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Nutrient Loss from an Agricultural Catchment and Landscape Modeling in Southeast China

W. Cao, H. Hong, S. Yue, Y. Ding, Y. Zhang

Key Laboratory for Marine Environmental Science, Ministry of Education, Environmental Science Research Center, Xiamen University, Xiamen, Fujian, 361005, People's Republic of China

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Losses in nitrogen and phosphorus from an agricultural catchment in China have had increasingly negative effects on sustainable agriculture, and contributed to the degradation of water quality in surface, ground and estuarine water. Reports on nitrate and pesticide contamination in water bodies have become common in the literature, and such contamination is strongly related to the excessive application of inorganic fertilizers and pesticides (Guo 1987; Li and Zhang 1999).

Much research has been done on nutrient dynamics and release to runoff, but the mechanisms and hydrologic pathways of nitrogen and phosphorus loss from intensive agricultural field and catchment remain poorly understood (Sharpley and Tunney 2000). The controlling factors of nutrient export from land to receiving water bodies can be categorized into those that influence the source of nutrients and those that influence its transport (Cirmo and McDonnell 1997; Gburek et al. 2000; McDowell et al. 2001). Therefore, nutrient export from agricultural catchments depends on the coincidence of source (soil, crop, and management) and transport (runoff, erosion, and channel processes) factors (Heathwaite et al. 2000). Hydrologic control affects not only the source factors of nutrient export, but also the transport factors (Gburek and Sharpley 1998; Mitchell 2001). In turn, it is central to investigate the hydrologic pathway of nutrient exports at the catchment scale. Topography is the dominant control on spatial variation of hydrological processes at the catchment scale, and landscape modeling, using high-resolution digital elevation models (DEMs), greatly facilitates analysis of the hydrologic factors that control nutrient export.

The objectives of this study were to: (1) characterize the nitrogen and phosphorus export pattern during different flow stages; (2) identify the critical source areas through landscape modeling; and (3) investigate the mechanisms and pathways of nutrient loss in the landscape of an agricultural catchment in southeast China.

MATERIALS AND METHODS

The agricultural catchment (1.74 km^2) of Wuchuan (Fig.1) was selected as an experimental catchment. The stream is a tributary of the upper Jiulong River in Fujian Province. Catchment elevation varies between 19 m and 130 m. Soil is

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Correspondence to: W. Cao

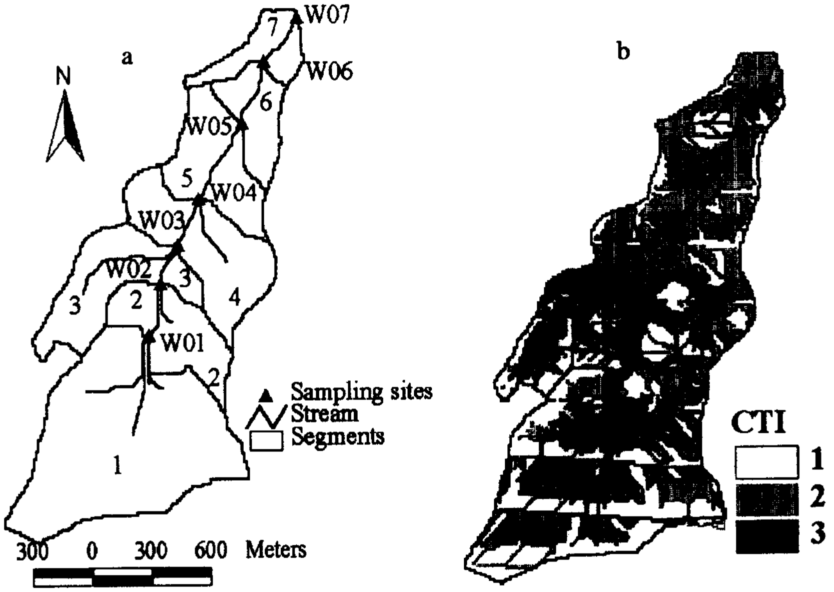

Figure 1. Wuchuan catchment: a, segments and sampling sites; b, grouped compound topographic index (CTI).

characterized as red soil with a texture varying from sand on the slopes to loamy sand or sandy loam in the valley. Soil pH ranges from 4.0 to 4.8 with a mean of 4.3. Mean annual precipitation is 1450 mm. Land use is primarily orchards (63%) with bananas (8%), paddies (3%), vegetables (1%), and forest (25%). A digital map of land use was generated based on field surveys (Cao et al. 2002).

Inorganic fertilizers were applied at levels ranging from 150 kg/ha to 300 kg/ha for nitrogen and 100-200 kg/ha for phosphorus, mostly to cash crops such as bananas and citrus. The predominant fertilizers applied were urea, ammonium hydrocarbonate (NH_4HCO_3), superphosphate and Ca-Mg phosphate.

Two rainfall events (11 December 2000, A; 18 May 2001, B) were monitored to investigate the hydrologic pathway of nutrient loss during stormflow. Other samples taken during the main crop growing seasons were used to characterize the nutrient export pattern in baseflow.

Runoff was measured every 30 min using a flowmeter installed at the outlet of the catchment. Water quality samples were taken manually every 4 hr for event A and every 30 min for event B. Nitrate-nitrogen (NO_3-N), and dissolved reactive phosphorus (DRP) were measured colorimetrically. All samples were delivered to a laboratory and analyzed within 24 hr.

A 10-m-resolution DEM was generated using the hydrologic module of a

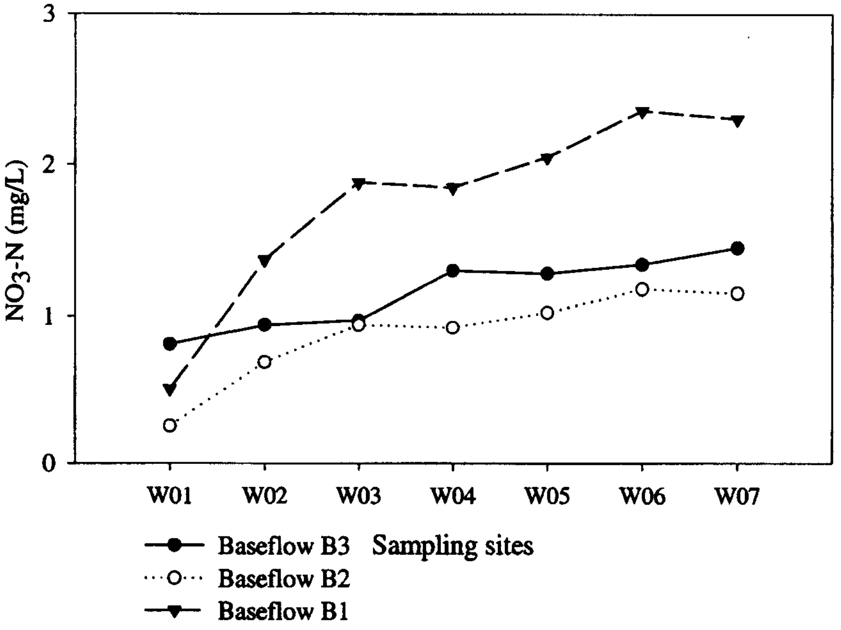

Figure 2. NO_3-N concentrations during baseflow.

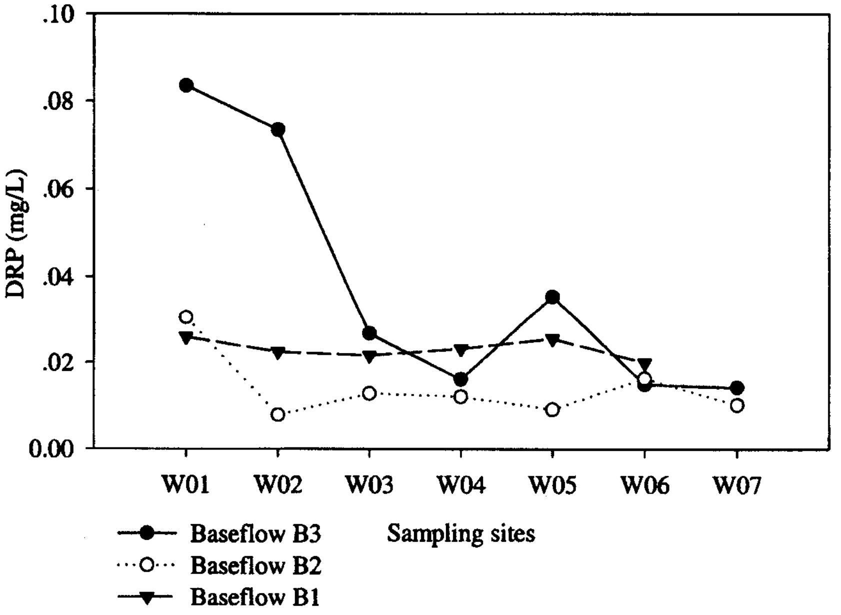

Figure 3. Dissolved reactive phosphorus (DRP) concentrations during baseflow.

geographic information system (ESRI 1996), based on the 1:5,000 contour map. The catchment was divided into seven segments based on topography, drainage pattern, land use and management data derived from the land-use survey and reconnaissance. Sampling sites from the outlet of the catchment (W07) to the uppermost site of the stream (W01) were marked for water quality analysis during baseflow (Fig. 1, a).

The Compound Topography Index (CTI) is a commonly used hydrologically based topographic attribute. CTI can be expressed as:

$$w_T = \ln\left(\frac{A_s}{T\tan\beta}\right) \text{ or } w = \ln\left(\frac{A_s}{\tan\beta}\right)$$

where, T is transmissivity when the soil profile is saturated, w_T and w are often referred to wetness indices, A_s is specific catchment area defined as the upslope area draining across a unit width of contour, and β is slope. In this study, the calculated CTI for each grid cell ranges from –15.8 to 16.3, with a mean of 2.8. The CTI was divided into three groups: Group 1 of $\text{CTI} \leq 0$; Group 2 of $0<\text{CTI}\leq 4.5$, and Group 3 of $\text{CTI}>4.5$ (Fig. 1, b).

RESULTS AND DISCUSSION

Baseflow or groundwater flow is defined as baseflow recession. Where there was no rainfall in the catchment for at least 3 days prior to sampling, the streamflow was considered to be baseflow. Water quality samples during baseflow were taken on 6 July 2000 (B1), 31 August 2000 (B2), and 10 November 2000 (B3). Table 1 lists the statistics of measured nutrient concentration for the three sample series during baseflow. The trends in concentration of NO_3-N and DRP from the uppermost sampling site (W01) to the outlet (W07) are reversed for the three sample series (Fig. 2 and 3). The concentration of NO_3-N increased downstream (Fig. 2), with the highest concentration being at the outlet (W07), and the lowest at the uppermost sampling site (W01). Conversely, in all samples, DRP concentration decreased from the uppermost sampling site (W01) to the outlet (W07).

Table 1. Statistics of measured nutrient concentration for three baseflow events.

Nutrient	Mean	Minimum	Maximum	Std. Dev.
NO_3-N (mg/L)	1.26	0.25	2.35	0.56
DRP (mg/L)	0.025	0.008	0.084	0.019

Rainfall events A and B were of a similar magnitude (event A=40.3 mm; event B=43.2 mm), but rainfall duration differed (event A=40 hr; event B=6 hr). The concentration dynamics of NO_3-N and DRP against flow rate for the two rainfall events are illustrated in Figures 4 and 5. The concentrations of NO_3-N and DRP in the streamflow began to increase gradually after the stormflow began, and NO_3-N and DRP were still increasing at peak runoff. At some point during the recession stage of the flood hydrograph the peak concentration of NO_3-N and DRP occurred,

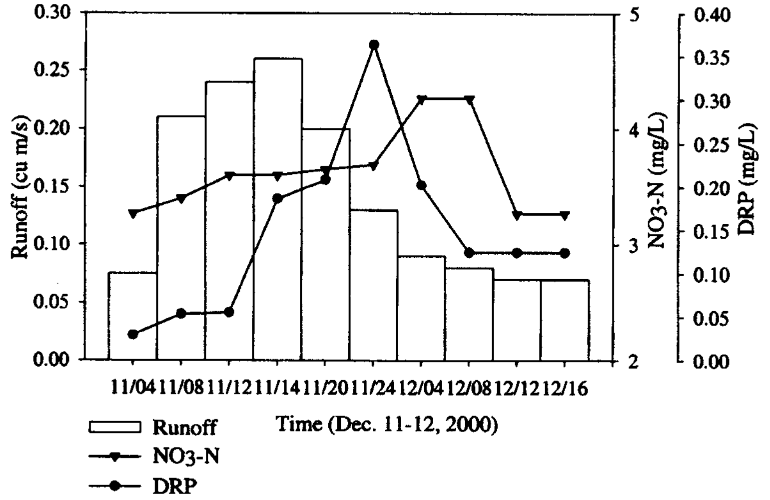

Figure 4. NO$_3$-N and dissolved reactive phosphorus concentrations (DRP) during stormflow at outlet for event A.

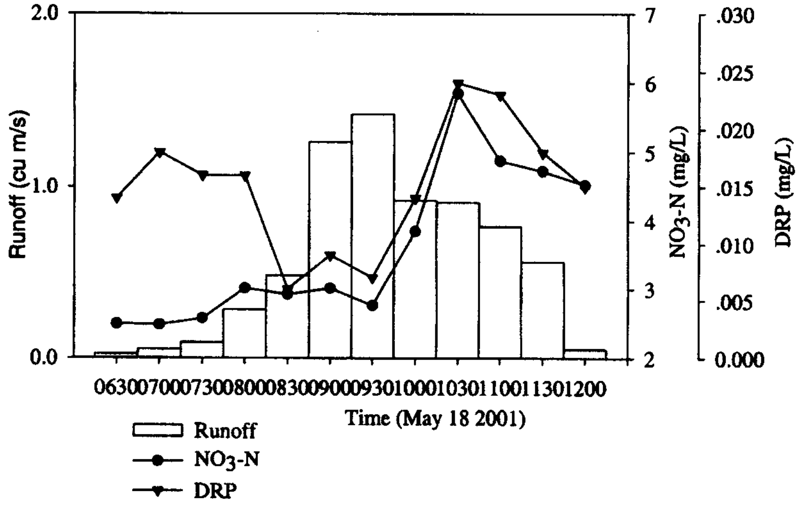

Figure 5. NO$_3$-N and dissolved reactive phosphorus (DRP) concentrations during stormflow at outlet for event B.

and then declined with the falling limb of the hydrograph. This showed that the subsurface flow was delayed and that nutrients were being removed from the soil by subsurface flow. This proportion of delayed subsurface flow resulted in the delay of the nutrient peaks until after the peak runoff had occurred.

Beven and Kirkby (1979) and O'Loughlin (1986) developed the wetness index and related it to the spatial distribution and size of zones of saturation and variable source areas for runoff generation. Likewise, significant percolation of soil water to groundwater occurs only when the soil water content exceeds field capacity. The wetness index could, therefore, possibly be used to derive the potential for groundwater recharge and non-point source pollution (Moore et al. 1991). The area of each catchment segment in the different CTI groups was calculated and listed in Table 2.

Table 2. Area of each catchment segment in the different CTI groups.

Segments	Group 1 (ha)	Group 2 (ha)	Group 3 (ha)
1	30.17	36.74	0.37
2	6.90	10.68	0.19
3	7.27	14.76	0.06
4	7.41	18.33	0.21
5	4.97	14.31	0.31
6	4.08	6.97	0.22
7	2.30	6.99	0.27

It is commonly held that the losses of nitrogen and phosphorus in their critical source areas and hydrologic pathways differ at the catchment scale (Heathwaite and Johnes 1996). In the Wuchuan catchment, under baseflow conditions, the local shallow groundwater is the primary source of streamflow. Therefore, the quality of groundwater determines streamwater quality. Generally, the concentration of DRP in groundwater flow is very low, because DRP is either immobilized by highly soluble aluminum and iron within the soil profile under low pH (<7) or taken up by the crop within the root zone. However, the area with the high CTI value (Segment 1) indicates a shallow groundwater depth or good hydrological connectivity to streams. Therefore, the DRP in percolation during antecedent rainfall events possibly bypasses the strong processes of sorption and immobilization through the thin soil layer, and causes a buildup in groundwater and finally contributes to the streamwater quality. This mechanism results in the declining trend (Fig. 3) of DRP concentration from sampling sites W01 to W07 (Fig. 1) during baseflow. In addition, at catchment scale, the significant hydrologic pathway of DRP transport in high CTI areas has great potential for DRP leaching loss. Therefore, the high CTI area (Segment 1) is a critical source area for environmental phosphorus management.

The leaching rate of NO_3-N governs its concentration in groundwater, and that primarily depends upon the soil texture. Thus, different trends in NO_3-N concentration were observed during baseflow (Fig. 2). Nevertheless, the dilution process and biological consumption in the stream channel may also contribute to the nutrient export patterns.

In conclusion, both surface and subsurface pathways of nutrient loss exist at the catchment scale. The mechanisms and hydrologic pathways of nutrient loss from an agricultural catchment depend mainly upon topography, soil properties, and flow stages. Therefore, landscape modeling can provide a useful tool to explain the mechanisms of nutrient loss and critical source areas in an agricultural catchment.

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