Water Quality: Current Trends and Expected Climate Change Impacts (Proceedings of symposium H04 held during IUGG2011 in Melbourne, Australia, July 2011) (IAHS Publ. 348, 2011).

Effects of extreme rainstorms on the export of diffuse pollution from an agricultural watershed in eastern China

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Abstract Agriculture is an important contributor to diffuse pollution in the aquatic environment system. The exact transfer of nitrogen (N) and phosphorus (P) in an agriculturally dominated area is still poorly understood. Export of pollutants shows significant spatial and temporal variation and the relevant factors are complex and nonlinear in nature. There has been a dramatic increase of synthetic fertilizer usage in southern China during recent decades due to decreasing farmland and increasing food demand. Massive N and P fertilizer application has led to many environmental problems, especially eutrophication. Research has shown that extreme rainstorms will increase in frequency with climate change. The objective of this study is to examine the diffuse agricultural pollution transfer at the watershed-scale and field-scale through event-based, on-site observation and sampling. Seven years of experiments carried out in Meilin watershed demonstrate the export of significant quantities of nutrients during high intensity rainstorms. Based on detailed field experiments, the N and P transfer in different seasons and land covers is described.

Key words extreme rainstorms; nitrogen; phosphorus; agriculture; field experiment; Meilin watershed, China

INTRODUCTION

During recent years, the eutrophication problems of Lake Tai and severely deteriorated water environment of the Taihu Basin, in China, have drawn worldwide concern. One of the major contributors is diffuse pollution from farming activities (Jin *et al.*, 1999; Cui *et al.*, 2009). Taihu Basin is famous for being the site of most of the agricultural activities in the history of China. Since the 1980s, with exponential growth in urbanization and economic development, cities have expanded and industry has boomed, resulting in significant reduction of the area under cultivation. But the reduction of farming area did not reduce the diffuse pollution as a result of cultivation (Zuo *et al.*, 2003; Zhang *et al.*, 2010). For example, in Yixin City the arable area was reduced by 13%, while there has been a three-fold increase in fertilizer application over the last two decades (Lin *et al.*, 1999). The generation of agricultural diffuse pollution is closely related with the rainfall–runoff process (Pionke *et al.*, 1999; Kovacs & Honti, 2008). Influenced by global warming and human activities, the frequency of flood disasters has been increasing in the Yangtze River Basin since the 1980s (Yang, 2007). Related studies indicate that climate change has significantly affected the water cycle and flood characteristics in this area (Zhang *et al.*, 2010). The middle and lower reaches of the Yangtze River, where Taihu Basin lies, experience more extreme rainstorms than they did in the period prior to 30 years ago. Precipitation has increased notably in January, March, June and July (Zhang *et al.*, 2007).

The Taihu Basin is in the subtropical monsoon region, which has abundant precipitation, reaching an annual value of 1154 mm. Dominated by western Pacific subtropical highs, it has persistent rainy weather during the summer, which is called plum rain. Typhoon rain is also one of the main causes of flood disasters (Luo *et al.*, 2004). Therefore, rainstorms are very intense during the season of plum and typhoon rains, and the precipitation during this season can account for over 50% of annual rainfall. Moreover, coupled with the impact of climate change, the extreme rainstorms tend to have a higher intensity and increased frequency (number of days). In contrast, agricultural activities such as tillage, seeding and fertilizing are also intense during this rainy period, which would significantly enhance the export of diffuse pollutants (Gao *et al.*, 2005; Li *et al.*, 2010).

The objectives of the research presented in this paper are: (1) to investigate seasonal effects on flow and nutrient concentration and export patterns in rainstorms at the watershed scale, (2) to examine these patterns under different land covers at the field-scale, and (3) to study the impact of a single extreme event on these patterns.

MATERIAL AND METHODS

Study site

The 0.57 km^2 Meilin watershed in Yixin City is located approximately 10 km southwest of Lake Tai within the Taihu Basin (Fig. 1). Agricultural cultivation is the major land use activity in the Meilin watershed; the watershed is composed of 78% cropland, 12% forest, 7% grass, and 3% water, with secondary and plantation forest dominating the ridges. Elevations range from about 3 m in the northeast to 46 m in the southwest. Cropland is dominated by cash crops, such as corn, vegetables and wheat, with sporadic poultry production by family farms. There are no urban or industrial areas within the watershed. Consequently, stream water quality (N and P concentrations) at the outlet is mainly affected by diffuse agricultural pollution. Yellow-brown soil and paddy soil are the main soil types in the area, and are slightly acidic. Groundwater in the area is predominantly located in the weathered rock of the Yangtze stratigraphic zone. The groundwater depths change with terrain, but are generally about 1 m in the plains to 3–5 m in hilly areas.

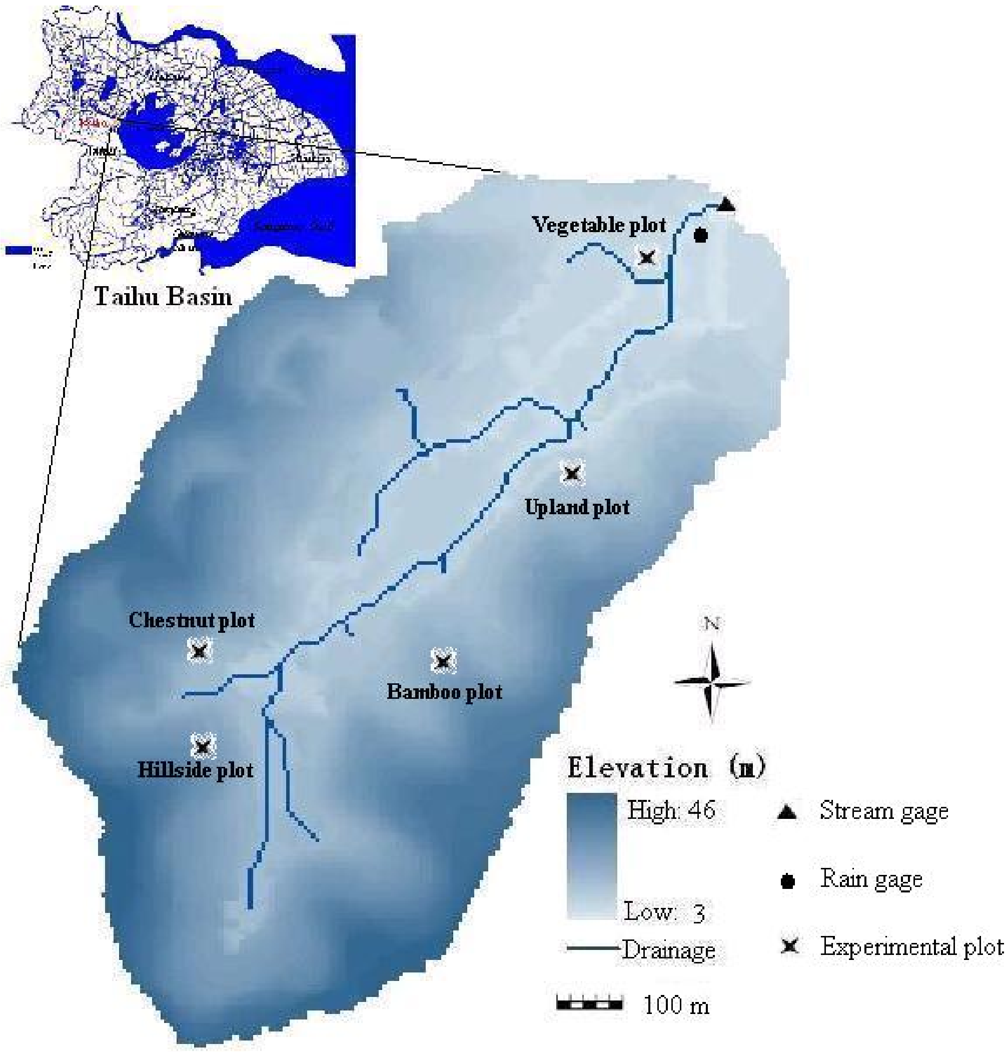

Fig. 1 Location and DEM of the Meilin watershed.

Sampling and analysis

A sharp crested weir is located at the watershed outlet, and the water level is continuously monitored using an automatic pressure water level gauge connected to a data storage instrument; discharge was determined from a stage–discharge relation. There is also a rainfall recorder in the watershed to record the rainfall data. Using an automatic sampler, water samples were collected during the rainstorms at a sampling interval of 15-min during the initial 2 h period, and at 30- and 60-min intervals during consecutive 4- and 8-h durations, respectively, until 24 samples were collected. If the rainfall persisted, samples were collected manually at 2- to 4-h intervals.

Five experimental plots with different land covers were established to observe the pollutant transfer patterns (Table 1). The hillside plot, which has a natural divide, was located on the ridge of the southwest watershed in a chestnut plantation. Other plots were separated by plastic plates.

Table 1 Areas and slopes of experimental plots in Meilin watershed.

Plot	Vegetation	Soil bulk density (g/cm^3)	Area (m^2)	Slope (°)
Vegetable plot	Spinach/cabbage	1.36	40	2.5
Upland plot	Corn	1.23	40	5.0
Bamboo plot	Bamboo	1.19	40	7.5
Chestnut plot	Chestnut	1.40	60	6.6
Hillside plot	Chestnut	1.31	80	19.0

Water depths were measured with self-recording water level gauges in rectangular runoff collection ponds for each plot. Water samples for the measurement of N and P were manually collected during rainstorms.

The water samples were stored on ice immediately after collection and were filtered (0.45 μm) and analysed within three weeks. Each water sample was analysed for total nitrogen (TN), nitrate (NO_3-N), ammonia (NH_4-N), and total phosphorus (TP) using the UV spectrophotometric method with alkaline potassium persulfate digestion, spectrophotometric method with phenol disulfonic acid, Nessler's reagent spectrophotometry, and ammonium molyhdate spectrophotometric method, respectively (Ministry of Environmental Protection of PRC, 2002).

The discharge and water quality data from rainstorms were categorized by season. In consideration of the climate characteristics and agricultural activities in the Meilin watershed, the seasons were March–May (spring), June–August (summer), September–November (autumn), and December–February (winter).

RESULTS AND DISCUSSION

The data sets were subjected to three analyses. First, the seasonal export patterns of N and P were examined with respect to nutrient loads during rainstorms. Second, the relative variation in nutrient export from experimental plots, i.e. with different vegetation, was evaluated. The third analysis aimed to examine the influence of a large rainstorm on discharge and N and P export.

Flow and nutrient export pattern in Meilin watershed

Nutrient loss from soil can be accounted for from two perspectives. One is through the particulate pollutants being transported along with soil erosion. The other is through the dissolved pollutants moving with runoff. Samples of 36 rainstorms from 2003 to 2009 were analysed for pollutant concentrations before and after filtration (Fig. 2). It is observed that, on average, 64% of TN and 87% of NO_3-N is exported in a dissolved state. TP and NH_4-N generally are adsorbed and tend to migrate along with soil particulate. However, 55% of TP and 53% of NH_4-N output still remain as a soluble component in Meilin because of limited sediment yields, even during heavy rainstorms. The Meilin watershed has good vegetation cover, and it is unusual for rainstorms to produce massive soil erosion. Therefore, most of the N and P export is dissolved.

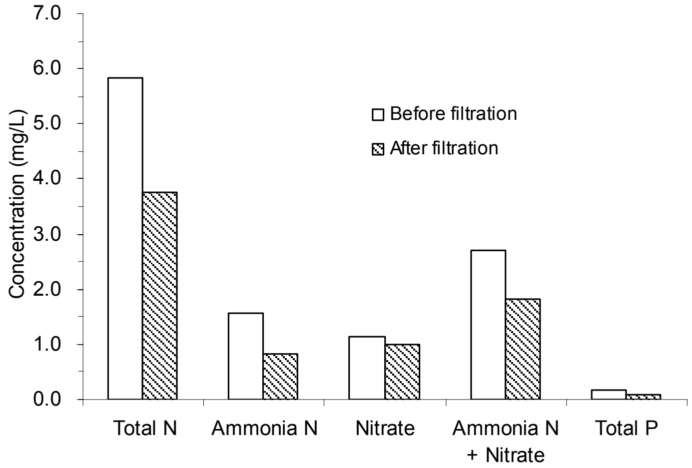

Fig. 2 Comparison of pollutant output concentrations in dissolved and particulate states.

Table 2 Summary of flow and nutrient concentrations by season for the Meilin watershed.

Season	Flow		Total N			Nitrate			Ammonia N			Total P		
	m	sd	m	sd	l	m	sd	l	m	sd	l	m	sd	l
Spring	0.05	0.01	4.83	0.94	807	3.66	0.97	627	0.52	0.14	82	0.12	0.06	21
Summer	0.15	0.10	4.84	0.89	2501	1.19	0.43	1126	1.40	0.48	880	0.18	0.10	181
Autumn	0.04	0.03	2.64	0.83	379	1.68	1.04	185	1.12	0.49	168	0.24	0.18	27
Winter	0.05	0.01	5.86	0.46	1671	3.79	0.59	1051	0.89	0.09	260	0.14	0.02	42

Units: flow mean (m) and standard deviation (sd), $m^3 s^{-1}$;
nutrient concentration mean (m) and standard deviation (sd), mg L^{-1}, load (l), g h^{-1}.

All data collected were analysed by season (Table 2). The rainstorm mean (m), standard deviation (sd), and load (l) values represent the averages of storm samples. Although fertilizer is applied in all seasons, more N fertilizer was consumed during summer, while P fertilizer was consumed both during summer and autumn. As expected, the flow rate during summer was about three times higher than that of other seasons due to the frequent occurrence of extreme rainstorms (> 25 mm d^{-1}). As a result, N and P concentrations during summer get diluted and tend to be lower relative to other seasons. However, different forms of N and P had very high export loads during the summer, indicating that intense extreme rainstorms cause large amounts of N and P to be exported from the watershed. Compared with nitrogen pollutants, the TP load during summer was much higher than in other seasons. This implies that extreme rainstorms significantly influence the export of P. Examination of the NO_3-N and NH_4-N concentrations in Table 2 indicates that NO_3-N dominated the N output in spring, autumn, and winter. The higher NH_4-N concentrations during summer reflect the large amount of ammonia fertilizer application and adsorption by soil particles. The high-intensity rainfall during summer resulted in higher rates of soil erosion relative to other seasons. The event average amount of NO_2-N constitutes only around 5% of TN. We assume that the sum of NH_4-N and NO_3-N is most of the inorganic N and consequently, the organic N output was obtained by subtracting inorganic N from TN. This analysis revealed that rainstorms during summer exported more organic N than rainstorms during other seasons.

Nutrient export pattern in experimental plot

Different vegetation and terrain characteristics have a variable effect on runoff and nutrient export processes (Liu *et al.*, 2008; Ouyang *et al.*, 2009). To study these variations, five experimental plots were instrumented to investigate N and P export patterns at the field scale. Because saturation excess runoff mechanism controls surface flow, surface runoff samples in experimental plots could be collected only during large rainstorms (> 25 mm d^{-1}). Samples of 10 rainstorms from 2006 to 2009 were analysed for nutrient export patterns.

Though the vegetable plot had the gentlest slope, it was located near the outlet of the watershed where groundwater is shallow and near the surface. The soil water content can remain relatively high due to the shallow groundwater level supplemented by frequent irrigation. Hence, more frequent saturation excess surface runoff was observed in the vegetable plot (Fig. 4). The hillside plot had steeper terrain, resulting in higher flow velocities. Therefore, surface runoff from the hillside plot was large as well. The chestnut plot and bamboo plot had good vegetation cover. Consequently, they generated less surface flow. In contrast, the upland plot produced more surface flow than these two with less vegetation coverage but a gentler slope. The nutrient export from the vegetable plot and upland plot showed more N and P losses, with surface runoff as expected (Figs 3 and 4), because the vegetable plot had the highest fertilization rate, followed by the upland plot. The chestnut and bamboo plots were fertilized only in June once a year and the application amount was much less than that applied to the vegetable and upland plots. In summary, the nutrient output from Meilin is controlled by both soil nutrient content and flow rate. Based on this data analysis, we can draw a conclusion that soil nutrient content plays an important role in N and P export for different types of land cover in Meilin.

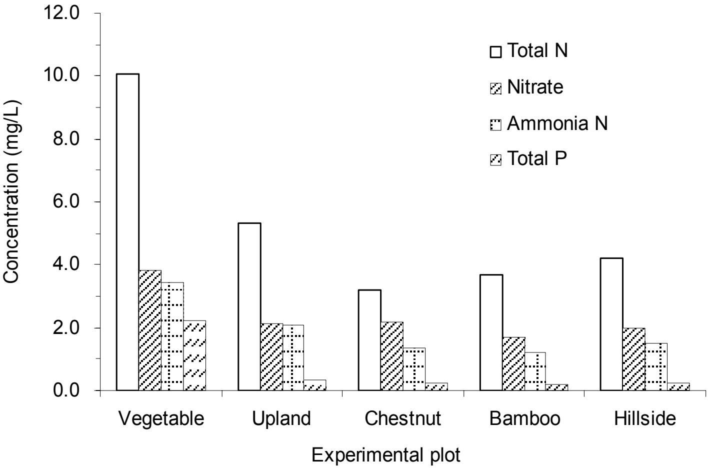

Fig. 3 Mean nutrient concentration of experimental plots.

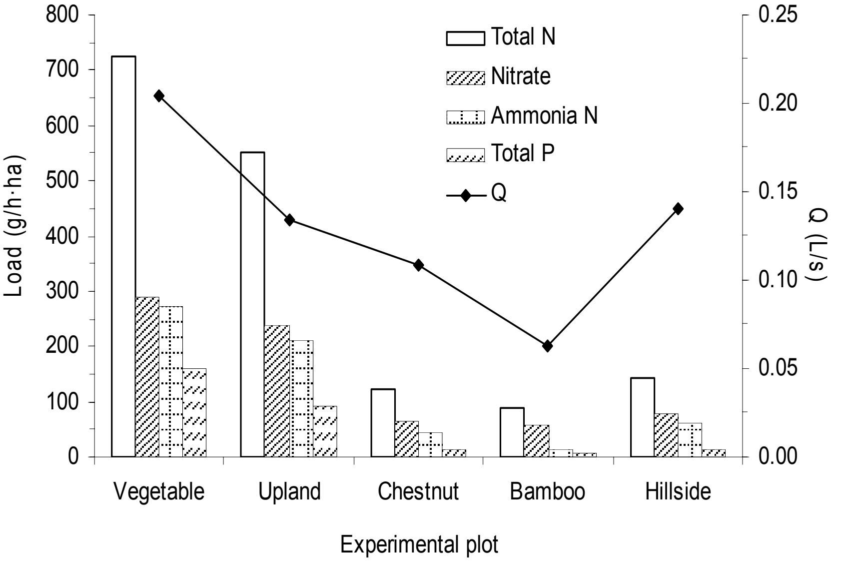

Fig. 4 Mean flow and nutrient load of experimental plots.

Impact of an extreme event on flow and nutrient export

A major rainstorm occurred on 10 July 2007 due to the influence of western Pacific subtropical highs. Seventy-two mm of precipitation fell over 7 hours, with intermittent gaps and with a maximum intensity of 7 mm per 10 min. The rainstorm generated a peak flow rate of 0.99 $m^3 s^{-1}$, which exceeded the June–August and annual average flow rates by 6 and 13 times, respectively.

Percent of change was calculated by dividing the concentration (Fig. 5(a)) or load (Fig. 5(b)) difference between selected events and event averages by event averaged values. The averaged concentrations or loads at the watershed outlet were computed for two time periods, which were the annual average (AA) and June–August average (SA).

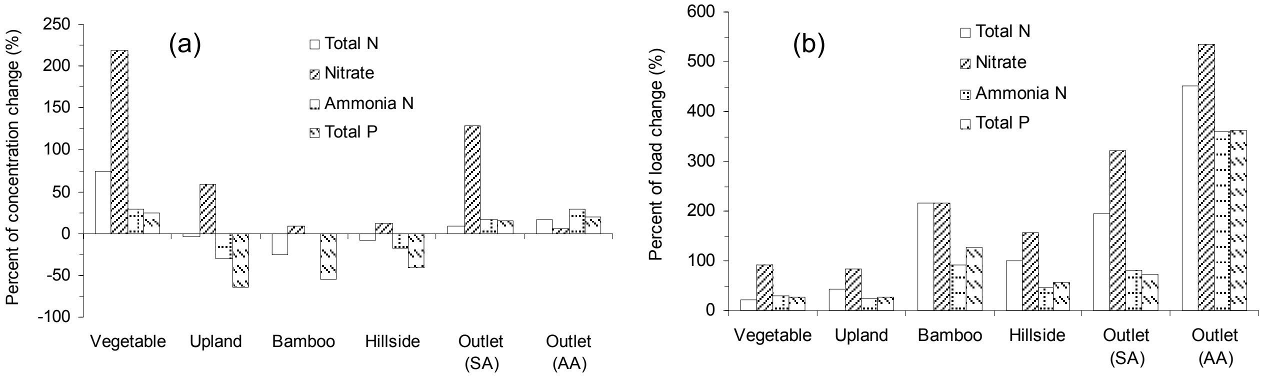

Fig. 5 (a) Comparison of nutrient concentrations of a large storm (10 July 2007) over event averaged values. (b) Comparison of nutrient loads of a large storm (10 July 2007) over event averaged values.

The extreme event exerted varied effects on the output patterns of nutrient concentrations among the experimental plots. For the vegetable plot, all N and P concentrations were higher, especially for NO_3-N. But TN, NH_4-N and TP concentrations of this rainstorm were all lower than in the other three plots. These patterns were consistent with the data in Table 2 in that larger rainstorms did not necessarily correspond with high nutrient concentrations. First of all, this indicates that excess soil nutrient content might have resulted from application of unnecessarily large amounts of fertilizer in the vegetable plot. Second, larger flow accelerated nutrient output, but the dilution effect induced by the high flow rate, except during extremely heavy rainstorms, exceeded the increasing pollutant output, which resulted in lower pollutant concentrations in the plots. Third, reduced TN concentration was mainly caused by decreased ammonia N and organic N concentrations. Low TN, NH_4-N and TP concentrations suggest soil erosion was low at Meilin. It is worth noting that the NO_3-N output concentration of the 10 July 2007 rainstorm was larger than event averages under all conditions, which demonstrates the high mobility of NO_3-N and its enrichment in Meilin. Compared with summer and annual averaged values, nutrient output concentrations during this rainstorm were all higher. The NO_3-N concentration was about 2.3 times the June–August average. The annual average increased little, however, because of high NO_3-N concentration in autumn. The rainstorm caused more nutrients to be exported under all conditions, which suggests that extreme rainstorms export more nutrients. As discussed above, bamboo and hillside plots exported lower nutrient loads than vegetable and upland plots did, but showed more nutrient export during the extreme events.

CONCLUSIONS

The flow rate pattern was consistent across seasons and experimental plots. The average flow rate during summer, when extreme rainstorms (typhoon and plum rains) occurred frequently, was three to four times greater than during other seasons. In experimental plots, soil water content, vegetation cover, and terrain were three major factors controlling surface flow as saturation excess runoff. The nutrient concentration pattern was not as clear as the flow pattern. The dilution effect of high flow rates during summer lowered nutrient concentrations at the outlet similarly for all experimental plots, except for the vegetable plot during large rainstorms. The average TN and TP concentrations of different land covers during rainstorms descended in the following order: vegetable > upland > chestnut > bamboo. Soil erosion in Meilin was relatively low during rainstorms, and nutrients were more likely to be exported in soluble states. The nutrient export load pattern showed a distinct relationship with flow rate, particularly for phosphorus. The time overlap between agricultural activities and extreme rainstorms inevitably caused more nutrient export, which was adverse to both the aquatic environment and agricultural production.

Acknowledgements This study was supported in part by the Natural Science Foundation of China (50979022), the program for Changjiang Scholars and Innovative Research Teams in Universities (IRT0717), National Basic Research Program of China (2010CB951101), the Natural Science Foundation of Hohai (2009423211), and the Fundamental Research Funds for the Central Universities.

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