SEDIMENT-RELATED TRANSPORT OF NUTRIENTS FROM SOUTHWESTERN WATERSHEDS

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ABSTRACT: Data from rainfall simulation experiments conducted in Arizona and New Mexico were used to identify relationships between total suspended sediment (TSS) concentrations (kg/ha/mm of runoff) in runoff and concentrations (kg/ha/mm of runoff) of total phosphorus (TP), total volatile suspended sediment (TVSS), and total nitrogen (TN). The units of kg/ha/mm of runoff are equivalent to mg/l divided by 100. Data were collected from pinyon-juniper, ponderosa pine, short grass prairie, creosote bush, and bottomland vegetation types. Lumping data from these five vegetation types yielded a relationship for total phosphorus of $TP = 0.0013(TSS)^{0.83}$ with a linear correlation coefficient of $r = 0.77$. The relationship for total volatile suspended sediment was $TVSS = 0.274(TSS)^{0.72}$ ($r = 0.91$). A poor relationship was found for total nitrogen with $TN = 0.008(TSS)^{0.15}$ (with $r = 0.11$). These relationships were validated using data from other rainfall simulation experiments and naturally occurring ephemeral streamflow in southern New Mexico.

INTRODUCTION

The transport of sediment and nutrients from watershed slopes into adjacent water bodies degrades the watershed and affects the water bodies. Watershed loss of sediment and nutrients through rainfall-runoff and erosion processes may reduce watershed productivity and lead to further loss of vegetation and increased erosion (Gifford and Busby 1973). Depending on conditions, watershed-derived inflows can provide organic matter and nutrients to aquatic organisms and lead to increased fish yields, or the inflows may contribute excess nutrients that can cause eutrophication and fish kills (Wetzel 1983).

Over the years, nutrient export from various ecosystems has been studied (Haith 1976; Likens et al. 1977; Timmons and Holt 1977; Clesceri et al. 1986; Byron and Goldman 1989). Work in arid regions typically has focused on sediment alone and not on nutrients (Lane 1982; "Proceedings" 1982). Few studies have addressed water quality of runoff in arid western regions, and those that have usually reported bacteriological or ionic information (Buckhouse and Gifford 1976; Schreiber and Renard 1978; Gosz et al. 1980; Fisher and Grimm 1985.)

In conjunction with ongoing modeling of New Mexico reservoirs (Cole et al. 1987), rainfall simulation experiments were conducted in a variety of ecosystems in New Mexico and Arizona during the summers of 1987 and 1988 (Ward and Bolin 1989a, 1989b). One goal of these experiments was

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to assess the magnitudes of nutrient and sediment exports from watersheds into fishable water bodies. This paper details results from those experiments that address organic matter and nutrient loadings of water bodies and is an expansion of the conference paper by Bolton et al. (1990).

METHODOLOGY

Data Procedures

Data were collected using a spray-down-type rainfall simulator on 1 m^2 plots (Ward and Bolin 1989a). Plots consisted of a three-sided steel frame, which was set into the ground. The fourth side was a sloping runoff tray that allowed runoff to exit the plot. This runoff tray sloped into a PVC pipe whose contents were periodically pumped into a large collection barrel. Plots were rained on in a "dry" antecedent condition and again 6–24 hr later in a "wet" condition. Rainfall intensities ranged from an average of 86 mm/hr at the bottomland site to 125 mm/hr for the creosote bush site. Rainfall was applied until a steady-state runoff rate was achieved.

Water to be analyzed for nutrient and sediment concentrations was collected in acid-washed bottles from barrels that contained the accumulated plot runoff from each experiment. Samples for phosphorus and nitrogen analyses were stabilized with sulfuric or hydrochloric acid and kept on ice or frozen until analyzed. Samples for total volatile suspended solids and total suspended solids were not chemically treated but kept on ice or frozen.

Runoff water from the experiments was analyzed by the New Mexico State University Soil and Water Testing Laboratory for concentrations of total phosphorus, Kjeldahl nitrogen, nitrate-nitrite nitrogen ("Methods" 1979), total volatile suspended solids (a measure of organic matter), and total suspended solids (*Standard* 1980).

Total sediment yield from the plots was composed of the suspended solids pumped into the collection barrel with the runoff and those sediments too coarse to be pumped, which were deposited elsewhere in the collection apparatus. Coarser sediments tended to be deposited on the runoff tray attached to the front edge of the plot and in the PVC pipe, which collected the water from the runoff tray. Sieve analyses showed that typically more than 90% of the sediment pumped into the barrels was finer than 0.074 mm diameter (by dry weight). Therefore, the TSS measurements (the suspended solids) consist of the finer fraction of sediment as sampled from the collection barrels.

Sample Sites

Twelve sites were studied: eight in New Mexico and four in Arizona (Fig. 1). A total of 194 plot runs, (97 plots, with dry-run and wet-run samples for each) were conducted using the simulator.

One of the goals of the study was to identify and predict different quantities of nutrients and sediments in the runoff from watersheds characterized by common vegetation-soil complexes. The 12 sites were placed in one of five broad vegetation types: pinyon-juniper (P-J), ponderosa pine, grassland, desert shrubland (creosote bush), and bottomland. Table 1 lists the general characteristics of each site. Sites were classified for analysis as indicated in Table 1. It should be noted that the Luna site was in a ponderosa pine area but is placed in a separate category because of the presence of unique bottomland soils subject to piping (Hansen (1989).

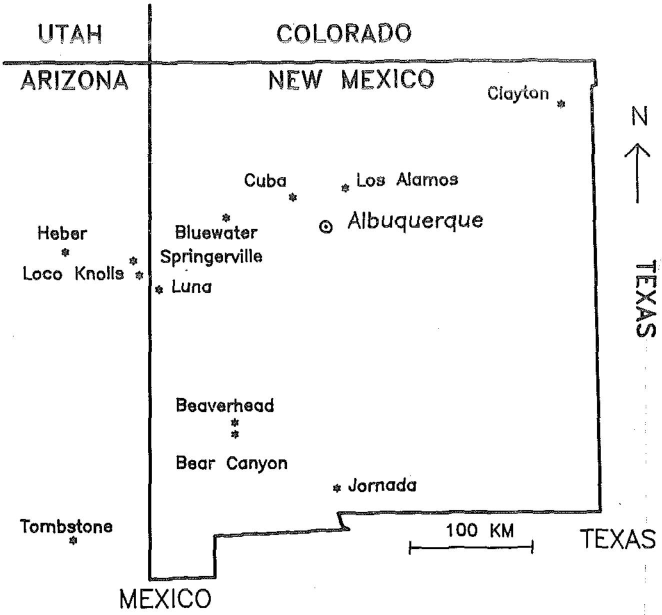

FIG. 1. Location of Simulation Sites Used to Estimate Equations

TABLE 1. Characteristics of Sample Sites

Site (1)	Elevation (m) (2)	Vegetation (3)	Soil[a] (4)
Bear Canyon, N.M.	2,250	Pinyon-juniper	Sandy loam
Beaverhead, N.M.	2,280	Pinyon-juniper	Loamy sand
Bluewater, N.M.	2,370	Ponderosa pine	Sandy loam
Clayton, N.M.	1,650	Grassland	Sandy loam
Cuba, N.M.	1,900	Pinyon-juniper	Sandy loam
Heber, Ariz.	2,000	Pinyon-juniper	Loamy sand
Jornada, N.M.	1,350	Creosote bush	Loamy sand
Loco Knolls, Ariz.	2,380	Pinyon-juniper	Sand
Los Alamos, N.M.	2,050	Pinyon-juniper	Sandy loam
Luna, N.M.	2,300	Bottomland	Sandy clay loam
Springerville, Ariz.	2,240	Pinyon-juniper	Sand
Tombstone, Ariz.	1,370	Creosote bush	Sand

[a] Soils classified by dry sieving and the USDA triangle chart.

RESULTS AND ANALYSES

Values of nutrients and sediment in the runoff water were examined as yields (kg/ha) and as concentrations (kg/ha/mm of runoff, or, equivalently, mg/l). If units of kg/ha/mm of runoff are multiplied by 100, the resultant is concentration in mg/l. Many published studies report yields as kg/ha/time, usually per year. For certain situations, such as areas where rainfall and runoff do not vary greatly from year to year, yields as kg/ha may be appropriate. However, in the Southwest, where rainfall and runoff vary considerably from year to year, a constant value of yield that does not account for the amount of runoff is not very applicable. To make the data more useful for the southwestern climate, yields are reported as kg/ha/mm of runoff. This accounts for the effects the amount of runoff has on yields and allows the estimation of chemical yields for any time period with a known runoff depth.

Chemical and sediment yields and concentrations from each site were analyzed for total phosphorus (TP), total nitrogen (Kjeldahl nitrogen + nitrate-nitrite) (TN), total suspended solids (TSS), and total volatile suspended solids (TVSS). Prior to statistical analyses, all data were log-transformed, resulting in normally distributed values for each variable of interest.

Nutrient and Sediment Yields among Sites

Table 2 lists the means and standard deviations (untransformed data) of nutrient and sediment yields (kg/ha) for all sites by vegetation type. There is a large degree of variance among plots within each vegetation type. Letters in Table 2 indicate whether the mean value for each constituent is significantly different ($p \leqq 0.05$) among vegetation types. If the same letter appears after more than one vegetation type, the yields from those vegetation types are not significantly different. A least-squares-means test was used to distinguish differences among sites.

The bottomland type had the greatest TP, TVSS, and TSS yields. The grassland (short grass prairie) type had the highest nitrogen yields. Yields of total suspended solids were not significantly different for any vegetation types except the bottomland, which had higher yields than any other area.

Nutrient and Sediment Concentrations among Sites

Analyses of material concentrations from the sites in each vegetation type show results similar to those for yields (Table 3). Again, considerable variance is evident in the data. Table 3, like Table 2, indicates whether means for each constituent are significantly different among vegetation types. As with the yields, the highest mean concentrations were from the bottomland for all measurements except for TN, which was highest at the grassland site (Clayton).

Relationships between Nutrients and Suspended Solids

Because more studies have been conducted on arid rangelands with respect to erosion, nutrient yields were related to sediment yields to develop predictive relationships. Power relationships of the form

$$N = a(\mathrm{TSS})^b \quad \text{(1)}$$

where N = nutrient constituent of concern − TP, TN, or TVSS; TSS = total suspended solids; and a and b = regression coefficients for intercept and slope, respectively, were identified for each constituent (Tables 4, 5, and 6).

Residual analysis confirmed the presence of one outlier value of measured TP and four outlier values of TVSS. After review, these outlier data were eliminated from further analyses. For TP relationships, only the a coefficient for creosote and the b power for grassland were more than two standard errors away from those for the lumped site equation.

For TVSS relationships, the coefficients for creosote and ponderosa pine

TABLE 2. Means and Standard Deviations

Vegetation type (1)	TP (kg/ha) Mean (2)	TP (kg/ha) Standard deviation (3)	TN (kg/ha) Mean (4)	TN (kg/ha) Standard deviation (5)	TSS (kg/ha) Mean (6)	TSS (kg/ha) Standard deviation (7)	TVSS (kg/ha) Mean (8)	TVSS (kg/ha) Standard deviation (9)
Creosote; 34[a]; 36[b]	0.60 **AB**	0.87	0.26 **A**	0.37	321.8 **A**	400.1	38.5 **A**	39.7
Grassland; 8[a]; 8[b]	0.18 **ABC**	0.12	1.85 **B**	0.74	147.9 **A**	76.6	18.1 **AB**	6.9
Pinyon-juniper; 112[a]; 118[bc]	0.16 **C**	0.22	0.49 **AC**	0.71	230.6 **A**	279.0	33.6 **AB**	37.4
Ponderosa; 11[a]; 12[b]	0.30 **BD**	0.20	0.53 **C**	0.35	126.4 **A**	96.0	16.6 **B**	16.7
Bottomland; 20[a]; 20[b]	0.96 **D**	0.94	0.18 **A**	0.11	1,230.4 **B**	1,233.1	90.2 **C**	78.7

[a] Number of samples for nutrient samples (phosphorus, nitrogen and volatile solids).

[b] Number of samples for suspended sediment samples.

[c] Number of nitrogen samples is 92. Heber was deleted because the simulator water supply was contaminated at the source.

TABLE 3. Means and Standard Deviations

Vegetation type (1)	TP (mg/l)		TN (mg/l)		TSS (mg/l)		TVSS (mg/l)	
	Mean (2)	Standard deviation (3)	Mean (4)	Standard deviation (5)	Mean (6)	Standard deviation (7)	Mean (8)	Standard deviation (9)
Creosote; 34[a]; 36[b]	1.59 **AB**	1.88	0.84 **A**	0.93	918.6 **A**	838.6	119.9 **AB**	74.1
Grassland; 8[a]; 8[b]	0.74 **AC**	0.53	7.28 **B**	2.88	607.6 **A**	349.3	74.2 **B**	38.4
Pinyon-juniper; 112[a]; 118[bc]	0.82 **C**	0.84	2.56 **C**	3.26	1,068.5 **A**	918.5	164.3 **A**	137.4
Ponderosa; 11[a]; 12[b]	2.20 **BD**	1.41	3.46 **B**	1.66	833.8 **A**	336.9	99.6 **B**	68.2
Bottomland; 20[a]; 20[b]	3.48 **D**	3.34	0.78 **A**	0.57	4,519.3 **B**	4,334.2	332.0 **C**	257.9

[a] Number of samples for nutrient samples (phosphorus, nitrogen and volatile solids).

[b] Number of samples for suspended sediment samples.

[c] Number of nitrogen samples is 92. Heber was deleted because the simulator water supply was contaminated at the source.

TABLE 4. Coefficients in Power Relationships for TP as Function of TSS

Vegetation group (1)	$TP = a(TSS)^b$ (Units of kg/ha/mm of Runoff) *a* (2)	 *b* (3)	 r[a] (4)	 *n*[b] (5)
Lumped	0.00130	0.83	0.77	184
Creosote bush	0.00241	0.78	0.84	34
Grassland	0.00830	1.18	0.97	8
Pinyon-juniper	0.00089	0.87	0.73	111
Ponderosa pine	0.00250	0.97	0.72	11
Bottomland	0.00097	0.93	0.95	20

[a] Linear correlation coefficient based upon log-transformed values. All values are significant at $p \leqq 0.01$.

[b] Number of samples.

TABLE 5. Coefficients in Power Relationships for TVSS as Function of TSS

Vegetation group (1)	$TVSS = a(TSS)^b$ (Units of kg/ha/mm of Runoff) *a* (2)	 *b* (3)	 r[a] (4)	 *n*[b] (5)
Lumped	0.274	0.72	0.91	181
Creosote bush	0.386	0.53	0.88	33
Grassland	0.229	0.66	0.95	8
Pinyon-juniper	0.238	0.82	0.91	111
Ponderosa pine	0.057	1.39	0.91	9
Bottomland	0.211	0.74	0.98	20

[a] Linear correlation coefficient based upon log-transformed values. All values significant at $p < 0.001$.

[b] Number of samples.

were more than two standard errors away from the lumped site coefficients. Some variation was expected because of the differences in soil-vegetation complexes; however, the overall relationships were quite good.

Significant relationships between TN and TSS were found for the ponderosa pine, pinyon-juniper, bottomland, and grassland sites, but only the ponderosa pine site and the grassland site had high correlation values. A small number of samples were collected at these two sites, so it is unclear whether the correlations reflect valid relationships between TSS and TN or are only artifacts of the sample size.

Validation of Relationships

To validate their applicability, the power relationship results were compared to four other data sets. Two of the data sets were from rainfall simulation experiments and two were from ephemeral stream runoff.

Cole et al. (1986) report the results of rainfall simulation in a variety of vegetation types in New Mexico as well as information from a monitored ephemeral channel in a coniferous forest area. These two sets of data are

TABLE 6. Coefficients in Power Relationships for TN as Function of TSS

Vegetation group (1)	a (2)	b (3)	r^a (4)	n^b (5)
	TN = $a(\text{TSS})^b$ (Units of kg/ha/mm of Runoff)			
Lumped	0.008	0.15	0.11	161
Creosote bush	0.007	−0.12	0.09	31
Grassland	0.024	0.63	0.97	8
Pinyon-juniper	0.005	0.47	0.32	91
Ponderosa pine	0.006	0.84	0.80	11
Bottomland	0.001	0.53	0.52	20

[a] Linear correlation coefficient based upon log-transformed values. Values greater than 0.30 are significant at $p < 0.05$ level.

[b] Number of samples.

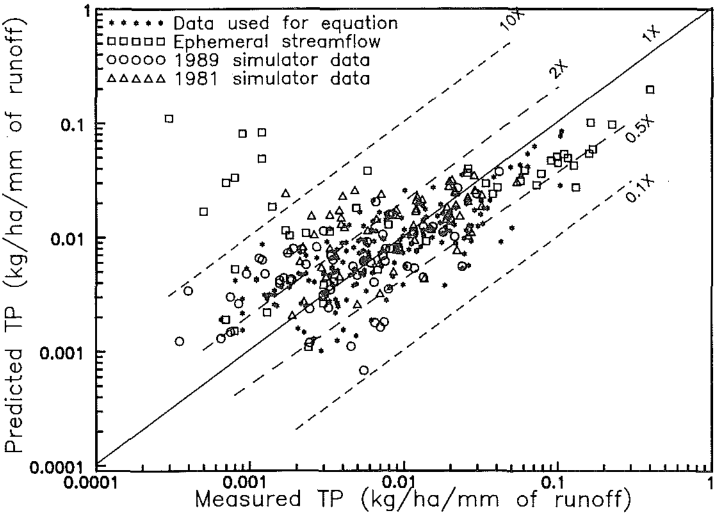

FIG. 2. Predicted and Measured Values of Total Phosphorus

referred to as 1981 simulator data and Sixteen Springs, respectively, in Figs. 2–4. Sixteen Springs data do not appear in Fig. 2 because TP was not measured. Ward and Bolton (1991) present data collected with a rainfall simulator in 1989 at some of the same sites which were used in developing the predictive equations, whereas the data used in developing the equations were collected in 1987 and 1988. The ephemeral streamflow data in Figs. 2–4 are from a creosote bush area (R. A. Cole, unpublished data). The lumped equations in Tables 4, 5, and 6 were used to predict TP, TVSS, and TN from these other studies.

The TP values predicted from the TSS values in the validation data sets are shown in Fig. 2 along with the simulator data (Ward and Bolin 1989a, 1989b), which were used to determine the lumped relationship shown in

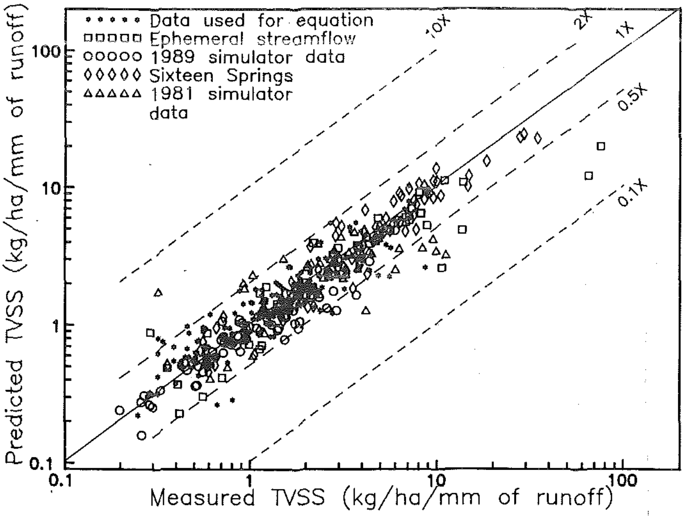

FIG. 3. Predicted and Measured Values of Total Volatile Suspended Solids (TVSS)

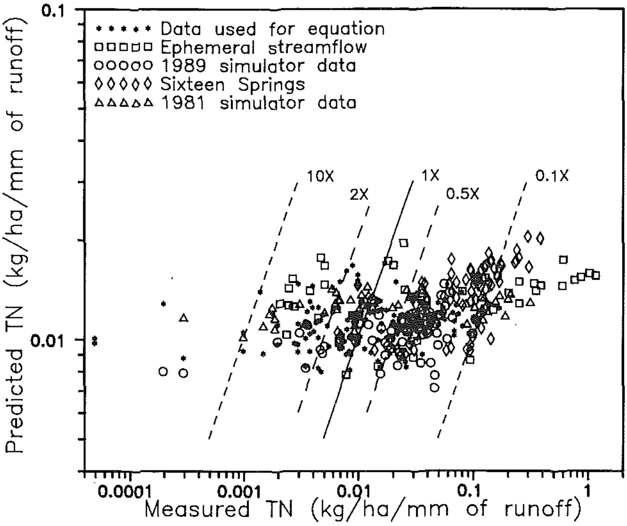

FIG. 4. Predicted and Measured Values of Total Nitrogen (TN)

Table 4. The 1981 simulator data are from Cole et al. (1986) and the 1989 simulator data are from Ward and Bolton (1991). The ephemeral streamflow data were collected in conjunction with Cole et al. (1987).

Figs. 3 and 4 show the relationship between the TVSS and TN predicted and measured values used in development of the lumped relationship in Tables 5 and 6 and the predicted and measured TVSS and TN from the validation data sets. Order-of-magnitude lines of 10 times and 0.10 times and factor lines of 2 times and 0.5 times are added to the graphs to illustrate the variability in the predictions.

COMMENT

Figs. 2, 3, and 4 show several important results. One noticeable point is the relatively small scatter of data on the TVSS graph as compared to the TP graph. This was expected because TVSS is measured as a portion of the TSS sample and for soils that were analyzed in this study, organic soil carbon (a source for TVSS) was relatively constant at a few percent by weight of the soil. By contrast, soil phosphorus values had a range of several hundred parts per million in the same soil. Thus, more variability in TP was expected. Even with the range in soil TP, the runoff TP relationship appears to adequately predict phosphorus concentrations for data from the ephemeral streams and other simulator experiments. Some overpredicted values of TP occurred for the ephemeral runoff in desert creosote bush. The measured TP values from those samples appear to be low, but there is no other reason to expect them to be in error. The predictive capability of TSS for TVSS is better than that for TP as evidenced by Fig. 3. All points lie within an order of magnitude of the one-to-one line, and most points are within the lines for factors of 2 and 0.5.

Fig. 4, which shows the predicted and measured TN relationships, appears about as expected given the results in Table 6. The lumped equation had a very low correlation coefficient between measured and predicted TN in the data sets used to develop the equations. The range of measured TN concentrations is much greater than the range of predicted values. There was no reason to expect better correlations on data sets not used to build the equation.

Studies (Monke et al. 1981; Smart et al. 1985; Byron and Goldman 1989) of nutrient yields from watersheds typically have addressed land-use effects on nutrient and sediment export. In the arid West, there are large tracts of essentially single-use rangeland with differing soil-vegetation complexes. This study indicates that there are differences in nutrient export among some vegetation types, but that in the case of TP and TVSS, these differences can be explained largely by the differential amount of sediment being removed.

Nitrogen, however, is problematic. Nitrogen occurs in many forms and can be fixed biologically or lost to the atmosphere. Nitrogen may be difficult to relate to sediment because it is less likely to be sediment bound than phosphorus. Monke et al. (1981) found that 90% of the phosphorus in Indiana runoff samples from an agricultural watershed was sediment bound, but only 50% of the nitrogen was sediment bound [see also Schreiber et al. (1980)]. Nitrogen is an important nutrient, and more study is required to determine if it can be accurately estimated from known amounts of runoff and sediment from rangelands.

CONCLUSIONS

The analyses and comments presented lead to the following conclusions for the sites studied.

Variations in TP and TVSS from different watersheds are strongly related to variations in TSS.

Suspended sediment yields (concentrations) can be used to estimate TP and TVSS concentrations.

TN is not strongly related to TSS. The range of measured concentrations is much greater than the range of predicted concentrations.

Models of nutrient export in arid and semiarid regions must account for variations in water yields from year to year.

ACKNOWLEDGMENTS

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