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Precipitation Effects on Sediment and Associated Nutrient Discharges from Rhode River Watersheds

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ABSTRACT

Total suspended sediment (TSS) concentrations and their nutrient composition were studied in discharges from seven contiguous small watersheds on the Atlantic Coastal Plain in Maryland for up to 22 yr. All watersheds were equipped with V-notch weirs and volume-integrating, flow-proportional samplers. Spot samples were also taken for analysis of TSS concentrations and the composition of dissolved and particulate nutrients at known water discharge rates. Interannual variations in annual and seasonal precipitation during this study spanned approximately the range of 160-yr weather records in the vicinity. Mean annual TSS fluxes were 263, 546, 134, and 92 kg ha^{-1} for the area-weighted mean of the overall Rhode River watershed, and for subwatersheds that were primarily-cropland, completely forested, and grazed, respectively. TSS fluxes were highest in the summer, followed by spring, winter, and fall. Regressions of TSS flux vs precipitation were used to calculate TSS fluxes for seasons and years with average, above and below the average precipitation. TSS flux from the Rhode River watershed was 12-fold higher in very wet years than in very dry years and 271-fold higher in very wet summers than in very dry summers. At base flow, TSS had high nutrient content, but as flow rates increased TSS nutrient content rapidly declined. At base flow, most of the total-P, TPi, TKN, and organic-C was in the dissolved phase, while at higher flows, most of these nutrients were in the TSS phase.

THE DISCHARGE of total suspended sediment (TSS) from watersheds into receiving waters can become a serious problem when natural vegetation is replaced by agriculture or urbanization (Haan et al., 1994; Reid and Frostick, 1994). TSS is, by weight, the most important aquatic pollutant and also contains large amounts of nutrients and other pollutants, some of which may later be released into the water column of the receiving waters. Many studies have measured the fluxes of TSS from small watersheds dominated by cropland (e.g., Alberts et al., 1978; Burwell et al., 1977; Schuman et al., 1973a,b), pasture land (e.g., Doran et al., 1981; Owens et al., 1982, 1983a,b, 1989; Schuman et al., 1973a,b; Smith, 1992), and forest (e.g., McDowell and Asbury, 1994; Naiman, 1982; Owens et al., 1983a, 1989). Other studies have measured TSS fluxes from larger mixed land use watersheds (e.g., Haith and Shoemaker, 1987; Jordan et al., 1986; Kronvang, 1992). These studies have demonstrated that land use and land use practices are important in controlling the magnitude of TSS fluxes, and that most TSS flux occurs during unusually large or intense storm events.

Many studies also have examined the nitrogen and phosphorus content of the TSS discharged from study watersheds and compared this with the discharge of dissolved nutrients (e.g., Alberts et al., 1978; Cooke, 1988a,b; Duffy et al., 1978; McDowell and Asbury, 1994; Schuman et al., 1973a,b). Some studies also measured the organic-C content of the TSS (e.g., Mulholland, 1981; Naiman, 1982; McDowell and Asbury, 1994). These studies concluded that most of the organic-P, TPi, and organic-N is discharged in the TSS. Many of these studies also developed regression models to describe the relationships among water discharge, TSS concentration, and the organic matter, total-N, and total-P contents of the TSS.

Our objectives in this study were to: (i) characterize the TSS fluxes from various Rhode River watersheds as a function of precipitation; (ii) examine the nutrient composition of the TSS and how this changed with discharge; (iii) determine how the proportion of dissolved and particulate nutrients changed with discharge rate; and (iv) compare our results with those of previous studies.

METHODS

Site Description

The seven watersheds studied are all subwatersheds of the Rhode River, a small tidal tributary to the Chesapeake Bay in Maryland (38°51′N, 76°32′W) on the inner Atlantic Coastal Plain. Four of the subwatersheds were second-order and had mixed land use, while three subwatersheds were small, first-order, and were dominated by a single land use (Table 1). The watershed has sedimentary soils from the Pleistocene Talbot formation at low elevations on the eastern portion, Eocene Nanjemoy formation soils at low elevations further west, Miocene Calvert formation soils at intermediate elevations, and Pleistocene Sunderland formations soils at the highest elevations. The soils are fine sandy loams, and the mineralogy of the soils is fairly uniform, with a high level of montmorillonite and quartz, intermediate levels of illite and kaolinite, and low levels of gibbsite, chlorite, potassium feldspar, and plagioclase (Correll et al., 1984). The surface elevations of the watersheds range from 3 to 50 m. Bedrock is about 1000 m below the surface, but the Marlboro Clay layer forms an effective aquiclude slightly above sea level throughout the watershed (Chirlin and Schaffner, 1977). Therefore, each sub-

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Abbreviations: TSS, total suspended sediment; TPi, total ortho-phosphate; TKN, total Kjeldahl nitrogen.

Table 1. Characteristics of Rhode River subwatersheds. The Rhode River watershed is located at 38° 51′ N, 76° 32′ W.

						Land use†				
Water-shed	Stream order	Area†	Channel slope‡	Basin slope‡	Mean discharge§	Forest	Row crops	Pasture and hay fields	Residential	Old fields
		ha	%	%	mm yr^{-1}	%				
101	2	226	0.76	7.2	337	38	10	27	6	19
102	2	192	0.76	6.3	290	47	18	22	6	7
103	2	253	0.81	9.0	274	63	2	16	5	14
108	2	150	1.27	6.8	282	39	24	20	3	14
109	1	16.3	2.65	5.4	240	36	64	0	0	0
110	1	6.3	5.10	8.3	182	100	0	0	0	0
111	1	6.1	5.86	10.8	196	27	0	73¶	0	0

† Correll 1977.
‡ Correll & Dixon 1980.
§ Correll et al. 1999.
¶ Until 1989 when it was planted in pine, Correll et al., 1995.

watershed has a perched aquifer, and overland storm flows, interflow, and ground water discharges all move to the channel draining each subwatershed. The slopes of the watersheds average between 5 and 11%, and the watersheds ranged in size from 6.1 to 253 ha (Table 1). The subwatersheds also differed in land use from heavily row-cropped to completely forested (Table 1). For more detailed descriptions of the site see Correll (1981) and Correll and Dixon (1980).

Sampling

The study period was from the spring of 1974 through the spring of 1998. Discharges of water from each watershed were measured with sharp-crested V-notch weirs, whose foundations were in contact with the Marlboro Clay aquiclude (Correll, 1977). All weirs were 120° notches, except for watershed 111, which was 150°. Each weir had an instrument building and a stilling well. Depths were measured to the nearest 0.3 mm with floats and counterweights and were recorded every 5 min for watersheds 101, 109, 110, and 111; every 15 min for the other watersheds.

For TSS flux measurements, water samples were composited and volume-integrated for 1-wk intervals, then promptly collected and returned to the laboratory. Until the summer of 1996, a Stevens flow meter (Model 61, Leuopold & Stevens, Beaverton, OR) actuated the sampling of an aliquot once every 154 m^3 of flow on the second order streams and once every 77 m^3 of flow on the first order streams. Beginning in the summer of 1996 a Cambell Scientific data logger (Model CR-10, Cambell Scientific, Logan, UT) was used to control volume-integrated sampling. The sample water was drawn from the stream channel upstream of the weir. After collection, samples were either analyzed immediately or stored at 4°C. To characterize the concentrations of suspended sediments as a function of discharge and to examine the composition of suspended sediments, spot samples also were collected at various stage heights and different times of year.

Rainfall volume data were obtained from the Center's weather station, located on Watershed 101 (Higman and Correll, 1982; and subsequent data). All of the watershed drainage under study was within 4 km of the weather station. Rainfall volumes were measured with standard manual rainfall gauges, and also with a Belfort weighing gauge.

Sample Analysis

The concentration of total suspended particulate matter (TSS) was measured by filtering sample aliquots through prewashed, preweighed Millipore 0.45-μm filters, rinsing with distilled water to remove salts, drying at 60°C, and reweighing.

The composition of TSS in spot samples was determined by analysis of whole and filtered sample aliquots, with the nutrient contained in the TSS being equal to whole values minus filtered values. Total-P was determined by digestion to ortho-phosphate with perchloric acid (King, 1932). Before filtration of samples for phosphate analysis the samples were acidified to 0.1 *M* with sulfuric acid. Total ortho-phosphate (TPi) in both digested and undigested acidified samples was analyzed by reaction with stannous chloride and ammonium molybdate (APHA, 1989). TPi in the undigested, acidified samples was the sum of dissolved and acid-extractable particulate phosphate. Organic-P was calculated by subtracting TPi from total-P. Total Kjeldahl nitrogen (TKN), which includes both ammonium and organic-N, was determined by digestion with sulfuric acid and hydrogen peroxide (Martin, 1972), steam distillation of the resulting ammonium, and Nesslerization (APHA, 1989). Ammonium also was determined on acidified but undigested aliquots and organic-N was calculated as the difference between TKN and ammonium nitrogen. Organic matter was measured as chemical O_2 demand (Maciolek, 1962). An empirical conversion factor of was used to convert to organic C concentration.

Data Preparation

Weir discharges and precipitation volumes were summed for watershed weeks and seasons, which were winter (December, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November). Watershed years began with December. Discharge volumes were multiplied by volume-integrated concentrations to obtain weekly fluxes. Overall area-weighted Rhode River watershed discharge data were calculated by multiplying each watershed flux by the area of that watershed, summing these values for all watersheds, then dividing by the total area of the studied watersheds (Table 1). Several significant gaps in individual watershed data records resulted from storm damage and lack of funding. Data from any individual watershed were only included in the analyses when the weir was operational for a complete season or year. When flow was too low to obtain an integrated sample for analysis, spot samples were analyzed. From 5 to 10% of the discharge data for any given weir were missing due to short-term equipment failures. When no significant precipitation occurred during the data gap, these data were estimated by interpolation of data from the same weir. When storm events occurred during the data gap, these data were estimated by correlation with discharge data from the watershed with the most similar TSS discharge behavior.

The mean and range of annual and seasonal precipitation that were observed during this study were compared with a longer-term record. Higman and Correll (1982) summarized data collected from 1967 to 1977 at our research center from

Table 2. Summary of long-term measurements of total suspended sediment discharges from Rhode River watersheds. Values are means ± one standard deviation from the mean and the number of years or seasons averaged is shown in parentheses.

Time period	Area-weighted Rhode River	Watershed 109 (crops)	Watershed 110 (forested)	Watershed 111 (grazed)
	kg ha^{-1}			
Annual	263 ± 199 (18)	546 ± 894 (17)	134 ± 123 (15)	92.1 ± 87.8 (14)
Winter	41.1 ± 30.9 (19)	72.5 ± 89.2 (18)	23.7 ± 37.6 (17)	41.4 ± 54.1 (16)
Spring	98.3 ± 93.0 (22)	148 ± 274 (19)	60.3 ± 66.2 (18)	44.8 ± 65.5 (17)
Summer	112 ± 153 (21)	288 ± 741 (20)	44.5 ± 72.4 (19)	25.4 ± 35.5 (18)
Fall	11.0 ± 18.6 (20)	26.3 ± 58.3 (19)	10.1 ± 27.8 (19)	3.44 ± 4.49 (17)

1857 to 1967 at the U.S. Naval Academy in Annapolis, MD; and from 1817 to 1856 at U.S. Army Fort Severn, on the Severn River near Annapolis for a total record of 160 yr. All three weather observation sites are on the upper western shore of Chesapeake Bay within 15 km of each other. At the times of data collection they were in fairly small towns, thus minimizing any heat island effects on local weather.

RESULTS

Total Suspended Sediment Flux

The fluxes of TSS from the watersheds had a high interannual variability (Table 2). This variability was highest in the fall, followed by the summer, when standard deviations greatly exceeded the means (Table 2).

Area-weighted mean annual Rhode River TSS flux was 263 kg ha^{-1} (Table 2). Fluxes per area of TSS from watershed 109, which was primarily in row crops, were over double those per area from the overall Rhode River watershed (Table 2). Fluxes of TSS from watershed 110 (completely forested) and from watershed 111 (primarily grazed) were only 51 and 35%, respectively, of those from the Rhode River watershed (Table 2) and paired T-tests found both these fluxes to be significantly lower than from the Rhode River watershed ($P = 0.002$ and 0.02, respectively).

Winter TSS fluxes from the overall Rhode River watershed were only 16% of the annual fluxes (Table 2), even though 35% of the annual water discharge occurred in the winter. Winter TSS fluxes from watershed 109 (crops) were 76% higher than from the Rhode River watershed. Paired T-tests found that TSS fluxes from watershed 110 (forest) and 111 (grazed) were significantly lower than from watershed 109 (crops), ($P = 0.02$ and 0.05, respectively).

Spring TSS fluxes from the Rhode River watershed were 37% of the annual fluxes (Table 2). Average TSS fluxes from watershed 109 (crops) were 51% higher than those from the Rhode River watershed. Fluxes of TSS from watershed 110 (forest) and 111 (grazed) were significantly lower than from the Rhode River watershed ($P = 0.008$ and 0.0003, respectively). Watershed 111 TSS fluxes also were significantly lower than from watershed 110 ($P = 0.04$).

Summer TSS fluxes from the Rhode River watershed were 43% of the annual fluxes (Table 2), making this the season of the highest TSS flux. Mean TSS flux from watershed 109 (crops) was 257% higher than for the Rhode River watershed. TSS fluxes from watershed 110 (forest) and watershed 111 (grazed) were significantly lower than those from the Rhode River watershed ($P = 0.01$ and 0.02, respectively).

Total suspended sediment fluxes were lowest in the fall. Only 4% of the annual flux for the Rhode River watershed occurred then (Table 2). Mean TSS flux from watershed 109 (crops) was 239% higher than from the Rhode River watershed, while mean TSS fluxes from watersheds 110 and 111 were lower.

Total Suspended Sediment Concentrations

Individual watersheds had differing patterns of TSS concentration (Table 3). For example, even though watersheds 101 and 102 were of similar size, mean slope, and land use composition, TSS concentrations were routinely significantly lower from Watershed 102 than Watershed 101, ($P < 0.01$), in each season except fall. Similarly, TSS concentrations from Watersheds 103 and 108 were significantly lower than those from Watershed 101

Table 3. Flow-weighted total suspended sediment concentrations in weekly integrated samples from Rhode River watersheds.

Watershed	N†	Mean	95% Confidence interval
		mg L^{-1}	
A. Winter			
101	268	83.9	50.0–118
102	276	21.8	17.4–26.2
103	264	35.5	26.4–44.6
108	217	22.8	18.4–27.2
109	186	90.6	40.8–141
110	100	35.7	24.1–47.3
111	148	59.8	23.5–96.1
B. Spring			
101	371	174	125–223
102	277	35.4	30.2–40.7
103	282	74.7	57.2–92.2
108	231	50.1	41.7–58.4
109	202	222	117–326
110	171	50.4	40.1–60.8
111	162	58.1	34.3–81.8
C. Summer			
101	205	550	413–686
102	157	148	116–180
103	160	247	173–320
108	125	208	143–272
109	137	703	468–937
110	57	142	92.6–192
111	143	251	139–363
D. Fall			
101	123	70.7	50.4–91.0
102	136	41.8	29.2–54.5
103	135	109	70.5–148
108	101	52.4	38.8–66.1
109	69	76.6	29.0–124
110	32	75.1	20.1–130
111	125	51.9	31.3–72.4

† N, number of samples.

Table 4. Regressions of total suspended sediment fluxes from Rhode River watersheds with precipitation volumes.

	R^2	P
A. Area-weighted Rhode River		
(Annual) TSS† = $0.000249X^{2.90}$‡	0.36	0.009
(Winter) TSS = $0.167X^{1.65}$	0.34	0.04
(Spring) TSS = $0.0161X^{2.52}$	0.69	0.0001
(Summer) TSS = $0.00163X^{3.00}$	0.39	0.004
(Fall) TSS = $0.187e^{(0.0975X)}$	0.21	0.005
B. Watershed 109 (crops)		
(Annual) TSS = $3.57e^{-9}X^{5.36}$	0.53	0.002
(Winter) TSS = $0.0136X^{2.44}$	0.32	0.01
(Spring) TSS = $0.000226X^{3.72}$	0.67	0.02
(Summer) TSS = $6.84e^{-7}X^{5.15}$	0.36	0.005
(Fall) TSS = $0.00173e^{(0.258X)}$	0.57	0.01
C. Watershed 110 (forest)		
(Annual) TSS = $7.51e^{-14}X^{7.33}$	0.59	0.0002
(Winter) TSS = $0.000148X^{3.29}$	0.48	0.13
(Spring) TSS = $0.0000225X^{4.18}$	0.69	0.001
(Summer) TSS = $2.80e^{-6}X^{4.42}$	0.32	0.0001
(Fall) TSS = $0.00407e^{(0.188X)}$	0.35	0.07
D. Watershed 111 (grazed)		
(Annual) TSS = $0.0418X^{1.52}$	0.04	0.59
(Winter) TSS = $0.000573X^{3.18}$	0.62	0.01
(Spring) TSS = $0.00677X^{2.33}$	0.29	0.01
(Summer) TSS = $0.0905X^{1.34}$	0.08	0.89
(Fall) TSS = $0.0758X+1.34$	0.02	0.62

† TSS, total suspended sediment flux in kg ha^{-1}.
‡ X, precipitation depth in cm.

(for 103, $P < 0.01$ in spring and summer, $P < 0.05$ in winter; for 108, $P < 0.01$ in all three seasons). Likewise, TSS concentrations were significantly lower from Watershed 102 than Watershed 103 in the winter ($P < 0.05$) spring ($P < 0.01$), and fall ($P < 0.05$). Thus, of the larger second-order watersheds, 101 routinely had higher TSS concentrations, followed by Watershed 103.

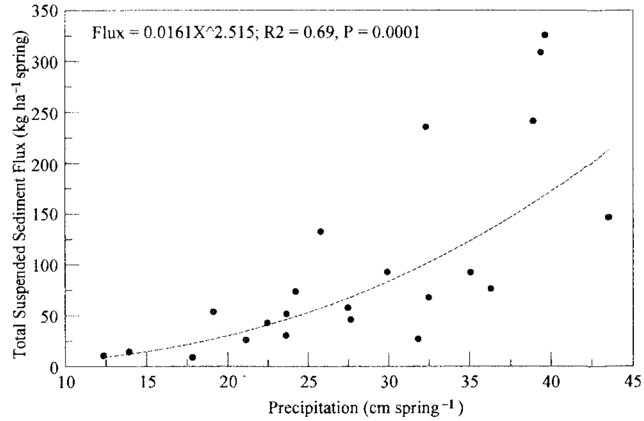

Fig. 1. The effect of variations in spring precipitation on volume-weighted total suspended sediment flux from the area-weighted Rhode River watershed.

For the smaller, first-order watersheds, Watershed 109 (crops) had the highest TSS concentrations and they were significantly higher in the summer than in the other seasons (Table 3). TSS concentrations from Watershed 110 (forest) were not significantly different from Watershed 111 (grazed) in any season.

Precipitation Effects on Total Suspended Sediment Fluxes

Annual and seasonal TSS fluxes were correlated with precipitation and the highest correlations were in the spring (Table 4). Regressions with the best fit to the data (highest R^2) were usually power functions, except

Table 5. Total sediment area yield fluxes from Rhode River watersheds as a function of precipitation. Flux values calculated from regressions of sediment fluxes vs. precipitation.

Precipitation	Area-weighted Rhode River	Watershed 109 (crops)	Watershed 110 (forest)	Watershed 111 (grazed)
cm	kg ha^{-1}			
A. Annual				
−2 SD (64.4)	43.8	17.7	1.36	23.5
−1 SD (86.2)	102	84.5	11.6	36.6
Mean (108.0)	196	283	60.3	51.5
+1SD (129.8)	335	758	232	68.1
+2SD (151.6)	525	1740	725	86.3
B. Winter				
−2SD (10.22)	7.73	3.95	0.310	0.929
−1SD (17.41)	18.6	14.5	1.79	5.06
Mean (24.6)	32.9	33.7	5.58	15.2
+1SD (31.79)	50.3	63.0	13.0	34.3
+2SD (38.98)	70.4	104	25.4	65.6
C. Spring				
−2SD (10.94)	6.69	1.66	0.496	1.78
−1SD (19.47)	28.6	14.1	5.52	6.84
Mean (28.0)	71.4	54.6	25.2	15.9
+1SD (36.53)	140	147	76.6	29.6
+2SD (45.06)	237	321	184	48.3
D. Summer				
−2SD (8.40)	0.966	0.0394	0.0341	1.57
−1SD (19.9)	12.8	3.34	1.54	4.98
Mean (31.4)	50.5	35.0	11.6	9.17
+1SD (42.9)	129	175	46.0	13.9
+2SD (54.4)	262	593	131	19.2
E. Fall				
−2SD (6.64)	0.357	0.00960	0.0142	1.84
−1SD (15.57)	0.853	0.0961	0.0760	2.52
Mean (24.5)	2.04	0.962	0.407	3.20
+1SD (33.43)	4.87	9.64	2.18	3.87
+2SD (42.36)	11.6	96.5	11.7	4.55

in the fall when they were sometimes exponential functions (Table 4). An example is shown for the overall Rhode River watershed in the spring (Fig. 1), in which a power function explained 69% of the variability in spring TSS fluxes as a function of spring precipitation. Correlations were usually lower in the fall. For example, the regression for watershed 111 had an R^2 of 0.02 and was not significant. Annual and seasonal regressions were all significant for the overall Rhode River watershed and watershed 109 (crops). For the forested Watershed 110 annual, spring and summer regressions were significant, while only winter and spring regressions were significant for grazed Watershed 111.

The regressions in Table 4 and frequency spectra for long-term precipitation in the Rhode River region were used to calculate TSS area yield fluxes for the watersheds for a series of precipitation levels; low, average, and high (Table 5). For convenience we used precipitation levels equal to the mean, ± one standard deviation (SD) from the mean, and ± 2SD from the mean. Generally, the ranges of precipitation that occurred during this study are bracketed by the ± 2SD category. These regressions and precipitation spectra constitute a statistical model for projecting TSS fluxes from Rhode River watersheds.

Our model predicts an increase of 12-fold in overall watershed TSS annual flux in very wet years (+ 2 SD) compared with very dry years (−2 SD, Table 5). For the small first-order forested and cropland watersheds the increase with precipitation is higher (533 and 98 times, respectively.). For the overall Rhode River, the model predicts the greatest increase with precipitation in the summer (271 times), when the greatest average TSS fluxes occur (Table 2), and the least effect of precipitation for the winter (9 times), when relatively little TSS flux occurs. For both the forested and cropland watersheds, the model predicts similar seasonal patterns, but much greater effects of increased precipitation than for the overall Rhode River watershed. For Watershed 111 (grazed), only the winter and spring regressions were significant and increases of 71 and 27 times are predicted, respectively.

Table 6. Composition of total suspended sediment in spot samples from Rhode River watersheds.

	Total-P			Total phosphate			TKN¶			NH_4^+			Organic C		
Watershed	*N*†	*X*‡	95% C.I.§	*N*	*X*	95% C.I.	*N*	*X*	95% C.I.	*N*	*X*	95% C.I.	*N*	*X*	95% C.I.
		%			%			%			%			%	
A. Winter															
101	73	0.57	0.39–0.74	72	0.38	0.23–0.53	24	0.55	0.13–0.96	37	0.41	0.13–0.69	33	26.2	10.5–41.9
102	60	1.12	0.70–1.53	59	0.48	0.35–0.61	9	3.10	−0.42–6.61	20	1.00	0.36–1.64	20	40.5	26.2–54.9
103	41	1.84	0.29–3.38	41	0.61	0.36–0.85	9	1.52	0.51–2.53	18	0.67	0.042–1.38	19	34.7	11.5–58.0
108	40	0.80	0.50–1.09	40	0.39	0.27–0.52	11	2.08	0.66–3.51	19	0.58	0.22–0.94	15	34.5	15.7–53.3
109	64	0.64	0.51–0.76	64	0.64	0.51–0.76	45	1.37	0.78–1.96	34	0.24	0.040–0.44	40	11.6	3.52–19.7
110	21	0.30	0.15–0.45	20	0.074	0.024–0.124	17	0.79	0.19–1.39	3	0.10	–	15	5.96	2.68–9.25
111	32	0.76	0.44–1.08	29	0.55	0.22–0.89	26	1.86	0.29–3.44	16	0.50	0.16–0.84	14	17.8	5.55–30.0
B. Spring															
101	141	0.37	0.32–0.41	155	0.17	0.14–0.20	126	0.54	0.47–0.60	125	0.050	0.026–0.074	137	5.28	3.81–6.75
102	30	0.73	0.45–1.01	30	0.37	0.24–0.50	9	0.41	0.092–0.73	9	0.41	0.092–0.73	12	27.6	8.97–46.2
103	33	1.07	0.54–1.60	34	0.50	0.28–0.73	0	–	–	11	0.35	0.14–0.56	13	17.0	6.62–27.5
108	29	0.33	0.24–0.43	38	0.24	0.14–0.33	9	0.70	0.063–1.34	9	0.40	−0.014–0.82	11	24.4	8.29–40.4
109	64	0.88	0.60–1.16	65	0.42	0.28–0.56	44	1.01	0.43–1.60	13	0.24	−0.15–0.63	44	7.75	4.74–10.8
110	51	0.28	0.22–0.33	51	0.088	0.062–0.11	35	0.55	0.28–0.83	4	0.18	−0.092–0.44	33	10.9	6.51–15.3
111	35	0.70	0.30–1.10	36	0.40	0.20–0.60	24	2.10	0.73–3.47	11	0.36	−0.16–0.88	23	14.2	1.23–27.1
C. Summer															
101	91	0.33	0.27–0.38	99	0.19	0.14–0.24	72	0.45	0.37–0.52	75	0.026	0.014–0.039	74	3.19	2.57–3.81
102	20	0.93	0.38–1.47	21	0.42	0.30–0.54	0	–	–	4	0.12	−0.12–0.36	4	13.2	8.71–17.7
103	16	0.76	0.30–1.21	17	0.34	0.21–0.47	0	–	–	3	0.10	−0.30–0.51	4	10.6	1.96–19.2
108	16	0.33	0.17–0.49	16	0.24	0.12–0.36	2	0.37	–	3	0.33	−0.32–0.99	2	18.6	–
109	56	0.80	0.54–1.06	56	0.48	0.32–0.64	49	0.57	0.39–0.76	39	0.026	0.011–0.041	42	2.96	1.72–4.21
110	15	0.32	0.19–0.46	15	0.17	0.078–0.25	11	0.50	0.31–0.69	7	0.027	0.0070–0.047	7	11.1	−2.30–24.4
111	27	0.66	0.42–0.91	25	0.36	0.19–0.54	15	0.36	0.21–0.52	13	0.027	−0.0033–0.057	14	14.1	−14.0–42.2
D. Fall															
101	22	0.45	0.30–0.61	25	0.33	0.25–0.42	7	1.41	0.52–2.30	7	0.51	0.054–0.96	9	11.9	3.84–19.9
102	16	0.93	0.35–1.51	18	0.31	0.20–0.43	3	1.36	–	4	0.38	−0.23–0.99	6	14.2	6.14–22.2
103	14	0.62	0.43–0.81	15	0.47	0.27–0.67	5	1.18	0.031–2.34	5	1.02	0.31–2.41	8	58.0	−38.8–155
108	20	0.57	0.25–0.89	20	0.47	0.25–0.70	6	0.66	−0.087–1.41	6	0.51	−0.25–1.26	8	20.4	−7.08–47.9
109	16	0.63	0.43–0.83	16	0.56	0.34–0.79	7	3.85	−4.02–11.7	7	3.85	−4.02–11.7	6	11.8	0.87–22.7
110	4	1.03	−1.50–3.55	4	0.29	−0.14–0.72	0	–	–	0	–	–	0	–	–
111	33	1.14	0.72–1.56	32	0.78	0.51–1.04	12	2.43	1.45–03.40	12	0.28	0.12–0.43	13	13.8	6.58–21.0
E. Year															
101	327	0.41	0.36–0.45	351	0.23	0.19–0.27	229	0.54	0.47–0.60	244	0.11	0.063–0.16	253	7.63	5.31–9.95
102	126	0.97	0.74–1.20	128	0.42	0.35–0.49	14	2.58	0.42–4.74	37	0.69	0.33–1.05	42	30.5	21.7–39.2
103	104	1.26	0.64–1.89	107	0.51	0.39–0.63	16	2.00	0.64–3.36	37	0.62	0.26–0.99	44	31.5	13.6–49.5
108	105	0.55	0.42–0.69	114	0.33	0.27–0.40	28	1.21	0.60–1.82	37	0.51	0.29–0.72	36	27.4	17.3–37.4
109	200	0.76	0.64–0.88	199	0.43	0.36–0.51	145	1.11	0.71–0.51	93	0.20	0.084–0.31	132	7.58	4.89–10.3
110	91	0.32	0.24–0.41	90	0.11	0.080–0.13	63	0.61	0.39–0.82	14	0.086	0.022–0.15	55	9.58	6.51–12.6
111	127	0.82	0.64–1.00	122	0.53	0.40–0.65	77	1.73	1.05–2.42	52	0.30	0.15–0.45	64	14.9	7.26–22.5

† *N*, Number of samples.
‡ *X*, Sample mean.
§ 95% C.I. = 95% confidence interval of the mean.
¶ TKN, total Kjeldahl nitrogen.

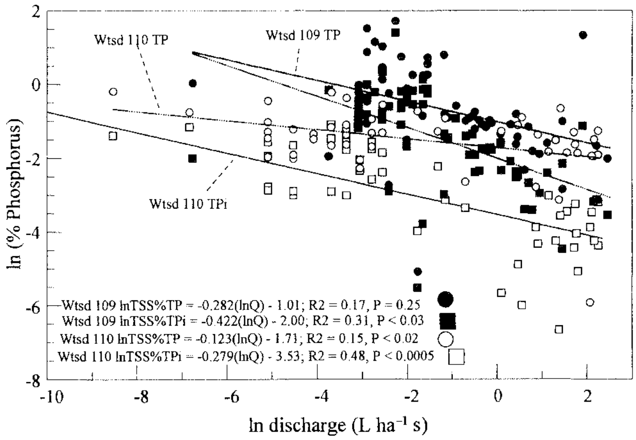

Fig. 2. Phosphorus content of total suspended sediments in spot samples taken in the spring as a function of unit area water discharge from Watersheds 109 (crops) and 110 (forest).

Total Suspended Sediment Nutrient Composition

There were significant differences in the nutrient composition of TSS among watersheds (Table 6E). Of the second-order watersheds, 102 discharged TSS with significantly higher contents of total-P than Watersheds 101 or 108, and 103 TSS had significantly higher contents of total-P than Watershed 101 (Table 6E). The TPi, ammonium, and organic C contents of TSS from the second-order Watersheds 102 and 103 also were significantly higher than Watershed 101. Of the first-order watersheds, forested Watershed 110 discharged TSS with lower contents of total-P and TPi than Watersheds 109 or 111 (Table 6E). Watershed 110 TSS also had significantly lower contents of TKN and ammonium than Watershed 111.

There also were some significant seasonal differences in nutrient composition of TSS (Table 6). More data were taken for Watershed 101, making it easier to discern significant differences in composition. Total-P content of TSS from Watershed 101 was lower in the summer than the winter and TPi content was lower in the spring than in the winter. TKN content was lower in the summer than the fall and ammonium and organic C content were lower in the spring and summer than in the winter (Table 6). Watershed 108 TSS contained less total-P in the spring and summer than in the winter. Watershed 111 (grazed) TSS contained less TKN in the summer than in the spring or fall and less ammonium in the summer than in the spring or fall. No significant differences in seasonal composition were found for the other watersheds.

Changes in Total Suspended Sediment Concentration and Total Suspended Sediment Nutrient Composition with Discharge Rate

In general, the nutrient content of TSS ranged to include higher values at low rates of water discharge, but as discharge increased, nutrient content stabilized at lower values. For example, total-P and TPi in the TSS of Watershed 109 (crops) in the spring were about 1.5–2.0 and 0.5–0.8%, respectively, at base flow, but decreased to about 0.3 and 0.1% at moderate to high discharges (Fig. 2). Similarly, total-P and TPi in the

Table 7. Concentration of total suspended sediments and nutrient content at base flow and at high discharge for Rhode River watersheds. Total suspended sediment (TSS) valnes at base flow and all nutrient content values were calculated with power function regressions, TSS concentration values at high flow were calculated with linear regressions.

	TSS Conc.		Total-P		Total phosphate		TKN†		NH_4^+		Organic-C	
Watershed	**B.F.‡**	**H.F.§**	**B.F.**	**H.F.**	**B.F.**	**H.F.**	**B.F.**	**H.F.**	**B.F.**	**H.F.**	**B.F.**	**H.F.**
	mg L⁻¹		% of TSS									
A. Winter												
101	16***	4 600***	0.37**	0.089	0.24**	0.022	0.49*	0.49	0.11*	0.0024	12**	0.007
109	13*	650	0.57*	0.26	0.34**	0.049	1.2	0.48	0.18*	0.0028	8.4	0.99
110	17***	160***	0.21	0.20	0.078	0.019	0.83	0.46	0.11	0.0034	7.5	3.8
111	12***	650***	0.44	0.17	0.19	0.023	0.71	0.53	0.096	0.0099	5.7	0.49
B. Spring												
101	33***	4 100***	0.35*	0.22	0.20***	0.033	0.58***	0.27	0.061*	0.0014	5.1	0.47
109	26***	4 100***	0.70	0.19	0.36*	0.051	1.1	0.19	0.17	0.0014	10*	1.0
110	23***	230***	0.24**	0.14	0.056***	0.015	0.61	0.36	0.14	0.056	8.6	5.1
111	19***	1 300***	0.32	0.036	0.13	0.012	1.2	2.2	0.098	0.0072	5.3	1.1
C. Summer												
101	170***	2 200***	0.31	0.22	0.13	0.099	0.58	0.27	0.018	0.0057	1.9*	2.8
109	140***	2 200***	0.59*	0.32	0.32**	0.098	0.58*	0.30	0.070*	0.0021	4.4*	0.90
110	83	200	0.26	0.24	0.12*	0.066	0.34	0.49	0.054*	0.013	33**	2.4
111	93***	16 000***	0.35*	0.20	0.13	0.046	0.38	0.10	0.016	0.00019	1.5	0.30
D. Fall												
109	23***	5 600***	0.49	0.43	0.33	0.25	1.3	0.45	0.056	0.00073	7.1	2.6
E. Year (all data)												
101	42***	2 700***	0.34*	0.19	0.17***	0.059	0.57***	0.23	0.053**	0.00026	4.3*	0.82
109	31***	2 200***	0.57**	0.28	0.31***	0.078	0.95	0.29	0.12	0.0021	7.1*	1.0
110	27***	190***	0.24*	0.18	0.070***	0.023	0.53	0.44	0.081*	0.019	8.5**	4.3
111	21***	1 400***	0.39	0.18	0.17	0.051	0.79	0.36	0.039	0.0010	3.9	0.51

*, **, *** Significance at propability levels of <0.05, 0.01, and 0.001, respectively. Since the same regressions were used for nutrient content at base flow and high flow, significance indicators are only shown for base flow data.
† TKN, total Kjeldahl.
‡ B.F., base flow (0.1 L ha⁻¹ s⁻¹).
§ H.F., high discharge (10 L ha⁻¹ s⁻¹).

TSS of Watershed 110 (forest) in the spring were about 0.4–0.6 and 0.1–0.3% at base flow, but decreased to about 0.2 and 0.05% at moderate to high discharges (Fig. 2). This general pattern was found for the total-P, TPi, TKN, ammonium, and organic C content of TSS from all watersheds in all seasons.

Regressions of TSS concentration and composition in spot samples vs. stream discharge rates were used to estimate TSS characteristics in two scenarios, base flow of 0.1 L ha^{-1} s and high flow of 10 L ha^{-1} s (Table 7). Linear regressions fit the TSS concentration data best at moderate to high flows, but a power function regression fit these data better at low flows. Although TSS concentrations were much higher at high flow, their nutrient contents were less per unit of weight. For example, Watershed 101 in the spring discharged 3.3 mg TSS s^{-1} at base flow and 41 g TSS s^{-1} at high flow. These TSS contained 12 μg total-P and 6.6 μg TPi at base flow and 90 mg total-P and 30 mg TPi at high flow. Thus, the flux of total-P increased about 7500-fold, but the proportion of total-P that was present as TPi at base flow was about twice as high as at high flow. Similarly, the proportion of TKN that was in the form of ammonium averaged seven times higher at base flow than at high flow. Watershed 110 (forest) had lower TSS concentrations and the TSS had lower proportions of total-P in the form of TPi, at both base flow and high flow than the other watersheds. Watershed 110 in the spring discharged 2.3 mg TSS s^{-1} and 2.3 g TSS s^{-1} at base flow and high flow, respectively. These TSS contained 5.5 μg total-P and 1.3 ug TPi at base flow and 3.2 mg total-P and 0.34 mg TPi at high flow. These TSS discharges and P contents were much lower than those for Watershed 101, described above.

Changes in the Ratio of Particulate to Dissolved Nutrients with Discharge

The percentage of total-P, TPi, TKN, and organic C in the dissolved phase in the stream water declined rapidly with increasing rates of water discharge (Fig. 3). For Watershed 109 (crops), at base flow much of these nutrients were dissolved, while at high flow only a small percentage was in solution. The same base flow (0.1 L ha^{-1} s) and high flow (10 L ha^{-1} s) scenarios were used to create the data in Table 8. Sufficient spot sample data were only available for Watersheds 101, 109, and 110. The proportion in the dissolved phase of all nutrient

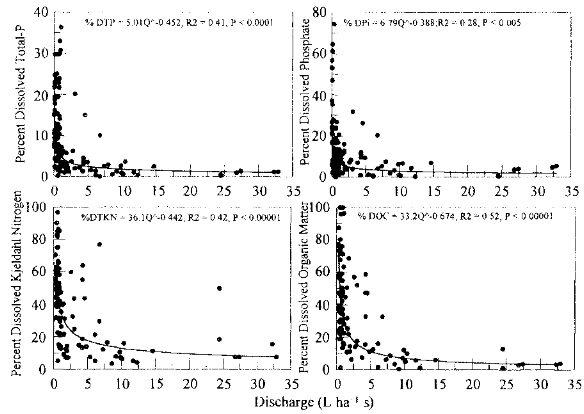

Fig. 3. Percentage of nutrients in the dissolved phase in spot samples from Watershed 109 (crops) as a function of unit area water discharge.

fractions except ammonium were much lower at high flow than at base flow. Although the data were noisy for ammonium, it would seem that the proportion of ammonium in the dissolved phase either increased or did not change at high flow.

DISCUSSION

Fluxes and Concentrations of Total Suspended Sediment

How typical were the TSS fluxes measured in this study? Although the soils of the Rhode River watershed are considered highly erodible and the watershed slopes are fairly steep for the Coastal Plain, the mean annual TSS flux from the area-weighted Rhode River watershed was not much higher than other literature values, and the TSS fluxes from the small, single-land-use watersheds were lower than most literature values (Table 9). It is interesting that the mean from 18 yr of measurements (this study) was about double that previously published (Jordan et al., 1986) from 3 yr of measurement. This points out the value of long-term measurements across a wide range of weather conditions and the possible dangers of broad extrapolation from shorter-term studies.

Watershed 109 (crops) discharged much less TSS than seven other cropland watersheds, even though precipitation is higher in Maryland than in Iowa and Oklahoma (Table 9). Even the highest of the 17 annual discharges measured from Watershed 109 was in the same range

Table 8. Percentage of various nutrients in the dissolved phase at base flow and at high discharge for Rhode River watersheds. All values were calculated with power function regressious.

Watershed	Total-P		TPi		TKN†		NH_4^+		Organic-C	
	B.F.	H.F.	B.F.	H.F.	B.F.	H.F.	B.F.	H.F.	B.F.	H.F.
	% of Nutrients in dissolved phase									
101	16***	0.8	13***	1.7	71***	9.1	11	37	80	8.6
109	14***	1.8	17**	2.8	99***	13	10	16	100***	7.0
110	25	18	44**	28	53**	40	33	16	80***	46

*, **, *** Significance at propability levels of <0.05, 0.01, and 0.001, respectively. Since the same regressions were used for nutrient content at base flow and high flow, significance indicators are only shown for base flow.
† TKN, total Kjeldahl nitrogen.
‡ B.F., base flow (0.1 L ha^{-1} s^{-1}).
§ H.F., high discharge (10 L ha^{-1} s^{-1}).

as the mean from the other seven watersheds. This may be explained, in part, by the presence of a continuous deciduous hardwood forest riparian buffer along the stream draining Watershed 109. The forest buffer, which occupied 36% of this watershed, has been shown to trap >90% of the TSS entering from the corn (*Zea mays* L.) fields in overland storm flow (Peterjohn and Correll, 1984). If we increased the TSS fluxes from watershed 109 by 10-fold, they would be comparable to those from the other seven watersheds, which did not have riparian forest buffers.

Watershed 111 (grazed) had very low mean annual TSS fluxes, compared with those from 14 other grazed watersheds (Table 9). TSS fluxes from Watershed 111 also had a greater interannual range (32-fold) than other long-term studies that reported ranges of flux. Although continuous grazing seems to usually be associated with higher TSS fluxes, the rates reported from New Zealand were much lower than those from Ohio and Oklahoma (Table 9).

Watershed 110 (forest) has lower mean annual TSS fluxes than reported for 10 other forested watersheds, but higher than reported from five forested watersheds in Quebec (Table 9). The very high TSS fluxes for three watersheds in Puerto Rico are probably the results of much higher volumes and intensities of precipitation. The study in Quebec picked five watersheds ranging in size from 25 to 1 980 000 ha and one might suspect that we are seeing an effect of watershed size, with larger watersheds having lower fluxes, due to storage in channels and floodplains. The second smallest, with an area of 183 ha, however, had by far the largest TSS flux (144 kg ha^{-1} yr).

The fact that TSS fluxes were higher in the summer and spring (Table 2) is probably due to several factors. In the winter, the soils are sometimes frozen and precipitation intensity is usually low. In the fall, Rhode River experiences relatively low water discharges (Correll et al., 1999) due to high evapotranspiration rates. In the summer and spring, however, precipitation is often quite intense and water discharges rates are often high. In addition, in the spring, cropland is being prepared and planted, making it especially vulnerable to erosion, as noted by Alberts et al. (1978). Most tropical storms and hurricanes occur in this region in the summer. All of these factors help explain the seasonality of TSS delivery from the Rhode River watershed.

It is difficult to explain why some Rhode River watersheds had significantly higher TSS concentrations than others. Watershed 110 (forest) had low TSS concentrations, but watershed 108, almost one-half of which was agricultural and housing (Table 1) had lower mean TSS concentrations except in the summer (Table 3), even though these differences were not statistically significant. TSS concentrations from Watersheds 101 and 109 were higher than the others, and usually these differences were significant. Watershed 109 results may be due to the fact that it had the highest proportion of row crops. Watershed 101 results are more difficult to explain. Land use, area, channel, and basin slopes were rather similar to the other second order watersheds.

Table 9. Comparisons of annual TSS fluxes among various watershed studies.

Location (management)	Years studied	Number of watersheds	Mean flux	Range	Source
			kg ha^{-1} yr^{-1}		
A. Primarily row cropped watersheds					
Iowa (corn)	7	2	12 000	1 020–44 800	Alberts et al., 1978
Iowa (terraced corn)	7	1	3 050	110–14 700	Alberts et al., 1978
Oklahoma (cotton)	11	2	3 900	2 000–8 900	Menzel et al., 1978
Oklahoma (wheat)	11	2	1 200	100–3 900	Menzel et al., 1978
Maryland (corn)	17	1	546	18–3 880	this study
B. Primarily grazed watersheds					
Nebraska (seasonal)	4	1	196	–	Doran et al., 1981
Oklahoma (rotational)	11	1	300	100–400	Menzel et al., 1978
Oklahoma (continuous)	11	1	8 100	1 500–23 000	Menzel et al., 1978
Ohio (continuous)	5	1	1 355	815–2 260	Owens et al., 1982a
Ohio (summer)	5	2	178	–	Owens et al., 1983a
Ohio (winter)	5	2	181	–	Owens et al., 1983a
Ohio (unstocked)	2	1	228	–	Owens et al., 1983b
Ohio (summer)	3	1	203	–	Owens et al., 1983b
Iowa (rotational)	3	1	600	90–1 430	Schuman et al., 1973a
New Zealand (continuous with no riparian forest)	9	1	210	–	Smith, 1992
New Zealand (continuous with riparian pines)	9	2	445	–	Smith, 1992
Maryland (rotational)	14	1	92	10–315	this study
C. Forested watersheds					
Mississippi (pine)	1	5	221	180–273	Duffy et al., 1978
Puerto Rico (hardwood)	3	3	1 200	155–4 165	McDowell & Asbury, 1994
Quebec (spruce & fir)	1	5	65	28–144	Naiman, 1982
Ohio (hardwood)	3	1	671	–	Owens et al., 1983b
North Carolina (hardwood)	10	1	258	–	Swank & Waide, 1988
Maryland (hardwood)	15	1	134	2–430	this study
D. Larger mixed land use watersheds					
W. Br. Delaware R., NY	2	1	240	–	Haith & Shoemaker, 1987
Rhode River, MD	3	1	136	–	Jordan et al., 1986
Denmark	1	2	250	228–271	Kronvang, 1992
Rhode River, MD	18	1	263	22–918	this study

Precipitation Effects on Total Suspended Sediment Fluxes

In the literature one seldom finds analyses of seasonal or annual TSS fluxes as a function of precipitation, even though such relationships are very useful for projecting TSS fluxes in space and time. The main impediment is the need for integrated TSS discharge data during a long enough time period. In addition to having long-term TSS discharge data, we are fortunate to have very long-term weather records from sites very near the Rhode River watershed.

Even relatively long-term data such as the 5 yr in Owens et al. (1983b) and the 7 yr in Alberts et al. (1978) are not long enough for a meaningful analysis. Such an analysis could be done on the 10-yr data set used by Swank and Waide (1988), the 11-yr data set used by Menzel el al. (1978) or the 18-yr data set of Smith (1992), but these data were not provided in adequate detail in their publications.

The relationship between seasonal or annual precipitation volume and TSS flux was not linear (Fig. 1, Table 4). Instead, the relationship was a power or exponential function of precipitation. The volume of water discharged had a similar nonlinear relationship to precipitation (Correll et al.,1999) and the concentration of TSS was much higher at high flow than base flow (Table 7). The regressions of our statistical model deviate the most from linearity in the summer, when the largest TSS fluxes occur.

Nutrient Composition of Total Suspended Sediment

There were significant differences in the nutrient content of TSS among watersheds. Many of these differences are probably the result of land use history. For example, Watershed 109 (crops) TSS had higher total-P and TPi content than Watershed 110 (forest) due to the application of agricultural fertilizer to the soils during many years (Vaithiyanathan and Correll, 1992). The forest on Watershed 110 has never been clear cut and the fields on Watershed 109 have been agricultural fields for at least two centuries (Vaithiyanathan and Correll, 1992). We seldom know, however, the land use history of a watershed in this detail. Some of the variation in nutrient content among watersheds also may be due to subtle geological differences. The soils are sedimentary, formed when sea level was higher, and there may be small areas where the sediments laid down were richer in P or other nutrients. It is surprising that relatively small, contiguous watersheds with similar geology, soils, and slopes, and similar present land use can discharge TSS with two to five-fold differences in average annual nutrient content.

Some significant seasonal differences in TSS nutrient content also were found, especially for Watershed 101, where nutrient content during the growing season was lower. Some of these differences, such as lower total-P and TPi content in the spring and summer than in the winter, are probably due to differences in mean size of the discharged particulates. Water discharge was more variable in the growing season and high water discharge is known to carry larger particles (e.g., Reid and Frostick, 1994). In the Rhode River system, these larger particles include significant amounts of fine sands, which have low nutrient content.

The total-P and TKN contents of Rhode River watershed TSS are high compared with those of other watersheds (Table 10), with the exception of the TKN content of TSS from forested watersheds. Even when fertilizers

Table 10. Comparisons of nutrient content of total suspended sediment (TSS) among various watershed studies.

Location (management)	Total-P	TPi	TKN†	TOC‡	Fertilizer N	Fertilizer P	Source
	% of TSS				kg ha^{-1}		
A. Primarily row cropped watersheds							
Iowa (corn)	–	0.0037	0.15	–	168	39	Alberts et al., 1978
Iowa (corn)	–	0.0046	0.16	–	448	97	Alberts et al., 1978
Oklahoma (wheat)	0.16	–	0.49	–	28	1.4	Menzel et al., 1978
Oklahoma (cotton)	0.14	–	0.25	–	33	25	Menzel et al., 1978
Pennsylvania (crops)	0.089	–	–	–	n.d.	n.d.	Pionke & Kunishi, 1992
Maryland (corn)	0.76	0.43	1.1	7.6	105	20	this study (#109, Table 6)
B. Primarily grazed & pastured watersheds							
Nebraska (grazed)	0.26	–	–	–	67	0	Schepers & Francis, 1982
Ohio (pasture)	–	–	0.59	–	56	n.d.	Owens et al., 1983b
Oklahoma (grazed)	0.027	–	0.17	–	0	0	Menzel et al., 1978
New Zealand (pasture)	0.18	–	1.3	–	0	25	Cooke, 1988
New Zealand (pasture)	0.22	–	0.73	11	0	40	Smith, 1992
Maryland (grazed)	0.82	0.53	1.7	15	0	0	this study (#111, Table 6)
C. Forested watersheds							
Mississippi	0.069	0.049	–	–	0	0	Duffy et al., 1978
North Carolina	–	–	0.73	–	0	0	Swank & Waide, 1988
Puerto Rico	–	–	0.17	2.6	0	0	McDowell & Asbury, 1994
Quebec	–	–	–	18	0	0	Naiman, 1982
Maryland	0.32	0.11	0.61	9.6	0	0	this study (#110, Table 6)
D. Mixed land use watersheds							
Denmark	0.45	0.23	–	–	nd	nd	Kronvang, 1992
New York	0.16	–	1.0	–	nd	nd	Haith & Shoemaker, 1987
Maryland	0.93	0.38	1.6	24	nd	nd	this study (area-weighted mean)

† TKN, total Kjeldahl nitrogen.
‡ TOC, total organic carbon.

Table 11. Comparisons of the proportions of nutrients discharged in the dissolved phase among various watershed studies. Values are percentages of mean annual fluxes.

Location	Land use	Total-P	TPi	TKN†	Organic-C	Source
		% of Nutrients in the dissolved phase				
Iowa	row crops	–	18	–	–	Alberts et al., 1978
Iowa	terraced crops	–	38	–	–	Alberts et al., 1978
New Zealand	pasture	63	–	91	–	Cooke 1988a,b
Mississippi	forest	29	–	–	–	Dnffy et al., 1978
Denmark	row crops	66, 34	62, 30	–	–	Kronvang, 1992
Puerto Rico	forest	–	–	61–78	65–74	McDowell & Asbnry, 1994
Oklahoma	cotton	16	–	–	–	Menzel et al., 1978
Oklahoma	wheat	14	–	–	–	Menzel et al., 1978
Oklahoma	grazing	3–7	–	–	–	Menzel et al., 1978
New Hampshire	forest	19	–	–	–	Meyer & Likens, 1979
North Carolina	forest	–	–	–	95	Mulholland, 1981
Quebec	forest	–	–	–	7	Naiman, 1982
Pennsylvania	row crops	28	–	–	–	Pionke & Kunishi, 1992
Nebraska	pasture	61	–	–	–	Schepers & Francis, 1982
North Carolina	forest	–	–	–	83	Swank & Waide, 1988

† TKN, total Kjeldahl nitrogen.

were applied at relatively high rates, Iowa corn fields (Alberts et al., 1978) and New Zealand pasture (Cooke, 1988a,b) TSS had lower nutrient content than Rhode River TSS from similar land uses (Table 10). We found very few published data on the TPi and organic-C content of TSS from other watersheds.

Changes in the Proportion of Dissolved and Particulate Nutrients with Discharge

There is general agreement in the literature that as water discharge increases on a given watershed, TSS concentration and the concentrations of particulate nutrients increase (e.g., Haan et al., 1994; Reid and Frostick, 1994). Our results are consistent with this generality. Far less information can be found in the literature on changes in the composition of TSS or the ratio of particulate to dissolved nutrients with discharge. Therefore, our findings should make a significant contribution to the literature (Tables 7 and 8).

A number of studies did report average annual discharges of dissolved and particulate nutrients from various land uses (Table 11). For New Zealand pastures, 63% of total-P discharge was dissolved (Cooke, 1988a), but for two Oklahoma grazing areas only seven and 3% was dissolved (Menzel et al., 1978). Similarly, one primarily-cropped Danish watershed discharged 66% of its total-P in solution, but another only 34% in solution (Kronvang, 1992). Mississippi forests discharged 29% of their total-P in solution (Duffy et al., 1978), but Hubbard Brook, NH, only discharged 19% of its total-P in solution (Meyer and Likens, 1979).

Several studies have shown that the proportion of particulate nutrients increases during high flow periods. For example, the concentrations of particulate total-P and TKN increased during storm events on New Zealand pastures, while the concentration of dissolved total-P and TKN changed very little (Cooke, 1988a,b). As a result, during base flow, dissolved TKN constituted 92% of TKN, but during storms declined to about 10% of TKN. Similarly, for a cropland watershed in Pennsylvania dissolved total-P was 28% of annual total-P discharge, but only 14% of average total-P during significant storm events (Pionke and Kunishi, 1992).

It would seem that some of the variation in the broad range of literature values for ratios of dissolved to particulate nutrients in watershed discharges is due to differences in the proportion of overland storm flow generated, the resultant erosion rates, and the methods used in sampling discharges. If a watershed seldom experiences overland storm flows, erosion rates will be lower and more nutrients will be discharged in solution. Also, if only nontargeted spot sampling is used, it is unlikely that storm events or periods of high flow will be adequately sampled and the proportion of particulate nutrient discharge will be underestimated.

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