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Gully treatment and water quality in the Southern Plains

Andrew Sharpley, S.J. Smith, J.A. Zollweg, and G.A. Coleman

ABSTRACT: Erosion of agricultural land and transport of associated fertilizer chemicals nitrogen (N) and phosphorus (P) in runoff, can be detrimental to both soil productivity and water quality. In the Southern Plains, gully erosion is of concern due to periodically intense rainfall and a large acreage of erodible soils. As little information is available, we studied the loss of sediment, N, and P in runoff over 13 yr (1980–1992) from two adjacent extensively gullied native grass watersheds (3.8 and 5.7 ha of 5% slope and class 4 erosion) in the Little Washita River Basin, OK. In 1983, the gullies on one of the watersheds were treated by land shaping, Midland Bermudagrass [Cynodon dactylon *(L.) Pers] establishment, and construction of a runoff detention pond. Prior to gully treatment, greater ($p > 0.05$) amounts of sediment, N, and P were lost from the subsequently treated than untreated watershed. Following gully treatment, 27,500 kg sediment, 7.1 kg N, and 4.1 kg P ha^{-1} yr^{-1} were lost from the gullied watershed, while only 4,900 kg sediment, 3.1 kg N, and 1.6 kg P ha^{-1} yr^{-1} were lost from the treated watershed. While gully treatment had no effect on nitrate-N and ammonium-N loss, dissolved P and bioavailable P losses were increased six-and three-fold, respectively. This was attributed to the application of fertilizer N and P to the treated watershed only. The loss of N and P in runoff from gullied and treated watersheds was accurately predicted using kinetic and enrichment ratio approaches with soil properties reflecting the main zone of runoff and soil interaction. Subsoil (5–20 cm) properties accurately predicted N and P release and transport in runoff from the gullied watershed, whereas accurate predictions for the treated watershed were obtained with surface soil (0–5 cm) properties. The cost of gully treatment was \$1,098 ha^{-1}, with a reduced loss of 210 kg sediment, 5 g N, and 3 g P in the ensuing 10 years for every dollar spent on treatment.*

In 1994, the U.S. Environmental Protection Agency reported that more than 70% of water quality problems in surveyed rivers and lakes resulted from agricultural nonpoint sources. In most cases, these problems arise from runoff losses of soil and agrichemicals, such as fertilizer nitrogen (N) and phosphorus (P). Erosion can have a major negative impact on soil productivity and siltation of water resources (Langdale et al. 1985; Barr et al. 1979). The input of N and P in runoff can accelerate eutrophication of fresh and coastal waters, impairing use for recreation, industry, and drinking (Sharpley et al. 1994). Agricultural runoff now accounts for a larger share of the water quality problems in the U.S. than a decade ago (US EPA 1994), because of control of point sources.

Nitrogen and P are transported in dissolved and particulate (associated with eroding soil and organic material) forms. Dissolved P and N (nitrate-N) are immediately available for biological uptake. Particulate P constitutes a variable but long-term source of potentially bioavailable particulate P (i.e., available to aquatic biota) (Sharpley et al. 1992). The bioavailable P content of runoff, therefore, is the sum of

Andrew Sharpley is a soil scientist and J.A. Zollweg is a hydraulic engineer, USDA-ARS, Pasture Systems and Watershed Management Research Laboratory, Curtin Road, University Park, PA 16802-3702, (814) 863-0948; S.J. Smith is a soil scientist and G.A. Coleman is a hydraulic engineer (retired), USDA-ARS, National Agricultural Water Quality Laboratory, P.O. Box 1430, Durant, OK 74702-1430, (405) 924-5066.

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Interpretive summary

Erosion and loss of crop nutrients in runoff from agricultural land can harm both soil productivity and water quality. Although only 10% of U.S. farmland is classed as highly erodible, it contributes over 40% of the total erosion and nutrient loss. Marginal grazing lands in the Southern Plains are susceptible to gully erosion. Runoff quality from two gullied watersheds in south central Oklahoma was measured for 12 years. On one watershed, the gullies were filled with soil, grass established and a runoff detention pond built. After this, erosion was reduced six-fold and nutrient loss cut in half. This fairly intensive remediation of eroding gullies cost \$1100 ha^{-1} for every dollar spent and the farmer saved more than 200 kg of soil or nearly 2 inches of topsoil.

Key words: algal-available phosphorus, best management practices, cost of remediation, erosion, eutrophication, fertilizer loss in runoff, nitrogen, phosphorus, nonpoint source modeling, remediation, runoff

dissolved and bioavailable particulate P.

Sediment and nutrient transport in runoff in the Southern Plains can be large, due to the erratic timing and intensity of rainfall and predominance of highly erodible soils. For example, highly erodible farmland in the U.S. comprises only 10% of total agricultural land, but contributes over 40% of total agricultural erosion and chemical loss (Economic Research Service 1988). On marginal farmland, gully erosion can be a major source of soil and associated N and P losses, which can be delineated and controlled to a varying degree of cost-effectiveness. However, no information is available on the loss of soil, N, and P in runoff from actively eroding gullies on marginal grazing lands in the Southern Plains. Furthermore, no attempts have been made to quantify the effects of gully treatment on soil and nutrient losses in runoff and the cost effectiveness of these remedial treatments.

Reliable field studies investigating the transport of N and P in runoff are lengthy and labor intensive. Thus, models simulating nutrient release from soil and transport in runoff have been developed to assess management effects on N and P loss in runoff (Sharpley and Smith 1993). These conceptually-based equations are described in the following section. However, the release of dissolved soil N and transport in runoff is not predicted, since the primary constituent, nitrate-N, is generally not sorbed by surface soil and moves downward in infiltrating water. The use of these equations has been limited to productive cropping and pasture systems, with little testing on highly erodible, gullied watersheds. Thus, information is needed to determine if these equations can provide accurate estimates of N and P losses in runoff from gullied watersheds.

This paper presents the effects of gully treatment in 1983 on the loss of sediment, N, and P in runoff from a gullied native grass watershed in the Little Washita River Basin of south central Oklahoma in comparison with losses from an adjacent untreated gullied watershed over 13 years (1980–1992). The losses of N and P in runoff from the gullied and treated watersheds were predicted using kinetic desorption and enrichment ratio approaches and compared with measured losses. The watersheds in 1990 are shown in Figure 1. The gullies on watershed L1 are similar to those on L2 prior to treatment.

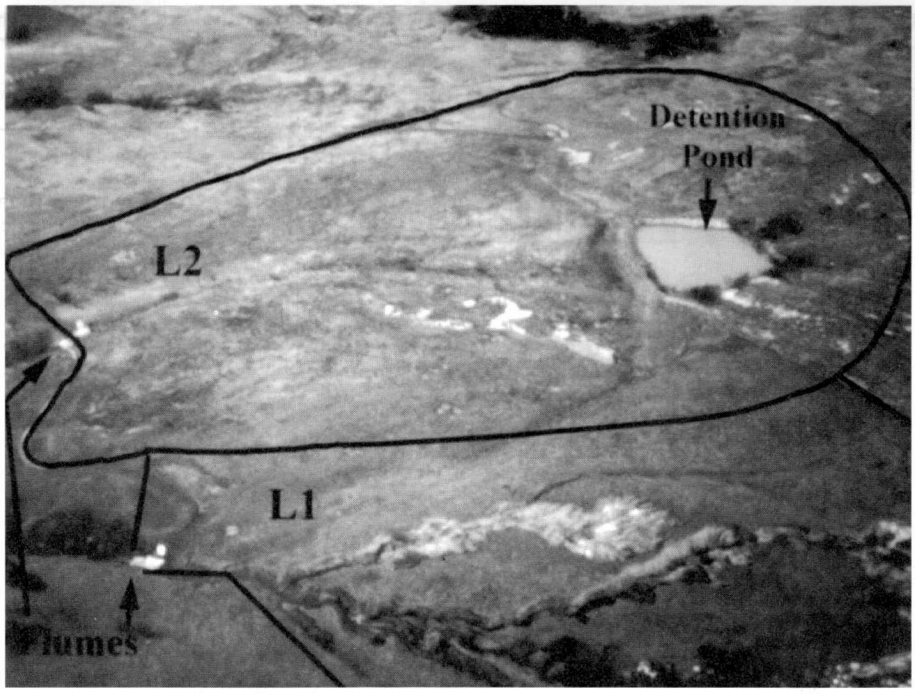

Figure 1. Watershed L1 (untreated gullies) and L2 (treated gullied) in the Little Washita River Basin, OK, 1990

Materials and methods

Watersheds. The two gullied, previously grazed native grassland watersheds are located in the Little Washita River Basin, OK, and Red Rolling Plains land resource area of the Southern Plains (SCS 1981). Management characteristics are summarized in Table 1. Watershed L1 is 3.8 ha, L2 5.7 ha, and both have approximate slopes of 5%. The gullies experienced class 4 erosion (Soil Survey Staff 1951) and comprised about 10% of the watershed area. The major soil type in the watersheds is Lucien-Nash complex loam (loamy, mixed, thermic, shallow Udic Haplustolls).

Runoff measurement and analysis was initiated in both watersheds in January 1980. In 1983, watershed L2 was shaped with a bulldozer to remove the gullies and a small pond (< 0.5 ha) constructed on the upper half of the watershed to reduce soil erosion (Figure 1). The next year, 1984, the treated part of the watershed (about 2.2 ha) was fertilized with broadcast N and P, disked to incorporate the fertilizer, and sprigged with 'Midland' Bermudagrass [*Cynodon dactylon* (L.) Pers.]. Fertilizer N and P was applied in subsequent years based on soil nitrate -N and Bray-I P (Bray and Kurtz 1945) tests (Table 1). In 1989 and 1990, atrazine was applied to control weeds.

The total cost of gully treatment and grass, fertilizer, and atrazine application to L2 during 1983 to 1992 was $2,417. The landowner's cost of fertilizer and grass sprigging in 1984 ($621; Table 1) was shared by the ASCS/SCS ($442) and ARS ($179). During the study period (1980–1992), the gullied watershed L1 remained untreated and unfertilized (Table 1).

Watershed runoff was measured using precalibrated flumes equipped with water-level recorders, with 5 to 15 samples collected automatically during each runoff event. The samples were composited in proportion to flow, to provide a single representative sample and stored at 4°C until analysis. Surface soil samples (0-5 cm depth) were collected annually in March at four sites near the flume of each watershed, composited, air dried, and sieved (2 mm). The N and P content of these soils were determined for input parameters to the nutrient runoff predictions.

Chemical analyses

Runoff. Aliquots of runoff samples were centrifuged [266×10^5 m sec^{-1} ($15000 \times g$) for 5 min] and filtered (0.45 μm) prior to nitrate-N, ammonium-N, and dissolved P determinations, while total Kjeldahl N and total P were determined on unfiltered samples. Analyses for nitrate-N, ammonium-N, and total Kjeldahl N were made by standard automated methods described in *Methods for Chemical Analysis of Waters and Wastes* (US EPA 1994). Total N was calculated as the sum of nitrate-N and total Kjeldahl N. Dissolved P was determined by the colorimetric method of Murphy and Riley, as was total P following perchloric acid digestion of unfiltered samples and neutral-

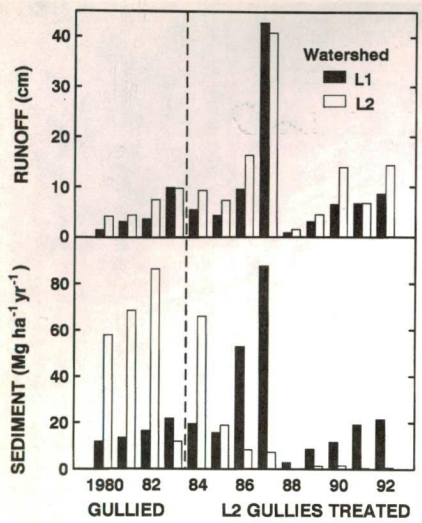

Figure 2. Runoff and sediment loss from gullied watersheds prior to treatment and after gully treatment (1983) on watershed L2, in the Little Washita River Basin, OK

Table 1. Management of the gullied watersheds

Site	Period	Management	Fertilizer N	Fertilizer P	Cost
			kg ha^{-1}		$
L1	1980-1992	None	0	0	0
L2	1980-1983	None	0	0	0
L2	06-09-83	Eroding channel smoothed, pond constructed	0	0	932
L2	03-19-84	Sprigged with Midland Bermudagrass	60	60	621
L2	08-22-86	Fertilizer broadcast	70	0	55
L2	05-08-87	Fertilizer broadcast	77	51	129
L2	05-18-88	Fertilizer broadcast	66	51	108
L2	03-19-89	1.75 kg ha^{-1} atrazine			184
L2	02-26-90	2.2 kg ha^{-1} atrazine			137
L2	06-18-90	Fertilizer broadcast	89	0	251
L2	1991-1992	None	0	0	0
				Total cost	$2417

ization of the digest (Olsen and Sommers 1982). Particulate P was calculated as the difference between total P and dissolved P. Suspended sediment concentration of runoff was determined in duplicate as the difference in weight of 250 mL aliquots of unfiltered and filtered runoff after evaporation (105°C) to dryness.

The bioavailable P content of runoff was measured by shaking one Fe-oxide strip with 50 mL of unfiltered runoff for 16 h on an end-over-end shaker at 25°C (Sharpley 1993a). The strip is then removed, rinsed free of adhering sediment particles, and dried. Phosphorus retained on the strip is removed by shaking the strip end-over-end with 40 mL of 0.1 *M* H_2SO_4 for 1 h, and following neutralization is measured by the method of Murphy and Riley. Phosphorus retained on the strip represents that associated with both dissolved and bioavailable particulate forms.

Iron-oxide impregnated strips were prepared by immersing filter-paper circles (15-cm diameter, Whatman No. 50[1]) in a 10% (w/v) solution of $FeCl_3 6H_2O$. The paper circles were then air dried and immersed in 2.7 *M* NH_4OH solution to convert $FeCl_3$ to Fe oxide. Immersion in NH_4OH was carried out as rapidly as possible to avoid uneven oxide deposition on the paper (Lin et al. 1991). After the paper circles were air-dried, they were cut into strips (10 by 2 cm) and stored for later use. Sharpley (1993a) found the Fe-oxide strips provided reproducible and reliable estimates of bioavailable P.

[1] Mention of trade names implies no endorsement by USDA.

Soil. Clay content of the soils was determined by pipet analysis following dispersion with sodium hexametaphosphate (Day 1965) and organic C by the dichromate-wet combustion procedure (Raveh and Avnimelech 1972). Total N was measured by a semimicro-Kjeldahl procedure (Bremner 1965). Available soil P was extracted by shaking 2 g soil with 20 mL of 0.03 *M* NH_4F and 0.025 *M* HCl for 5 min (Bray and Kurtz 1945). The bioavailable soil P content (Fe-O strip P) of each soil sample was determined by shaking a 1 g soil sample in 40 mL 0.01 *M* CaCl2 and a Fe-oxide strip end-over-end for 16 h at 25°C. The strip was then removed, rinsed free of adhering soil particles, and dried. Phosphorus retained on the strip was removed by shaking the strip end-over-end with 40 mL 0.1 *M* H_2SO_4 for 1 h and measured. Total P content was determined by perchloric acid digestion (Olsen and Sommers 1982). In all extracts, P concentration was measured on neutralized filtrates by the colorimetric method of Murphy and Riley.

Statistical analyses. Statistical analysis of runoff, sediment, N, and P losses between watersheds was conducted using analysis of variance. Although we recognize the problems inherent in attempting to apply any type of statistics to large, natural unreplicated watersheds, we considered years of measurement as a type of replication. Measured and predicted N and P losses in runoff were compared using linear regression analysis, analysis of variance for paired data, and standard error of the predicted value (Barr et al. 1979). In the latter analysis, the measured value (x) was assumed to be correct and have no error, with the standard error in the predicted value (y) representing all variability associated with the predictive equations.

Predictive equations

Dissolved phosphorus. Concentrations of dissolved P in runoff are predicted by the following equation, which describes the kinetics of soil P desorption (Sharpley and Smith 1989).

$$\text{Dissolved } P = \frac{K P_a D B t^{\alpha} W^{\beta}}{V} \qquad [1]$$

where dissolved *P* is the average concentration of an individual runoff event (mg L^{-1}), P_a is available soil *P* content (Bray-I, mg kg^{-1}) of surface soil (0-50 mm) before each runoff event, *D* is effective depth of interaction between surface soil and runoff water (mm), B is bulk density of soil (Mg m^{-3}), *t* is duration of the runoff event (min), *W* is runoff water/soil (suspended sediment) ratio, *V* is total runoff during the event (mm), and K, α, and β are constants for a given soil. Values of K, a, and b were estimated from the ratio of surface soil clay/organic C content (Sharpley 1983):

$$K = 0.630 \text{ (percent clay/organic C)}^{-0.698} \qquad [2]$$

$$\alpha = 0.815 \text{ (percent clay/organic C)}^{-0.540} \qquad [3]$$

$$\beta = 0.141 \text{ (percent clay/organic C)}^{0.429} \qquad [4]$$

Values of *D* were estimated from soil loss (kg ha^{-1}):

$$\text{Ln } D = i\,A + 0.576 \text{ Ln soil loss} \qquad [5]$$

where *i* is a function of soil aggregation (A) (Sharpley 1985a). In a simulated rainfall study, Sharpley found that *D* was a function of rainfall intensity and soil slope and cover, the effects of which could be summarized by soil loss.

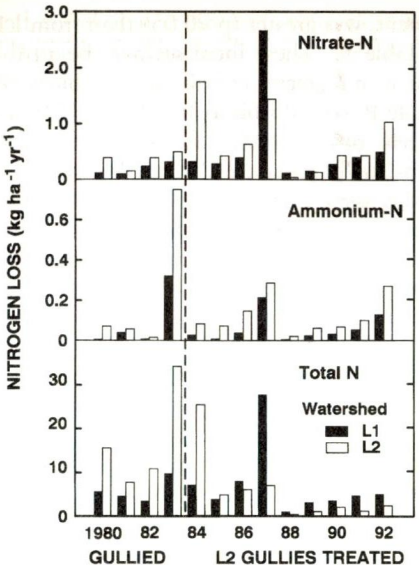

Figure 3. Nitrogen loss from gullied watersheds prior to treatment and after gully treatment (1983) on watershed L2, in the Little Washita River Basin, OK

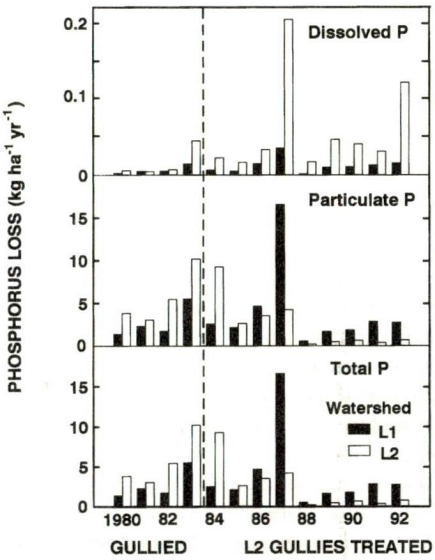

Figure 4. Phosphorus loss from gullied watersheds prior to treatment and after gully treatment (1983) on watershed L2, in the Little Washita River Basin, OK

Particulate nutrients. The selective transport of clay-sized particles in runoff has led to the concept of nutrient enrichment ratios (ER), which are defined as the ratio of the nutrient content of eroded sediment to that of the original surface soil. Enrichment ratios have been used to predict particulate N and P transport in runoff (Menzel 1980). The concentration of particulate N and P in each runoff event is calculated from the total N, total P, and bioavailable P content of surface soil, respectively, using the enrichment ratio for each nutrient form (NER, PER, and BIOER):

Particulate N = Soil total N × sediment concentration × NER [6]

Particulate P = Soil total P x sediment concentration × PER [7]

Bioavailable particulate P = Soil bioavailable P × sediment concentration × BIOER [8]

The unit of soil N and P is mg kg^{-1}, and for sediment concentration of runoff is g L^{-1}. The enrichment ratio was predicted from soil loss (kg ha-1) for each runoff event, using the following equation developed by Sharpley (1985b):

Ln ER = 1.21 - 0.16 Ln soil loss [9]

Bioavailable phosphorus. The bioavailable P concentration of each runoff event is calculated as the sum of predicted dissolved and bioavailable particulate P concentrations.

Table 2. Mean annual runoff and sediment discharge and concentration and loss of N and P from the gullied watersheds before (1980-1983) and after gully treatment (1985-1992)*

Parameter	Concentration, mg L^{-1}				Loss, kg ha^{-1} yr^{-1}			
	1980-1983		1985-1992		1980-1983		1985-1992	
	L1 Gullied	L2 Gullied	L1 Gullied	L2 Treated	L1 Gullied	L2 Gullied	L1 Gullied	L2 Treated
Sediment	—	—	—	—	15900a	56200b	27500a	4900b
Runoff†	—	—	—	—	4.6a	6.5b	10.3a	13.2a
Nitrate-N	0.51a	0.57a	0.62a	0.44a	0.19a	0.35b	0.59a	0.57a
Ammonium-N	0.13a	0.28a	0.07a	0.12a	0.09a	0.22b	0.06a	0.13a
Total N	17.75a	25.91b	7.93a	2.73b	5.84a	17.11b	7.13a	3.13b
Dissolved P	0.01a	0.02a	0.02a	0.06b	0.01a	0.02a	0.01a	0.06b
Particulate P	6.89a	8.41a	4.43a	1.34b	2.74a	5.64b	4.13a	1.60b
Bioavailable P‡	—	—	0.14a	0.40b	—	—	0.17a	0.50b
Total P	6.70a	8.41a	4.45a	1.39b	2.74a	5.66b	4.14a	1.64b

* Concentrations and losses of each parameter followed by the same letter are not significantly different ($p < 0.05$) as determined by analysis of variance.
†Units of runoff are cm.
‡ Data for 1986 to 1992 only.

Table 3. Relative bioavailability of P transported in runoff from gullied (L1) and treated (L2) watersheds*

Year	DP / BAP		BPP / PP		DP / TP		BAP / TP	
	L1	L2	L1	L2	L1	L2	L1	L2
	%							
1986	8	7	4	7	2	3	3	9
1987	5	9	4	11	1	5	4	19
1988	9	12	3	13	1	7	3	21
1989	18	20	3	15	2	9	3	25
1990	14	31	4	45	2	9	4	50
1991	14	36	3	47	1	11	3	51
1992	17	60	3	56	1	15	3	59
Average†	13a	28a	3a	31b	1a	9b	3a	38b

* DP represents dissolved P, BAP-bioavailable P, BPP-bioavailable particulate P, PP-particulate P, and TP-total P.
†Averages followed by the same letter are not significantly different ($p > 0.05$) as determined by analysis of variance for paired data.

Results and discussion

Transport in runoff. Prior to gully treatment, runoff was slightly greater and sediment loss appreciably greater from watershed L2 than L1 (Figure 2). Following treatment of the gullies on L2, sediment loss gradually decreased and after 1985 was consistently lower than from the untreated L1 watershed (Figure 2). Gully treatment had no effect on sediment loss during the 2 years immediately after the operations were conducted, due to extensive land disturbance during treatment. Soil erosion tolerance values (T) from area grasslands is about 6.5 Mg ha^{-1} (SCS 1979). Sediment loss from the gullied watersheds (average 28 Mg ha^{-1}) was consistently greater than the *T* value (Figure 2). However, gully treatment reduced average annual erosion to 4.9 Mg ha^{-1} to slightly below the *T* value.

In contrast to sediment loss, gully treatment had little effect on annual runoff, even though treatment included construction of a pond in the upper half of the watershed (Figure 2). This may result in part

Table 4. Parameter values of Eqs. [1 to 5] for the surface (0 – 5 cm) and subsurface (5 – 20 cm) Nash-Lucien complex soil at the gullied watersheds

Parameter	Surface	Subsurface
Clay, %	14	20
Organic C, g kg^{-1}	16.3	3.1
Bulk density, Mg m^{-3}	1.30	1.35
Soil aggregation*	24	13
K	0.140	0.034
α	0.255	0.086
β	0.355	0.842
i	-1.43	-2.21

* Ratio of percent clay in dispersed and undispersed soil.

from hydrologically active runoff producing zones in the watershed being located below the pond. Apparently, runoff detention ponds should be targeted to areas located below runoff producing zones in a watershed, to decrease the potential for runoff, the mechanism for sediment and chemical transport from a watershed.

Gully treatment dramatically reduced annual total N loss in runoff after the grass cover had become established on the shaped areas (post 1986; Figure 3). This reduction was even more dramatic considering prior to treatment, consistently greater amounts of total N were lost from watershed L2 than L1 (Figure 3). However, treatment had no effect on nitrate-N or ammonium-N losses (Figure 3). In fact, nitrate-N and ammonium-N losses were generally greater from the treated watershed L2 than untreated L1 (Figure 3). This probably resulted from the transport in runoff of fertilizer N applied only to the treated L2 (Table 1). Unlike P, nitrate-N is not sorbed by soil material and thus, is not likely to be transported with eroding soil material. Most of the total N transported in runoff as particulate N will originate from native soil N sources and not fertilizer N.

Phosphorus loss from L2 was consistently greater than from L1 prior to gully treatment (Figure 4). However, 2 years after gully treatment, annual particulate P and total P losses were appreciably lowered compared to the untreated watershed. In contrast to particulate P and total P, annual dissolved P losses were consistently greater from watershed L2 than L1 during the 12-year study, both prior to and after gully treatment (Figure 4). The greater losses of dissolved P from L2 than L1 following gully treatment, probably originate from fertilizer P applied to L2 (Table 1).

The mean annual flow-weighted concentration and loss of sediment, N, and P in runoff from L1 and L2 was determined for the 4 years before treatment (1980-1983) and 8 years after treatment (1985-1992; Table 2). Data for the year of treatment itself was not included, due to the influence of shaping operations of gully treatment on sediment and nutrient losses (Figures 2, 3, and 4). Mean annual N and P concentrations of runoff from L1 and L2 were influenced little by gully treatment, except for a reduction ($p < 0.05$) in total N, particulate P, and total P concentrations and increase in dissolved P and bioavailable P (Table 2). Measurement of BAP was initiated in 1986, thus, no estimates prior to gully treatment were available.

Prior to treatment, runoff and sediment losses from L2 were greater ($p < 0.05$) than from L1 (Table 2). This trend was reversed following treatment, with an 82% reduction in sediment discharge from L2 compared to L1. Similar reductions ($p < 0.05$) in total N (56%), particulate P (61%), and total P (60%) occurred after gully treatment. However, gully treatment with the increase in soil fertility via fertilizer application, increased ($p < 0.05$) both dissolved P (6 fold) and bioavailable P (3 fold) (Table 2).

Although nutrient loss was reduced by gully shaping and establishment of grass cover, long-term management of treated watersheds must consider soil fertility build up via fertilizer applications. In the case of P, added fertilizer increased the bioavailability of P transported (Table 3). The proportion of bioavailable P transported in runoff from L2 following treatment, was greater ($p < 0.05$) than from L1 (Table 3). These increases may be attributed to a greater contribution to bioavailable P from dissolved P (13% for L1 and 28% for L2) leached from plant material; and to particulate P from bioavailable particulate P (3% for L1 and 31% for L2) with preferential transport of clay-sized particles in runoff, accentuated by increased grass cover (Table 3). Generally, clay-sized particles (<2 μm) have a higher P content than coarser particles (>2 μm) (Sharpley and Smith 1990).

The greater transport of dissolved P, and bioavailable P, and relative bioavailability of P in runoff from L2, steadily increased each year after treatment as gully shaping stabilized and grass cover became more complete (Table 3). For example, the proportion of total P as bioavailable P increased from 9% in 1986 (3 years after treatment) to 59% in 1992 (9 years after treatment), while dissolved P increased from 3 to 15% of total P (Table 3). A similar increase in the transport of total P as bioavailable P in runoff with an increase in vegetative cover, was observed by Sharpley (1993b) for no-till (69%) compared to conventionally-tilled wheat (32%) at El Reno, OK.

Prediction of nitrogen and phosphorus loss. The loss of N and P in each runoff event was predicted using Equations [1] through [9]; soil loss; soil clay content, aggregation, and organic C; and available (Bray 1), bioavailable (Fe-oxide strip P), and total P content of surface soil before runoff. As equation constants were calculated from soil physical and chemical properties, all equation parameters were independently determined with no field calibration conducted. Values of the constants and properties for surface soil (0-5 cm) used in the prediction equations are given in Table 4.

The loss of N and P in each runoff event from the treated watershed, L2, was accurately predicted (Table 5). Measured and predicted losses were not significantly different ($p > 0.01$) and regression slopes

Table 5. Measured and predicted mean event N and P loss (g ha^{-1} $event^{-1}$) in runoff from the gullied (L1) and treated (L2) watersheds for 1986 to 1992, using equations [1] to [6] and constants based on surface (0 - 5 cm) or subsoil properties (5 - 20 cm)*

Parameter	Surface soil constants								Subsoil constants			
	L1				L2				L1			
	Meas.	Pred.	Slope	r^2	Meas.	Pred.	Slope	r^2	Meas.	Pred.	Slope	r^2
Total N	433	5874	7.1	0.15	198	211	1.2	0.92‡	433	396	1.1	0.94‡
Dissolved P	1	13	-5.2	0.04	4	5	0.9	0.85†	1	1	0.9	0.84†
Bioavailable P	8	36	1.7	0.03	17	14	1.3	0.81†	8	6	0.8	0.86†
Particulate P	250	639	0.6	0.10	97	88	1.1	0.90‡	250	283	1.2	0.95‡
Total P	263	754	13.6	0.06	102	110	0.9	0.89‡	263	290	1.2	0.91‡

* 127 events analysed for L1 and 112 for L2.
†, ‡ Significant at $p < 0.01$ and 0.001, respectively.

and correlation coefficients were close to 1.0 (Table 5). This held over a wide range in measured total N (1-2728 g ha^{-1} $event^{-1}$), dissolved P (0.03-134 g ha^{-1} $event^{-1}$), bioavailable P (0.04 - 538 g ha^{-1} $event^{-1}$), particulate P (0.3-1763 g ha^{-1} $event^{-1}$), and total P (0.4-1897 g ha^{-1} $event^{-1}$). The error in N and P prediction averaged 21% of the mean event loss.

In contrast to L2, N and P losses from the gullied watershed L1 were consistently over-predicted by a factor of 3 to 14, respectively (Table 5). As a result, measured and predicted losses were not related ($p > 0.05$). On the highly eroded gully watershed, the main zone of interaction of rainfall-runoff and source of runoff sediment is primarily subsoil material. When properties reflecting subsoil material (5-20 cm) for L1 were used in Equations [1] through [5] (i.e., Bray-I P, K, α, β, and i) more accurate dissolved P predictions were obtained (Table 5). Improved N and P predictions were also obtained when subsoil N and P contents were used in Equations [6, 7, and 8] (Table 5). Overall predictive error for N and P loss from the gullied watershed was decreased from 350 to 24% of the measured mean by use of subsoil rather than surface soil properties. Consequently, realistic nutrient predictions ($p < 0.01$), were possible for both gullied and treated watersheds.

Conclusions

The treatment of actively eroding gullies by land shaping, grass establishment, and pond construction improved water quality by reducing sediment and total nutrient loss in runoff. In fact, sediment loss from the treated watershed (4,900 kg ha^{-1}) was slightly lower than T values (6,700 kg ha^{-1}), while loss from the gullied watershed remained greater (27,500 kg ha^{-1}). However, the loss of dissolved nutrients was unaffected and even increased bioavailable P transport in runoff due to the increased soil P fertility afforded by fertilizer applications. Even though the increase in bioavailable P loss was small relative to total reductions, it suggests long-term treatment of gullies should involve careful fertilizer management to avoid soil nutrient accumulations, as well as runoff and erosion control measures. The accurate prediction of N and P loss in runoff with and without gully erosion, indicates the versatility of the equations if appropriate parameters and constants are used. The predictions held over a wide range in event sediment (0.2 – 62,800 kg ha^{-1}), total N (3 – 23,100 g ha^{-1}), and total P losses (1 – 14,000 g ha^{-1}). The cost of this fairly intensive gully treatment amounted to $424 ha^{-1} on a watershed basis and in terms of the critical eroding area (about 2.2 ha) was $1,098 ha^{-1}. In terms of reducing soil and nutrient losses in runoff, the benefit to the farmer was 210 kg sediment, 5g N, and 3 g P for each dollar spent on gully treatment.

The total amount of soil eroded since gully treatment (1985 to 1992) amounted to the loss of a 0.9-cm layer of soil from the gullied area in runoff. Without gully treatment, an appreciably greater 4.3 cm of soil was eroded in runoff from L1. Clearly, gully remediation is essential to improving the areas' surface water quality.

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