that the predicted P concentration varied widely in runoff water generated from different soils and land covers. For cropped soils, the P concentration in runoff water ranged from 80 to 738 μg/L, with an average of 194 μg/L, whereas it ranged from 87 to 605 μg P/L, with an average of 202 μg P/L for soils under grass. The predicted area-weighted average P concentration for the runoff water generated from the entire watershed (cropland and grassland) was 196 μg/L.

Phosphorus loss from soils generally occurs from hydrologically active areas of a watershed where surface runoff contributing to stream flow is coincident with areas of high soil P (Gburek and Sharpley, 1998; Gburek et al., 2000). They concluded that P loss may be most efficiently managed by focusing on controlling soil P levels and fertilizer as well as manure applications in the watershed zones most likely to produce surface runoff. Accordingly, management practices to prevent P loss from agricultural watersheds should focus on defining, targeting, and remediating the critical source areas of P loss (hot spots).

We applied GIS to present the data in the watershed map (Fig. 4). This approach allowed us to identify the area and location of hot spots as well as soils generating runoff water with high P concentration. The dark area in the map shows Nodaway, Colo, and Sharpsburg soils, which produced runoff water exceeding 300 μg P/L.

Soluble P concentration of at least 20 μg/L in fresh waters can cause eutrophication (USEPA, 1996). To reduce the impact on surface water bodies, USEPA (1986) recommended a limit of 50 μg/L for total P in streams that enter lakes and 100 μg/L for total P in flowing water. The data in Table 6 and Fig. 4 indicate that the predicted P concentration in runoff water exceeded the recommended limits and could cause an environmental problem for WT reservoir.

We used the predicted average P concentration in surface water runoff generated from the entire watershed (196 μg P/L) and the volume of monthly surface water runoff (Table 5) to estimate the monthly P loading (kg) for WT reservoir, which is illustrated in Fig. 5. Expectedly, the results indicated that P loading into the reservoir was least during the winter and averaging about 20 kg/mo. Most of P loading in the reservoir occurred during the spring and summer (93 kg/mo) due to the rainfall pattern. The predicted annual loading for WT reservoir is 846 kg P, which was generated from the entire area of the watershed (4042 ha).

The LPSNRD (2004) collected monthly surface water samples from five locations in WT reservoir to monitor the concentration of P and other contaminants. The dissolved P concentration ranged between 70 and 260 μg/L, with an average of 140 μg/L. This average was lower than the predicted average P concentration in the surface water runoff of 196 μg/L. The difference could be attributed to the high pH values observed for water in the reservoir. The LPSNRD (2004) reported a pH value ranging from 7.33 to 9.64, with an average of 8.49 for the five water samples collected at different locations in the reservoir.

The water pH values for the 12 cropped soils were mainly within the acidic range fluctuating between 5.56 and 6.58, with an average of 5.92 (Table 1). Under grass, pH values ranged

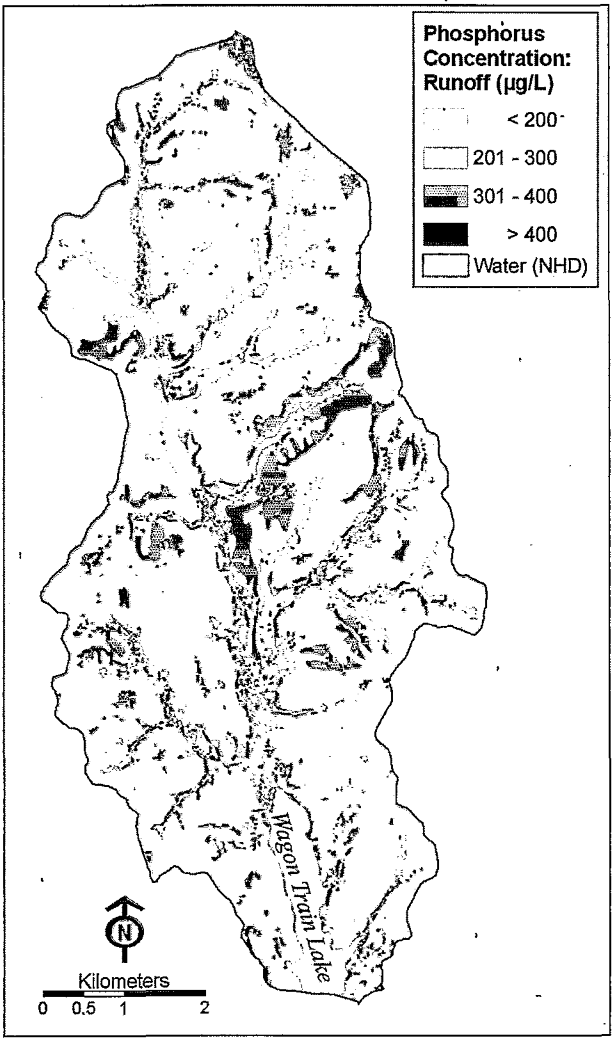

Fig. 4. Phosphorus concentration in runoff water from soils (µg/L) in Wagon Train watershed.

between 5.55 and 7.00, with an average of 6.15. Monocalcium phosphate [$Ca(H_2PO_4)_2$] is the major form of phosphate fertilizers usually added to these soils. Changing pH of the runoff water from acidic and near neutral to the alkaline range in the reservoir could transform the $Ca(H_2PO_4)_2$ to $CaHPO_4$ or $Ca_3(PO_4)_2$, which both have lower solubility in water (Lindsay, 1979). Further, a presence of large populations of algae, weeds, and aquatic plants in the reservoir could assimilate P and decrease the concentration in water.

Most of the runoff from agricultural land in WT watershed is expected during the spring, summer, and early fall (Fig. 3). Phosphorus concentration from major streams at the beginning of spring (March), ranged from 99 µg/L to 240 µg/L, with an average of 162 µg/L (S.D. = 40 µg/L). The predicted value of 196 µg P/L is greater than and is within 1 S.D. of the observed average P concentration in streams. Meanwhile, the pH value in stream water samples ranged from 8.10 to 8.57, with an average of 8.39. This pH was higher than the average pH value (about 6.00) measured in soils (Table 1). The technique used in this study predicted P concentration in runoff at the edge of field. The increase in water pH as well as P removal by aquatic weeds and algae could be the cause of the lower P concentration observed in stream water.

Furthermore, the average P concentration observed in the main stream samples for the

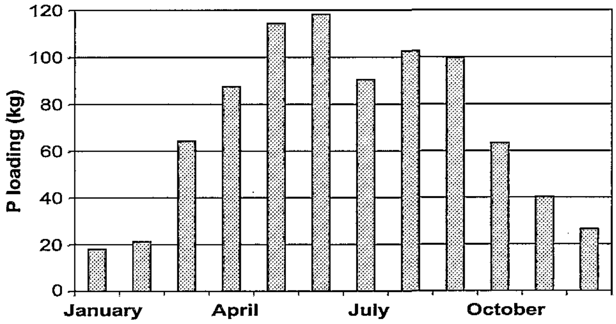

Fig. 5. Predicted average monthly phosphorus loading by runoff water (kg) in Wagon Train reservoir.

entire rainy season (March through October) ranged between 157 µg/L (March) and 346 µg/L (July), with an average of 252 µg/L (S.D. = 65 µg/L) (Fig. 6). This average rainy season P concentration is greater than the predicted P concentration of 196 µg/L. Field applications of P fertilizer (April and May) for the summer crops could contribute to the relatively higher observed P concentration (May through August) in water. However, the predicted P value is within one standard deviation of the observed stream P concentration for the entire rainy season.

In conclusion, we need to emphasize that the predicted P value was calculated for runoff water generated at field sites and not in WT streams or reservoir. Factors affecting P concentration in runoff water after leaving field sites such as change in water chemistry as well as P removal by aquatic weeds and algae should be taken into consideration. The data suggested that the two factors have lowered P concentration by approximately 17% (from 196 to 162 µg/L). Therefore, when we consider factors affecting P concentration in runoff after leaving field sites, the technique could provide a reasonable estimation of P concentration in stream water.

In this study, soil samples were collected before fertilizer application to reflect background soils condition. This also explains the low P content found in soils. However, future study should include sampling from fertilized soils to predict the worst-case scenario for P loss by runoff.

CONCLUSIONS

Agricultural chemicals such as phosphorus and nitrogen can be transported from surface soils by runoff to freshwater bodies. Therefore, agricultural watersheds, particularly in high rainfall areas, may pose risk to the water quality in streams, rivers, and lakes. The NRCS technique uses existing climatic, hydrologic, and soil survey databases to estimate the loss of water and P by runoff from agricultural watersheds. It can be applied on a small watershed (20 to 40 ha) or a large area of agricultural land that may include thousands of hectares. The GIS software, which uses available spatial soil and land cover layers as well as the predicted data for water and P losses, can be applied to develop digital maps. These maps improve data presentation and communications with the clientele as well as identify P hot spots within a watershed.

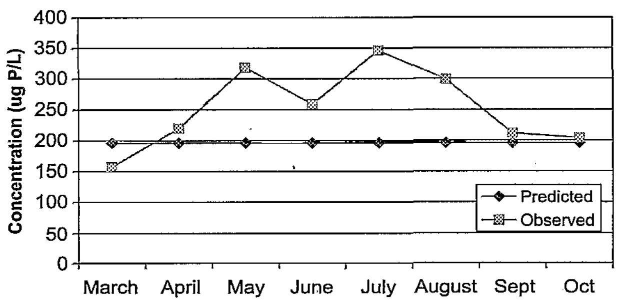

Fig. 6. Predicted and observed average monthly phosphorus concentration (µg/L) in Wagon Train watershed stream water.

The technique predicted annual runoff water of 4.31 million m^3, with an average P concentration of 196 µg/L for WT watershed. The predicted and observed values for the runoff and P loss appeared to have reasonable agreement, particularly when factors affecting P concentration in streams are considered. The technique offers a cost-effective, quick, and reliable tool to conduct exploratory evaluation for large area of agricultural watershed. Thus, lengthy and site-specific studies could be focused on certain areas of high risk.

Even in the absence of potential sources of P contamination such as animal feedlot, intensive cattle grazing, heavy P fertilization or P-enriched soil minerals, the agricultural land in WT watershed still can release enough P in runoff to cause eutrophication of fresh waters. Compliance with the recommended P limits for confined and flowing water systems appears to be a formidable task. Management practices or nutrient attenuation mechanisms (i.e., riparian wetland) that can reduce P concentration in runoff waters before discharging into freshwater bodies should be considered. To be most effective, P management efforts should be targeted to identified hot spot areas within a watershed that are most vulnerable to P loss.

ACKNOWLEDGMENTS

The authors would like to acknowledge the input from many individuals at the National Soil Survey Center (NSSC). We are especially grateful to Robert J. Ahrens, NSSC Director, for his support during the course of this study. We also appreciate the invaluable suggestions and constructive criticism from Robert Grossman, Warren Lynn, Tom Reedy, and Lyle Steffen. The authors also thank members of the Soil Survey Laboratory: Patty Jones, Chris Lee, Tom Zimmer, Jan Lang, and Pam VanNeste for soil and water analysis.

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