Dissolved Phosphorus Transport During Storm and Base Flow Conditions from an Agriculturally Intensive Southeastern Coastal Plain Watershed

J. M. Novak, K. C. Stone, D. W. Watts, M. H. Johnson

Abstract. *The high density of animal production in southeastern Coastal Plain watersheds has caused some soils to contain excess amounts of plant–available soil phosphorus (P). Runoff, erosion, and leaching can transport P to surface water systems and out of these watersheds. High P concentrations in downstream aquatic ecosystems can increase the risk of eutrophication. Our objectives were to determine stream dissolved phosphorus (DP) mass loads transported under storm and base flow conditions and to examine relationships between precipitation, stream flow, and DP concentrations and export loads from an agriculturally intensive Coastal Plain watershed. This watershed was separated into four subwatersheds, and stream flows at their outlets were separated into base and storm flow conditions. Over the 2–year study period, stream base flow accounted for the majority of total stream flow at all outlets (58% to 73%). Average stream total DP mass loads at the watershed outlet in 1994 and 1995 were 234 and 477 mg DP ha^{-1} d^{-1}, and higher DP mass loads (57% to 71% of the cumulative total) were exported during base flow conditions. In 1995, a series of intense storm events over two months caused a large DP pulse (approximately 63% of the stream's yearly annual DP mass load) to exit the watershed. Regression analysis showed a linear relationship ($P < 0.001$) between $\log_{10}$ instantaneous stream flow and $\log_{10}$ DP export. Our results showed that more DP was exported during stream base flow conditions. However, intensive summer storms can greatly accelerate stream DP export from this agriculturally intensive Coastal Plain watershed.*

Keywords. *Coastal Plain watershed, Loads, Phosphorus concentrations, Stream flow.*

In the southeastern Coastal Plain region, intensive manure applications to limited land areas have produced excess P concentrations in some soils (Sims et al., 1998; Kellogg et al., 2000; Novak and Chan, 2002). As a result, these soils have an increased potential for P movement to surface water systems (Sims et al., 1998; Kellogg et al., 2000). Excessive P concentrations in surface waters may stimulate growth of algae and aquatic weeds and can accelerate eutrophication (USEPA, 1996). Since eutrophication may occur at concentrations below 0.01 mg DP L^{-1} and 0.02 mg total P L^{-1} (Sharpley and Rekolainen, 1997), relatively small increases in surface water P concentrations can have disproportionally negative environ–mental consequences.

Runoff from storm events can transport both dissolved and particulate P forms from manure–treated, medium– to fine–textured soils (Sharpley and Halvorson, 1994; Pote et al., 1999). In coarse–textured soils with low P retention capacities, P from manure can leach to shallow groundwater tables and move with subsurface lateral flows (Graetz and Nair, 1995; Sims et al., 1998; Novak et al., 2000). Dissolved phosphorus (DP) movement into surface water systems from runoff and leaching is an environmental concern because DP is readily available to algae and aquatic weeds (Sonzogni et al., 1982).

Riparian buffers consisting of permanent grass strips and/or vegetated wetland areas can effectively minimize P movement (Lowrance et al., 1984; Cooper and Gilliam, 1987; Novak et al., 2002). These riparian buffers temporarily store both dissolved and particulate P forms through plant and microbe P uptake, sorption to solid phases, and incorporation into soil organic matter (Richardson, 1985; Dosskey, 2001). Dissolved and particulate P forms can also be stored in sediments of in–stream wetlands, impoundments, or small reservoirs (Reddy et al., 1999). However, P in these areas is only temporarily stored. Riparian areas can be flooded by high stream and river flow conditions, remobilizing sediment–bound P and DP. These P forms may be removed as flood waters recede (Pionke et al., 1999; Bales et al., 2000; McDowell et al., 2001).

High stream flows in two southeastern Coastal Plain watersheds increased P export (Asmussen et al., 1979; Lowrance and Leonard, 1988). Precipitation in these storm events increased stream flow and removed P stored within the watersheds. These watersheds had limited animal operations and were primarily in row crop, pasture, and timber production. Since these studies were completed, livestock production has increased dramatically in many southeastern

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Coastal Plain watersheds (Kellogg, 2000). Consequently, intensification of livestock production in these watersheds coupled with elevated stream/river flow conditions may amplify DP export loads compared to the previous studies of Asmussen et al. (1979) and Lowrance and Leonard (1988). Few studies in southeastern Coastal Plain watersheds have addressed the effects of concentrated animal production on DP export under differing stream flow conditions. Such a study would be particularly germane to southeastern seaside communities that financially depend on good water quality for tourism. Our objectives were to determine stream DP mass loads transported under storm and base flow conditions and to examine interactive effects of precipitation and stream flow characteristics on DP concentrations and export loads from an agriculturally intensive Coastal Plain watershed.

Materials and Methods

Watershed, Soil, Stream, and Animal Production Description

The Herrings Marsh Run (HMR) watershed is located in Duplin County, North Carolina, and flows into the Northeast Cape Fear River and, ultimately, the Cape Fear River. The 2312 ha watershed contains features typical of the Middle Coastal Plain physiographic region. The landscape has a combination of nearly level to gently sloping upland areas and riparian areas along stream systems (Daniels et al., 1999). Soils that formed in upland landscape positions are sandy and are somewhat poorly to well drained. Examples of soil series in upland positions include Autryville (loamy, siliceous, subactive, thermic Arenic Paludults) and Norfolk (fine–loamy, siliceous, thermic Paludults). Wide (3 to 15 m) riparian zones form borders along many stream systems in the HMR watershed. These zones are flat (0% to 1% slope) and contain soils that are poorly to very poorly drained. Examples of soils series located in riparian areas include the Bibb (coarse–loamy siliceous, acid, thermic Typic Fluvaquent) and Johnston (coarse–loamy siliceous, acid, thermic Cumulic Humaquepts).

Primary, secondary, and tertiary streams dissect the watershed and form a confluence at the HMR watershed outlet (Novak et al., 2002). Based on two years of measurements, stream width and depth at the outlet can vary from 3 to 7 m wide and from 0.2 to 0.75 m deep. Annual total precipitation recorded at Warsaw, North Carolina (approximately 6 km away) for 1994 and 1995 was 1170 and 1360 mm, respectively.

Because agricultural activity varied considerably across the watershed, it was subdivided into four subwatersheds (SW). The subwatersheds ranged in size from 214 to 559 ha (table 1). Approximately 57% of the watershed was farmed with row and vegetable crops, along with hay and pastureland. In 1993, there were 23,931 swine, 176 cattle, and 94,000 poultry (turkey + chicken) within the HMR watershed (table 1; Star Maready, Duplin Co. Cooperative Extension Agent, personal communication, 1999). The swine and poultry were confined operations, while the cattle were grazed in open fields. Estimates for animal manure P production were calculated using animal manure production and livestock liquid manure slurry characteristics, as described in the *North Carolina Agricultural Chemicals Handbook* (1994). The quantities of manure P produced by animals within each subwatershed were then compiled (table 2).

Table 1. Livestock type and population for each subwatershed (SW) and the total Herrings Marsh Run Watershed (HMR) in 1993 (estimates provided by Star Maready, North Carolina Cooperative Extension Service).

Location	Total Land (ha)	Agric. Land (ha)	Animal Type (n)			
			Swine	Turkey	Chicken	Cattle
SW1	1,036	559	6,240	16,000	50,750	0
SW2	425	279	3,300	0	3,250	0
SW3	537	262	14,391	24,000	0	53
SW4	314	214	0	0	0	123
HMR	2,312	1,314	23,931	40,000	54,000	176

Table 2. Estimated annual manure P produced by livestock populations on a subwatershed basis (based on 1993 population count).[a]

Location	Manure P (Mg)				
	Swine	Turkey	Chicken	Cattle	Total
SW1	23.3	0.9	7.2	—	31.4
SW2	35.0	—	0.4	—	35.4
SW3	48.0	0.7	—	1.3	50.0
SW4	—	—	—	3.1	3.1

[a] Manure P estimates calculated using data from the *North Carolina Agricultural Chemicals Handbook* (1994).

Stream Sampling Locations, Stream Flow, and DP Export Estimates

Stream sampling locations were established at the outlets of each subwatershed and the HMR watershed (Red Hill, fig. 1). Site 1 was located at the outlet of SW1, a subwatershed with intensive swine and poultry operations (table 1). Site 2 was located at the outlet of SW2, a subwatershed with a moderate population of swine and poultry. Animal production facilities in SW1 and SW2 were generally located 100 to 400 m from the stream network (Star Maready, personal communication, 1999). Site 3 was located at the outlet of SW3, which has a substantial area of riparian buffers along with a high population of swine, poultry, and cattle. Site 4 was located at the outlet of SW4, which is limited to row crop and cattle production. Animal production facilities in SW3 and SW4 were located farther from the stream network (450 to 1100 m) than those in SW1 and SW2.

At each sampling location, stream grab samples were collected in mid–stream using a pre–cleaned glass bottle (acid washed, deionized H_2O rinsed) that had been rinsed with stream water three times prior to final sample collection. The study period began on 1 January 1994 (day 1) and continued until 31 December 1995 (day 730). Stream grab samples were collected weekly from March to October and twice per month from November to February. This resulted in a total of 41 and 42 grab samples collected during 1994 and 1995, respectively. Samples were filtered (0.45 μm) and acidified to pH 2 prior to analyses. They were analyzed for DP on a TRACCS 800 Auto Analyzer (Bran Lubbe, Elmsford, N.Y.) using USEPA method 365.1 (Kopp and McKee, 1983). The minimum DP concentration detection limit (7.5 μg L^{-1}) was established at one–half the concentration of the lowest standard.

The U.S. Geological Survey in Raleigh, North Carolina, has installed and maintained stream gauging stations at the outlets of HMR, SW2, SW3, and SW4, as described by Stone

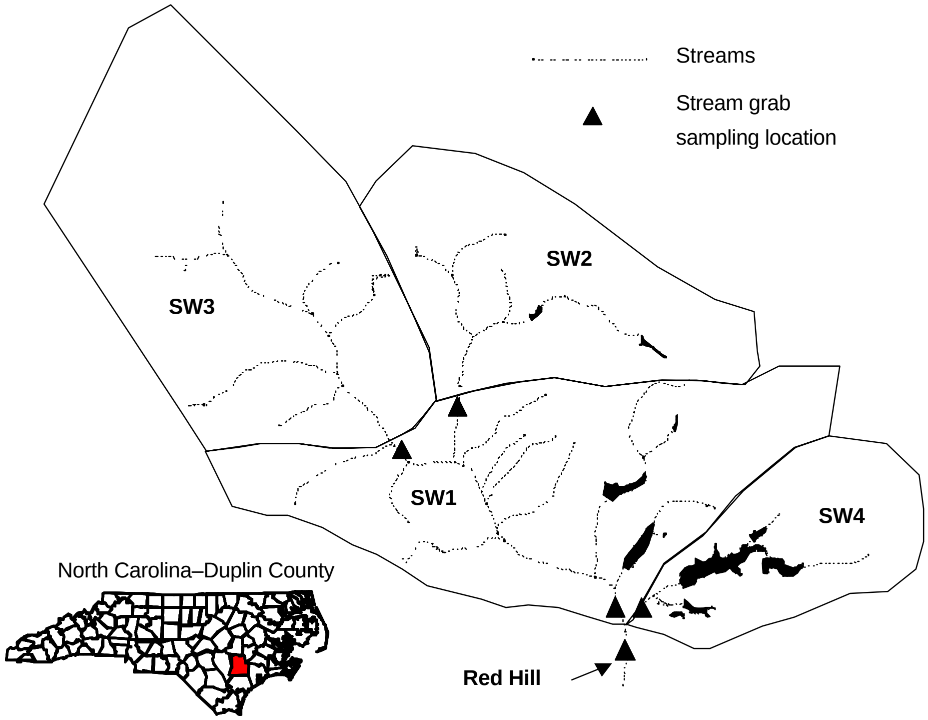

Figure 1. Location of the Herrings Marsh Run watershed, subwatershed boundaries (SW), and stream sampling locations.

et al. (1995). These gauging stations measured stream flow at 15 min intervals using an automated water level recorder. These values were used to calculate daily (24 h) mean stream flows. Because a stream gauging station at the SW1 outlet was not available, water flow was estimated manually using the stream velocity method (Buchanan and Somers, 1969). This method involved segmenting the stream channel into 5 to 10 segments (varied with stage) and measuring stream velocity within each segment. Instantaneous flow values were measured for each segment by multiplying cross–sectional areas by stream velocities and summing these products. Our manually estimated stream flow measurements when compared to USGS estimates in a sister study (Stone et al., 2000) were found not to be significantly different.

Estimates of DP mass export loads (except SW1) were calculated by multiplying USGS daily mean flow values by DP concentrations. Because DP concentrations were measured in grab samples collected weekly and biweekly, DP concentrations were interpolated over a 7– to 14–day interval to provide a continuous estimate of daily DP mass export loads. DP mass loads from SW1 were estimated by multiplying the instantaneous flow rates by the DP concentrations and interpolating the flow rates and concentrations over the 7– or 14–day interval. Other statistical methods of DP load estimation were considered (e.g., ESTIMATOR, LOADEST2, etc.), but they are not recommended for small watersheds such as the HMR (Dr. Tim Cohn, personal communication, 2002). Daily DP mass loads were then summed by week, month, and year to provide cumulative export mass loads. Mass DP export estimates were normalized for agricultural land area by subwatershed (table 1) in order to compare DP fluxes between subwatersheds. The average daily DP loads exported from the HMR watershed for 1994 and 1995 were determined using the annual cumulative DP mass export loads and dividing by the total watershed area in agricultural land (1,314 ha, table 1).

Base and storm flow events from the HMR and all subwatersheds were separated using the algorithm model of Arnold and Allen (1999). The model separates daily stream flow ($m^3\ d^{-1}$) into estimates of daily base and storm flows using an automated derivation of the Roabaugh hydrograph recession curve displacement method (Rorabaugh, 1964). The DP mass loads transported during base and storm flow events were calculated by multiplying the daily total DP mass load ($g\ d^{-1}$) by the proportion of base or storm flow to total flow.

Stream DP Data Evaluation and Regression Analyses

Regression relationships were examined between total flow rates, precipitation, DP concentrations, and DP loads at the HMR outlet in 1994 and 1995 using the instantaneous data (41 and 42 grab samples, respectively). Preliminary analyses of the instantaneous DP concentrations, DP loads, precipitation, and total flows at the HMR outlet using the Kolmogorov–Smirnov test showed that these data sets were not normally distributed. Prior to regression analyses, total flows, DP concentrations, and daily export values were $\log_{10}$ transformed (Zar, 1999). Descriptive data, transformations, and regression analyses were determined using SigmaStat version 2.03 software (SPSS Corp., Chicago, Ill.).

Results and Discussion

Animal Populations and Manure P Production

Animal populations within the HMR watershed were dominated by poultry (turkey + chicken), with a medium swine and low cattle population (table 1). Among the subwatersheds, SW3 had the highest swine population, while SW1 had the highest poultry population. Comparing manure

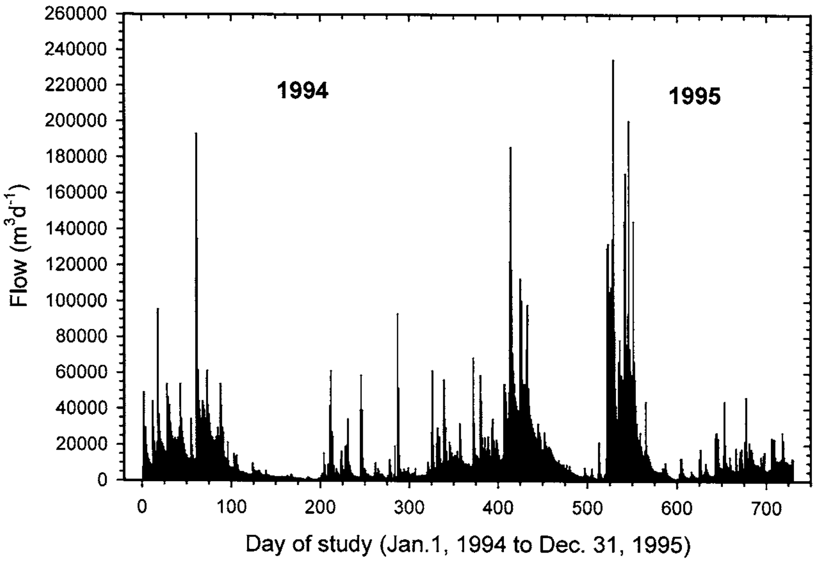

Figure 2. Total stream flows at the Herrings Marsh Run watershed outlet (Red Hill, 1994 through 1995).

Table 3. Annual cumulative total, storm, and base flow rates, and the percentage of annual stream discharge during storm and base flow events from each subwatershed (SW) outlet and at Red Hill.

Location	Year	Cumulative flow rate (m^3 d^{-1} × 10^3) Total	Storm	Base	Percentage of Stream Flow as: Storm	Base
SW1	1994	2,515	873	1,643	35	65
	1995	5,124	1,913	3,212	37	63
SW2	1994	741	252	488	34	66
	1995	1,822	679	1,411	37	63
SW3	1994	803	264	539	33	67
	1995	1,382	574	808	42	58
SW4	1994	524	142	382	27	73
	1995	976	356	620	36	64
Red Hill	1994	3,792	1,323	2,469	35	65
	1995	6,777	2,535	4,241	37	63

P production by animal populations, swine were estimated to produce the most manure P (table 2). The highest total amount of manure P produced occurred in SW3 (50 Mg, table 2).

Stream Flows

In 1994 and 1995, total daily stream flows measured at Red Hill were >5000 m^3 d^{-1} for extended periods of time (fig. 2). There were five total stream flow measurements at Red Hill that exceeded 160,000 m^3 d^{-1}. This suggests that, at times, episodes of high stream flows from this watershed did occur. On the other hand, base flow (from groundwater flow) dominated total annual flow at Red Hill and its subwatershed outlets (table 3). In both years, total annual base flow exceeded storm flow conditions by 1.4– to 2.7–fold at all outlets. This finding is similar to stream flow conditions in a few Coastal Plain watersheds in the Delmarva Peninsula (Jordan et al., 1997).

DP Concentrations

The 1994 and 1995 annual mean stream DP concentrations and SD are presented in table 4. Mean stream DP concentrations for all locations ranged between 16.1 and 87.7 μg L^{-1}. Stream water discharged from SW3 and SW4 had low mean DP concentrations (<30 μg L^{-1}); however, mean DP concentrations in stream water flowing out of SW1 and SW2 were higher (>45.6 μg L^{-1}). Although there were two subwatersheds that discharged stream water with relatively high DP concentrations, significant dilution occurred at Red Hill, resulting in a mean DP concentration decrease (table 4).

Table 4. Annual means and standard deviations (SD) of DP concentrations (μg L^{-1}) in stream water at each subwatershed (SW) and Red Hill outlet.

Location	1994 Mean	1994 SD	1995 Mean	1995 SD
SW1	51.0	37.4	45.6	31.6
SW2	87.7	38.5	78.7	56.2
SW3	28.5	12.9	26.1	12.8
SW4	16.1	6.7	16.4	8.2
Red Hill	36.5	18.4	38.7	27.7

Stream water discharged from SW2 had the highest mean DP concentrations (table 4). To explain this trend, we examined past agricultural activity (prior to 1994) and stream hydrology, as reported by Hunt et al. (1995) and Stone et al. (1998). They reported that prior animal operations within SW2 applied high amounts of manure to soils. Additionally, stream water hydrology at the SW2 outlet was drastically altered in April 1993 when beavers (*Castor canadensis*) created a 3.3 ha pond that temporarily impounded water (Hunt et al., 1999). We hypothesized that P from animal manure and inorganic P fertilizer from past cropping activity was transported into the stream and later deposited into the pond. Additionally, in the late 1980s, an old swine lagoon located a few hundred meters upstream from the pond was suspected of periodically releasing P, potentially contributing P loads into the pond. This lagoon was replaced in 1993 as part of the USDA Water Quality Demonstration Project. In a separate study, in which we examined exchanges of DP between stream water and sediments of the pond, we found high sediment pore water DP concentrations (data not published). The stored sediment DP in the pond probably had sufficient time to equilibrate with the overlying surface water

(Reddy et al., 1999). The equilibration process would contribute to high pond water DP concentrations, resulting in the high stream water DP concentrations exiting SW2 (table 4).

There have been conflicting reports in the literature concerning the importance of riparian zone characteristics and proximity of agricultural lands in predicting their influence on reducing nutrient inputs to streams. Osborne and Wiley (1988) reported only minimal differences in stream P and N concentrations near riparian buffers zones of different widths (<100 m to >1000 m). Omernik et al. (1981) and Johnson et al. (1997) both reported that proximity of agricultural lands to streams did not bear a significant relationship to stream nutrient concentrations. In contrast, the beneficial effects of riparian zones on reducing nutrient movement from agricultural sources into stream have been reported (Peterjohn and Correll, 1984; Lowrance et al., 1985; Novak et al., 2002). In this study, we hypothesize that certain subwatershed landscape characteristics may explain the large stream DP concentration variations. These subwatershed landscape characteristics comprise the proximity of each animal operation to the stream, animal populations and manure production, and the buffer zone width. Mean DP concentrations were lower at the outlets of SW3 and SW4 than at the outlets of SW1 and SW2. Although SW3 had the highest estimated total manure P production (50 Mg, table 2), the low annual mean stream DP concentrations may be due to a wide (several hundred meters) riparian zone, which separated the SW3 animal production facilities from the stream network. This greater distance increased the probability of DP removal from runoff within the riparian area by physical interception of P–enriched sediments, uptake by plants, and sorption by solid phases (Novak et al., 2002). The low livestock population and manure P production in SW4 probably accounted for the low mean DP concentration at its outlet. In contrast, high animal populations in SW1 and SW2 and manure P production and their close proximity to the stream probably increased the potential for more DP movement. The narrower and smaller riparian areas that separated the stream and animal production operations in these two subwatersheds may have lowered DP removal by physical and chemical mechanisms. Differences between the annual mean stream DP concentrations may also have been influenced by variations in stream abiotic (P sorption to sediments, P–oxide solubility) and biotic (mineralization, microbial and plant uptake) processes known to influence P dynamics (Reddy et al., 1999).

DP Loads

Dissolved phosphorus export loads were sorted by flow conditions and were then reported on an annual cumulative mass load basis (table 5). In all cases, higher cumulative DP mass loads were exported during base flow events. The ratio of DP mass exported during base and storm flow ranged between 1.3 and 3.2 (table 5). Calculating DP mass loads sorted by flow conditions as a percentage of the total mass revealed that 57% to 71% of the total DP mass exported occurred during base flows. We noted that the cumulative DP mass loads and the percentage of total DP exported from all locations were higher in 1995 than in 1994. We speculate that the higher amounts of DP exported during base flow were probably due both to the predominance of base flow and to within–stream P exchange equilibria. As previously discussed, more DP was exported during base flow conditions because it dominated total stream flow (table 3). Additionally, storm events probably transported more P into the stream systems than expected during these events, but due to within–stream P exchange dynamics, equilibrium was achieved that provided a steady release of DP during base flow conditions.

Table 5. Yearly cumulative DP mass loads and percentage of DP mass loads exported during stream flow events at each subwatershed (SW) and Red Hill outlet.

Location	Year	Cumulative DP Mass Loads Exported During Flow (kg)			Percentage of Total DP Mass Load Exported During Flow	
		Total	Storm	Base	Storm	Base
SW1	1994	83	33	50	40	60
	1995	183	80	103	44	66
SW2	1994	77	25	52	32	68
	1995	173	67	106	39	61
SW3	1994	19	7	12	37	63
	1995	39	17	22	44	66
SW4	1994	7	2	5	29	71
	1995	13	5	8	38	62
Red Hill	1994	109	42	67	39	61
	1995	221	95	126	43	57

The large relative differences between the 1994 and 1995 stream DP exports prompted a closer examination of cumulative DP export on shorter time scales. We initially examined annual cumulative DP loads at all outlets on a monthly basis (fig. 3). In 1994, there was a gradual increase in the cumulative monthly DP exported at all outlets. The lack of oscillations in the 1994 curves may be related to a low number of high–intensity storm events (n = 5, >40 mm precipitation). The higher number of low–intensity storms probably caused P movement into the stream system in small gradations. In 1994, SW4 had the lowest cumulative DP loss, while SW1, SW2, and SW3 had high cumulative DP losses.

In 1995, there were large increases in cumulative DP export at all outlets during June and July (fig. 3). This sharp increase in cumulative DP export prompted a comparison between weekly DP loads, total stream flows, and precipitation amounts during June and July 1995 at Red Hill (fig. 4). Several tropical storms crossed the region in early June and deposited almost 200 mm of precipitation. This high precipitation in early June caused a large rise in stream flows and an increase in DP mass export. Additional storms in mid– to late June also caused higher stream flows and an increase in the weekly DP mass exports. At the end of June 1995, a total of 121 kg of DP was exported at Red Hill, with a higher monthly load exported during storm flows (68 kg) than during base flows (53 kg). This suggests that high precipitation from severe summer storms caused a large DP export pulse from this watershed. During July 1995, however, precipitation amounts decreased relative to June; consequently, total stream flows and the cumulative monthly DP mass exported also declined to 18 kg.

During this 8–week period, approximately 139 kg of DP was exported, which represented 63% of the 1995 annual DP mass exported (221 kg). High precipitation (435 mm) during this 8–week period accounted for about 32% of the 1995 total precipitation. Similarly, increased P transport in the Northeast Cape Fear River occurred after Hurricanes Dennis,

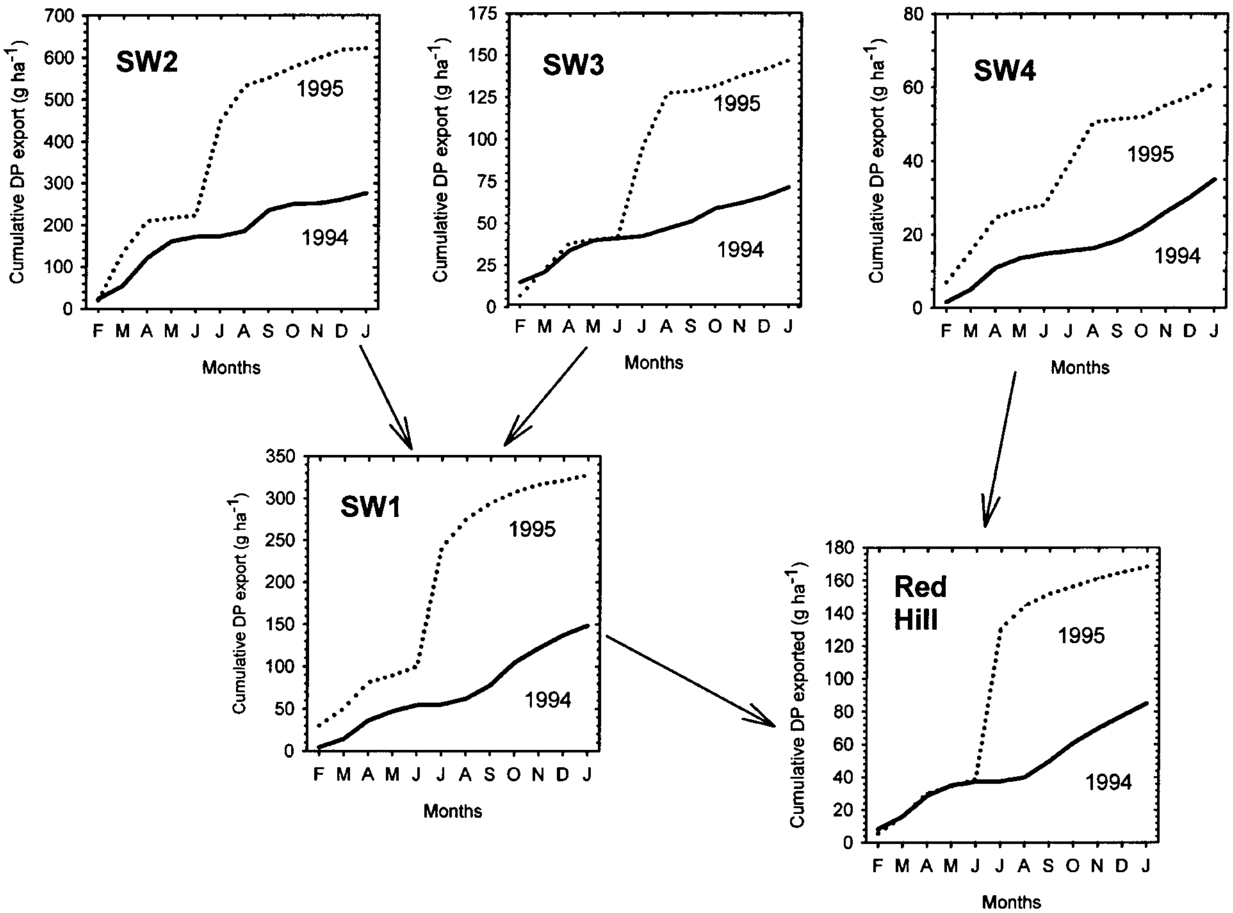

Figure 3. Cumulative DP export at Red Hill and the subwatersheds (arrows are used to indicate flow direction for DP load contributions).

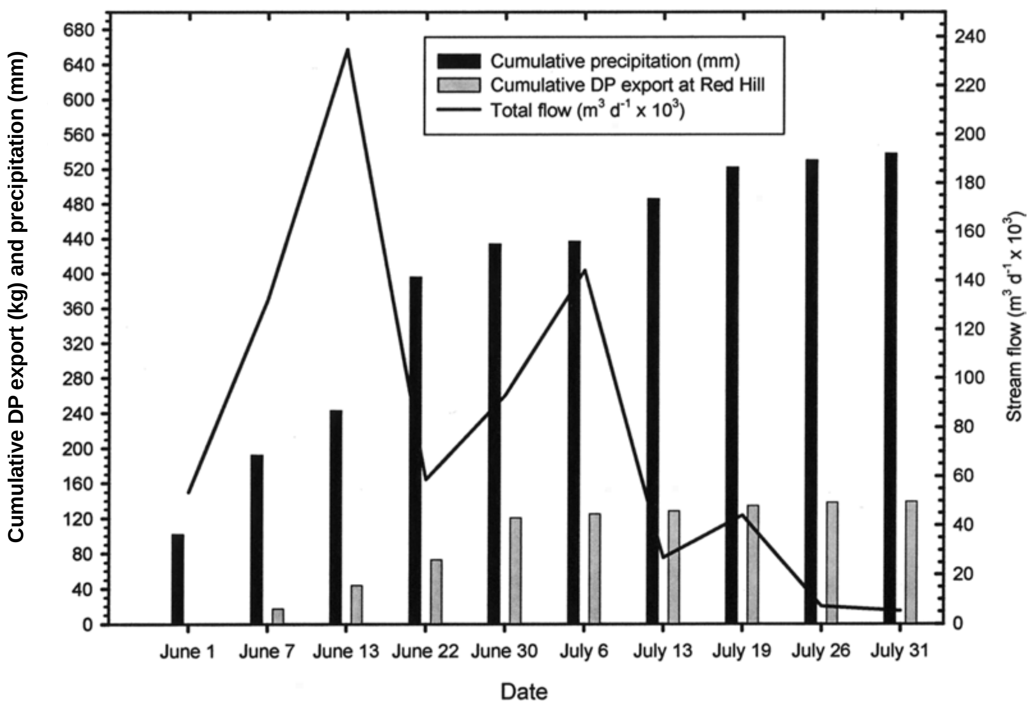

Figure 4. Cumulative precipitation, total stream flows, and cumulative DP export at Red Hill during June and July 1995.

Floyd, and Irene. These hurricanes occurred between September and October and delivered 58% of the 1999 annual precipitation (Bales et al., 2000).

The average total DP load value in 1995 was 2–fold higher than the 1994 value (447 vs. 234 mg DP ha^{-1} d^{-1}, respectively) and is probably due to the higher 1995 total flow rate (table 3). Lowrance and Leonard (1988) reported that from 1982 to 1985, 137 and 274 mg DP ha^{-1} d^{-1} were exported from five Coastal Plain watersheds in Georgia under row crop, pastures, and timber production. Asmussen et al. (1979) reported that from 1974 to 1976, 394 mg DP ha^{-1} d^{-1} were exported from an agriculturally intensive Coastal Plain watershed in Georgia. Our 1994 annual mean total DP load was similar to these two reports, but the 1995 load value was slightly higher.

Stream Flow, Precipitation, DP Concentrations, and Export Relationships

Using untransformed instantaneous data, relationships were non–linear at all outlets, between total stream flow and DP concentration, total stream flow and total precipitation, or DP concentration and DP export ($r^2 < 0.05$, $P = 0.16$ to 0.90). This implied that stream DP concentrations could not be estimated by total stream flow or total precipitation. This was not unexpected after matching instantaneous stream DP concentrations with total flow rates. There were several occurrences of samples having similar DP concentrations but having largely dissimilar total flow values.

Because the instantaneous stream DP concentrations, daily DP loads, and total flows were not normally distributed, these data pools were $\log_{10}$ transformed. Linear regression analyses at all four subwatershed outlets showed a significant relationship between $\log_{10}$ total stream flow and $\log_{10}$ DP exported (r^2 between 0.79 to 0.91, $P < 0.001$). A significant relationship also occurred at Red Hill in both years (fig. 5) and explained 72% to 76% of the variation between $\log_{10}$ total stream flow and $\log_{10}$ DP exported. This strong relationship allows a reasonable estimate of mass DP export at Red Hill using total stream flow rates. For example, assuming a stream total flow rate at Red Hill of 1,000 m^3 d^{-1}, about 25 to 40 mg DP ha^{-1} d^{-1} would be transported out of this watershed.

Conclusions

The objectives of this study were to determine stream DP mass export loads transported under storm and base flow conditions, and to establish relationships between DP concentrations and loads with precipitation and stream flow characteristics in an agriculturally intensive Coastal Plain watershed. The watershed was divided into four subwatersheds because of variable agricultural production. Stream grab samples were collected at Red Hill and the four subwatershed outlets over a two–year period (1994 to 1995). We found:

- Total stream flows at all outlets were usually dominated by base flows. Only during one high precipitation month (June 1995) did the storm flow volume exceed the base flow volume.
- Higher DP mass loads were exported during base flow than during storm flow conditions.
- Over a 2–month period in 1995, several intensive summer storm events produced increased stream flows that caused large DP pulses transported out of this watershed. The cumulative DP mass loads transported during these two months accounted for almost 63% of the annual cumulative total DP mass load exiting this watershed.
- Mean stream DP concentrations varied across the HMR watershed. Two subwatersheds discharged stream water with relatively high DP concentrations, while the remaining subwatersheds discharged stream water with low DP concentrations. Overall, the annual mean stream water DP concentrations at Red Hill were <40 μg L^{-1}.
- Using untransformed instantaneous data, there were no linear relationships between precipitation, total stream flow, and DP concentrations at all outlets.
- In both years of the study, a strong linear relationship between $\log_{10}$ total stream flow and $\log_{10}$ DP export indicated that DP export rates could be estimated from measured total stream flow rates.

We conclude that stream flow characteristics had a large influence on the cumulative mass of DP exported, and high precipitation associated with severe summer storms can greatly increase the mass of DP exported.

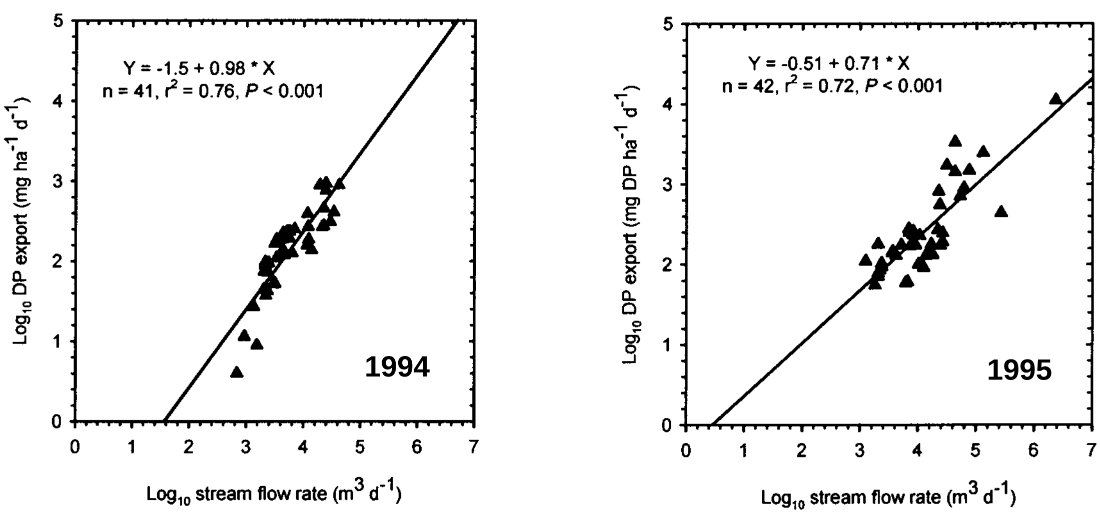

Figure 5. Relationship between $\log_{10}$ stream flow rate and $\log_{10}$ DP export at Red Hill in 1994 and 1995.

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