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Nutrient loss to water bodies from a rice-cropped farm

M. Shah Alam Khan[1], Abul Fazal M. Saleh[1], A. B. M. Badruzzaman[2]
and M. A. Rashid[3]

[1]Institute of Water and Flood Management
Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh
[2]Department of Civil Engineering,
Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh
[3]Irrigation and Water Management Division
Bangladesh Rice Research Institute, Gazipur, Bangladesh

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Abstract

Fertilizer application to increase rice production has significantly increased in Bangladesh in the recent decades. However, excess nutrients from fertilizer application pose a threat of contamination of water bodies. This paper presents the results of monitoring nutrient concentration in an intensively rice-cultivated area to assess the pollution risks of the receiving water bodies. Field observations indicate that approximately 4.53 kg/ha and 6.00 kg/ha nitrogen (N) are transported to the receiving surface water bodies from the 2 drainage compartments, or Blocks, of the study site during a rainfed crop season in an average-rainfall year. Corresponding phosphorus (P) loads are 2.16 kg/ha and 2.35 kg/ha. Supplementary lysimeter experiments conducted to assess the potential groundwater contamination show that N and P concentrations in the leachate approach 0.25 mg/L NO_3-N and 0.6 mg/L PO_4, respectively, toward the end of Boro season. At the water quality monitoring locations, the maximum observed N and P concentrations meet the drinking water standard. From soil and plant sample analyses, the N recovery rate at the site is found to be 34.8%. An estimated nitrogen balance shows that of 80 kg/ha N applied, 27.84 kg/ha are taken up by the rice plants and 5.15 kg/ha are transported to the surface water bodies. The remaining 47.01 kg/ha N are either transported with infiltration or interflow, or adsorbed to the soil. Characteristic relationship between rainfall amount and observed nutrient load during 31 rainfall events provide a basis to estimate the nutrient loads from observed rainfall data.

Keywords: Fertilizer, nutrient load, rice cultivation, agricultural return flow, nonpoint-source pollution

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1. Introduction

Fertilizers provide nutrients that are not present in sufficient amounts in the soil for plant growth. Although, application rate and timing of fertilizers are determined based on specific needs of the plants, almost in all cases excess nutrients remain as residues. In developing countries like Bangladesh, the general trend is to overuse fertilizers to increase soil fertility. However, for rice plants, only 40-80% of applied nitrogen (N) and 5-20% of applied phosphorus (P) are utilized. The efficiency of plant uptake decreases as more fertilizer is applied (De Datt, 1991). The excess nutrients may remain in the field as residue or eventually reach the receiving water bodies by surface runoff, leaching, interflow and soil erosion. Jimoh *et al.* (2003) found an increase in N and P concentrations in surface and groundwater, exceeding the safe drinking water standard, after fertilizer application in an irrigation scheme in Nigeria. Similar decline in water quality from excess nutrient in irrigation return flow in many developing countries is reported by Pearce (1998). Excess nutrient load in water bodies are known to have severe impacts on public health and environment in developing countries. These include *methaemoglobinaemia*, commonly known as 'blue baby syndrome', liver and lung damage, cancer, eutrophication in receiving surface waters, and large-scale algal blooms (Pearce, 1998; Ongley, 1996).

In Bangladesh, fertilizer use has considerably increased in the recent decades due to intensification of agriculture to meet the food demand of the growing population. Fertilizer sales increased from 875,179 metric tons in 1980-81 to 3,364,080 metric tons in 2003-04 (BBS, 2005). During this period the sales of Urea for N input and Triple Super Phosphate (TSP) for P input increased by about 315% and 68%, respectively. In 2002-03, the estimated demand for Urea and TSP were approximately 2,350 and 450 thousand metric tons, respectively. However, studies on possible effects of increasing fertilizer use in the country are very limited. EGIS (2002) monitored the surface water quality in a *beel* area, and followed an analytical and a modeling approach to assess the eutrophication potential of nitrogen emission from fertilizer application. Nitrate concentration as high as 8.5 mg/L in the *beel* water is attributed to agricultural runoff. An attempt to model the complex physical processes of the *beel* system was partially successful. Alam *et al.* (2001) monitored the presence of excess fertilizers by measuring levels of ammonium, nitrate, phosphate and potassium to assess the impact of agricultural practices on groundwater quality, and found relatively high concentrations of ammonium and nitrate.

Because of the risks of pollution associated with the use of agrochemicals including fertilizers, the National Water Management Plan (NWMP) (WARPO, 2001) emphasizes that agrochemicals be used more carefully to minimize their effects on the environment, and that their residues in receiving water bodies be monitored. Since N and P fertilizers applied to rice plants, especially the High Yield Varieties (HYV), are the most widely used agrochemicals in Bangladesh, pollution risks of their application are likely to be higher. This paper presents the results of a short-term monitoring of the effects of fertilizer application on receiving water bodies in an intensively rice-cultivated area.

2. Field setup and monitoring

2.1 *Site description*

The study was conducted in the western part of the experimental plots of Bangladesh Rice Research Institute (BRRI) in Joydevpur, Gazipur (Fig. 1). The site is divided in 3 drainage compartments or Blocks, namely Blocks A, B and C, having areas of 8.99, 9.88 and 7.18 ha, respectively. The main channel at the site runs across the 3 Blocks and passes the Block-divider roads through 2 culverts. There are 3 flow entry points and 1 flow exit point at the site. Water enters into the site from the adjacent farmlands, residential areas, and small-scale commercial and industrial complexes. Water flow from the site is discharged to a drainage channel outside the northern boundary.

The climatic data from BRRI weather station show that the mean annual rainfall at BRRI is approximately 2,000 mm. Rainfall is concentrated in 4 climatic seasons: Pre-monsoon (March to May), Monsoon (June to September), Post-monsoon (October to November) and Dry season (December to February). Approximately 70% of the annual rainfall occurs during the monsoon. July and August are the months of the heaviest rainfall. The mean monthly temperature varies between 18^oC and 29^oC, while the mean monthly evaporation varies between 62 mm in January and 155 mm in May, approximately.

The plots of the study site are situated at 3 levels or landforms of the Madhupur tract/terrace: (i) High terrace, (ii) Mid terrace, and (iii) Broad valley. The associated soil types are: (i) Bhatpara clay, (ii) Chhiata clay, and (iii) Naga clay, respectively. The combined upper clay layers are approximately 140-ft deep on an average.

Crops are grown in 2 crop seasons, Aman and Boro, at the study site. The planting and harvesting dates of the crops are given in Table 1. Most of the plots at the site are used for varietal trials. Fertilizer application experiments are conducted in a few plots. The overall fertilizer application schedule is approximately the same for the whole area. Three types of fertilizers are usually applied to provide nutrients to rice plants: (i) Urea, (ii) TSP and (iii) Muriate of Potash (MP). The composition and available nutrient content of these fertilizers are given in Table 2. Fertilizers are applied in 2 ways: (i) ‘Basal Dressing’ before planting and (ii) ‘Top Dressing’ during the growing period. Fertilizer is applied in wet soil and no drainage is allowed when applied in standing water. N, P and potassium (K) are applied to rice fields at the rate of 80, 60 and 40 kg/ha, respectively. N (as Urea) is applied in 3 equal splits: (i) 10-15 days after planting (for tillering), (ii) 30-40 days after planting (during panicle initiation), and (iii) 50-60 days after planting (during flowering). Usually 100% of P and K (as TSP and MP, respectively) are applied during Basal Dressing and land preparation. The process of nutrient uptake at different growth stages of rice plant is a function of climate, soil properties, amount and method of fertilizer application and variety of rice (De Datt 1981).

2.2 *Monitoring arrangement*

Surface water quality, flow and level have been monitored during 2 consecutive crop seasons, Aman and Boro of 2005, at 6 locations of the site (see Fig. 1). Three of these locations, SW1, SW2 and SW3, are at the flow entry points and 1 location, SW4, is at the flow exit point of the site. SW5 and SW6 are at the flow exit points of Blocks B and C, respectively. Water levels have been measured by staff gauges at all locations. Flow rates have been measured by 1.8-m long Parshall flume at SW1 and SW4, and by 0.9-m long Cut-throat flume at SW2. At other locations, flow rates have been estimated from approximate cross-section, water depth and average velocity have been determined by float method.

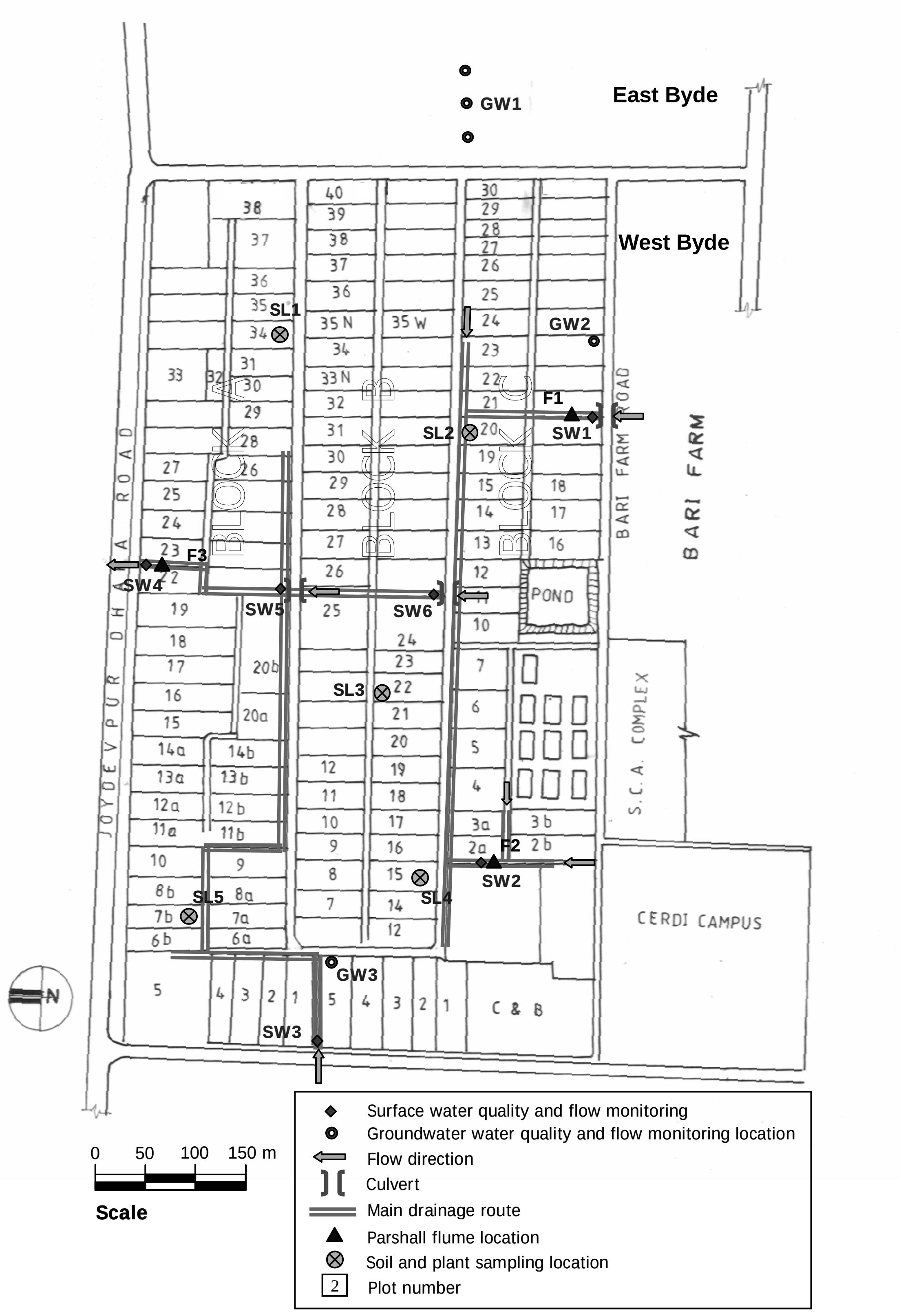

Fig. 1. Study site at Bangladesh Rice Research Institute

Groundwater quality and level have been monitored at 3 locations: GW1, GW2 and GW3. The observation wells have an inside diameter of 4 cm, and have their strainers placed at a depth of about 170 ft. Additional field monitoring have been conducted in 6 lysimeters, L1 through L6, during the Boro season of 2006 to assess the potential contaminant contribution of leachate to groundwater. These lysimeters are 2 m X 2 m plots enclosed by 2-m deep concrete walls. A tap located at the bottom of the side wall, 2 m below the surface, allows collection of leachate. The same planting and fertilization procedures and schedules as in the field have been used in the lysimeters.

Table 1
Planting and harvesting dates of Aman and Boro crops

Crop	Planting date	Growing period	Harvesting date
Aman	mid-July to mid-August	105-110 days	November - December
Boro	Early January	110-115 days	April -May

Table 2
Composition and nutrient content of commonly applied fertilizers
(Source: De Datt 1991)

Fertilizer	Composition	Available nutrient content
Urea	$CO(NH_2)_2$	46.0 % N
Triple Super Phosphate (TSP)	$Ca(H_2PO_4)_2$	19.4 % P
Muriate of Potash (MP)	KCl	49.7 % K

Soil samples have been collected using a hand auger from 5, 10, 15, 25 and 30 cm depths at 5 locations, SL1 through SL5 in Fig. 1, to determine the variations in N and P contents at different growth stages of rice plants. Samples have been also collected during the pre-harvest and post-harvest periods. Additionally, plant samples have been collected from these locations during the pre-harvest period of Boro 2006 season to determine the N and P uptake by the plants.

2.3 Analysis of water, soil and plant samples

Water samples have been analyzed in the Environmental Engineering Laboratory of Bangladesh University of Engineering and Technology following standard methods (APHA, 1998). HACH DR4000U UV-VIS Spectrophotometer has been used for analysis of NO_3-N and PO_4. Hanna pocket pH meter, calibrated with pH standards 4.0 and 7.0, has been used for pH measurements. NO_3 and P contents in soil and plant samples have been analyzed at BRRI following methods given by Huq and Alam (2005).

3. Water quality of receiving water bodies

3.1 Surface water quality

Variations in N and P concentrations at the surface water monitoring locations are shown in Fig. 2. The overall concentrations are relatively low; the maximum N concentration of about 1.3 mg/L NO_3-N (equivalent to 5.8 mg/L NO_3) is within the allowable limit of 10 mg/L NO_3-N (equivalent to about 44 mg/L NO_3) for drinking water (DoE, 1997), and WHO guideline value of 50 mg/L NO_3 (WHO, 2004). P concentrations at all locations, except one, also meet the drinking water standard of 6 mg/L PO_4 (DoE, 1997).

Both N and P concentrations are generally the lowest at the flow entry point SW1, indicating relatively low input of nutrients. N concentrations at SW2 and SW3 are slightly higher than those at SW1. Concentrations at the site exit (SW4), Block B exit (SW5) and Block C exit (SW6) are generally the highest. The range of variation in P concentration at SW2 is much higher than that at other locations. Water entering through SW2 originates mainly in residential areas, causing the high variability in P concentration due to relatively high phosphate content in domestic wastewater. A slightly increasing trend in N and P concentrations is seen as flow rates reduce and stagnant water bodies form at the monitoring locations toward the beginning of the dry season. In addition to N and P, total solids (TS) and suspended solids (SS) concentrations have been also monitored at these locations. TS concentrations are generally the lowest at SW1, and the highest at SW2. SS concentrations are the highest at SW4.

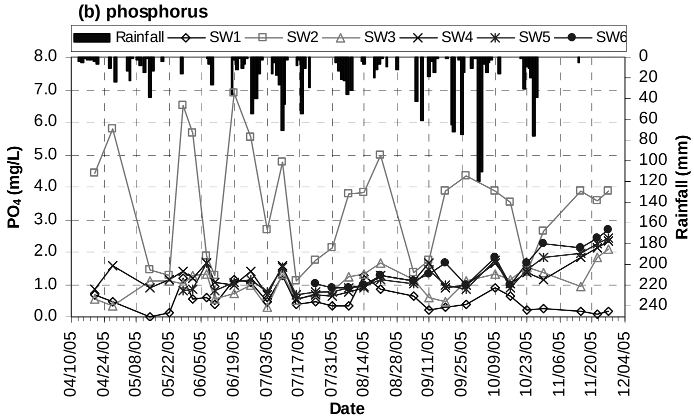

Fig. 2. Variation in nutrient concentration in surface water:
(a) nitrogen, (b) phosphorus

3.2 Groundwater quality

The groundwater level is the lowest in March-April and the highest in November-December. Groundwater flows in the West-to-East direction from GW3 to GW1. Average slope of the groundwater level is approximately 1:965.

Variations in N and P concentrations in groundwater are shown in Fig. 3. The concentrations are the highest at GW3, near the western boundary of the site, but below the allowable limits of N and P for drinking water. Concentrations increase at the beginning of the dry season and remain more or less constant at that level. The reason for this rise in concentration is unknown.

Because of the thick upper clay layer, the risk of nutrient contamination of groundwater at this site is very low. Fig. 4 shows the potential leaching of nutrients toward groundwater estimated from the test results of the 6 lysimeters (L1 through L6). From a maximum concentration of about 1.5 mg/L, NO_3-N and PO_4 concentrations in the leachate decrease relatively fast during the vegetative period, indicating a relatively high plant uptake rate. The concentrations reach a constant level near harvesting time. These final concentrations of N and P are about 0.25 mg/L NO_3-N and 0.6 mg/L PO_4, respectively. However, this only indicates the nutrient contribution in the vertical direction below the root zone. Assessment of actual leaching to the groundwater, situated at a much greater depth, would require a more detailed analysis of flow and soil column characteristics.

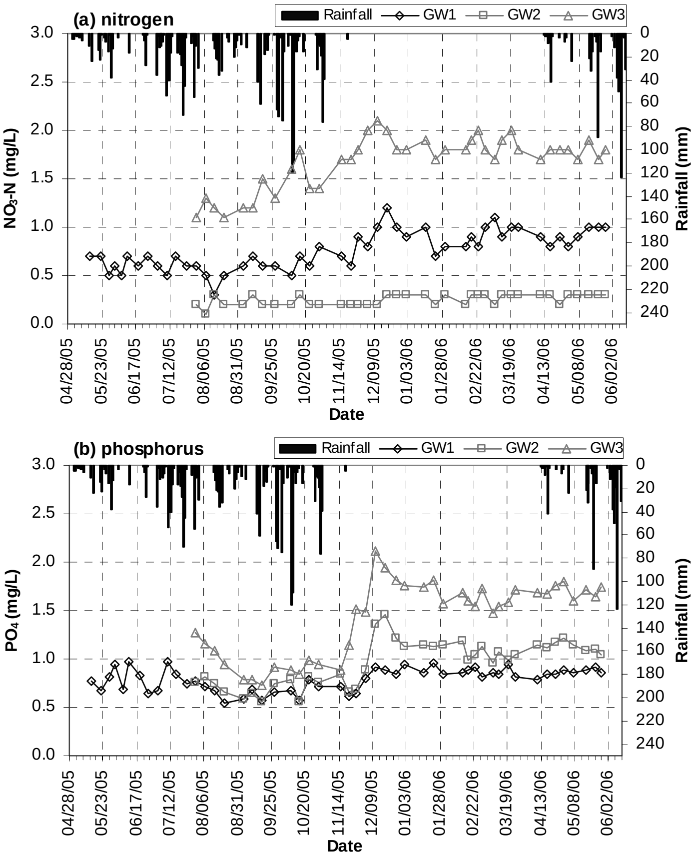

Fig. 3. Variation in nutrient concentration in groundwater:
(a) nitrogen, (b) phosphorus

4. Contaminant contribution of nutrients

4.1 N recovery rate and balance

Soil analyses indicate that both N and P contents increased during the Aman 2005 season (see Fig. 5). The post-harvest N and P contents of Aman 2004 and Boro 2005 are about the same. However, the pre-harvest P content of Boro 2006 is much higher than the 2005 post-harvest content. These variations occurred due to variation in plant uptake rates and fertilizer application timing during the season.

Uptake of nutrients by rice plants from the applied fertilizer only is expressed as 'recovery' of the nutrient. From plant (straw) sample analyses, the field-averaged N content is found to be 1.93 % (by weight as NO_3), which is equivalent to 0.435 % N by weight. For an average application of 80 kg/ha N at the site, the average yield of straw is 5,000 kg/ha (BRRI, 1998), giving an average 21.75 kg/ha N content in straw. Assuming the N content in straw to be about 30% of the total uptake by plants (De Datt, 1991), the average plant uptake at the site is 72.24 kg/ha N. For this site, the overall plant uptake of N in plots, where no fertilizers are applied (control plots) is found to be about 44.4 kg/ha

(BRRI, 1998). Therefore, the 'recovery rate' by rice plants for an application of 80 kg/ha of N is 34.8%. This confirms a previous recovery rate of 32.4% estimated in 1994 for the BRRI farm (BRRI, 1998).

A mass balance of the applied N at the study site is computed based on field observations and secondary information. At a nitrogen recovery rate of 34.8%, 27.84 kg/ha N of the 80 kg/ha N applied are taken up by the rice plants. Therefore 52.16 kg/ha N are left in the field. The average N contribution from Blocks B and C combined is 5.15 kg/ha (Table 3), which is assumed to be valid for the entire site. The remaining 47.01 kg/ha N are available for leaching to groundwater, soil retention, or loss by interflow and tile drains.

4.2 Nutrient loads in surface runoff

Dissolved and particulate nutrients are transported to the surface water bodies by runoff during the rainfall events. The difference in nutrient concentrations at the flow entry and exit points of each Block represents the pollutant load contributed from that Block by surface runoff. The runoff volume is calculated from the Block area, rainfall during the event, estimated loss by evaporation and infiltration, and an estimated runoff ratio. Nutrient loads at the flow entry or exit points are computed from the observed flow rate and event-mean concentration estimated from Fig. 2. The nutrient contribution from the Block is then calculated from a mass balance. Table 3 gives the monthly nutrient loss from Blocks B and C. Nutrient loss is relatively low during the fallow period (April – June) when the rainfall is also low. During the next Aman season (July – December), excess nutrient is available because of fertilization and nutrient loss increases with higher rainfall. Residual nutrients in the field after the Aman season are transported with surface runoff during the fallow period. Since 2005 was an average-rainfall year, with 2,044 mm of total rainfall, total nutrient losses given in Table 3 represent average conditions during the Aman season.

Table 3
Monthly nutrient loss from Blocks B and C during Aman season

Month	Rainfall (mm)	N (kg/ha)		P (kg/ha)	
		Block B	Block C	Block B	Block C
April	84.4	0.199	0.195	0.089	0.059
May	153.4	0.330	0.294	0.176	0.181
June	121.6	0.345	0.330	0.160	0.121
July	444.2	1.183	1.128	0.565	0.617
August	202.4	0.295	0.631	0.235	0.192
September	645.8	1.831	2.691	0.668	0.912
October	201.8	0.331	0.705	0.253	0.253
November	5.2	0.012	0.025	0.011	0.013
	Total	4.526	5.998	2.158	2.347

Figures 6 and 7 show the variation in observed nutrient loss from Blocks B and C, respectively, during the rainfall events of Aman 2005 season. For relatively low rainfall (within 50 mm), the nutrient loss can be reasonably predicted from the event rainfall amount using the characteristic relationships. The prediction will be less reliable for higher rainfall events.

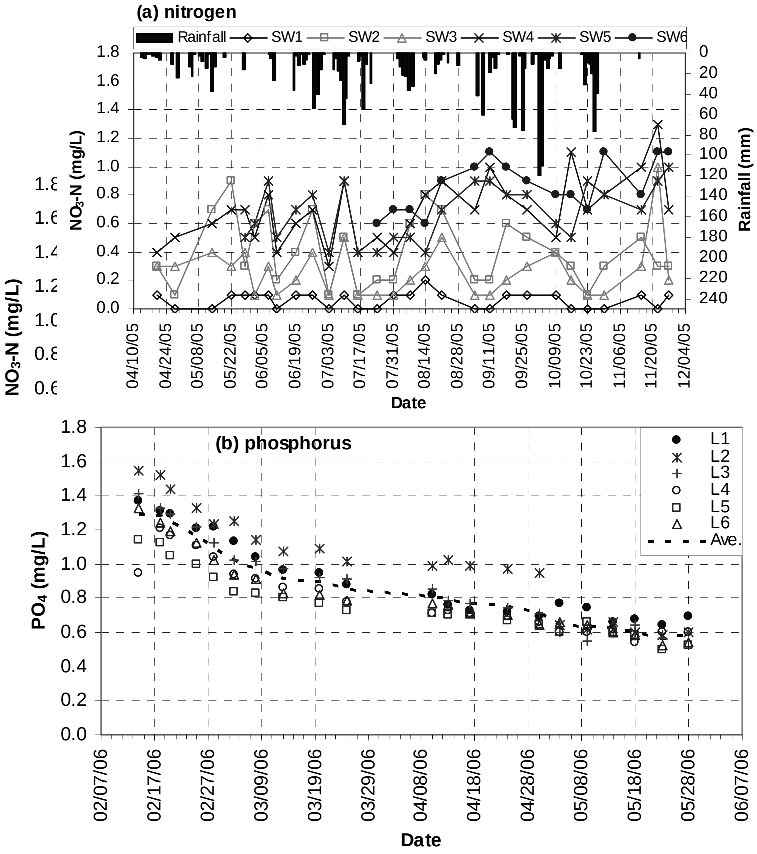

Fig. 4. Variation in nutrient concentration at lysimeter outlet:
(a) nitrogen, (b) phosphorus

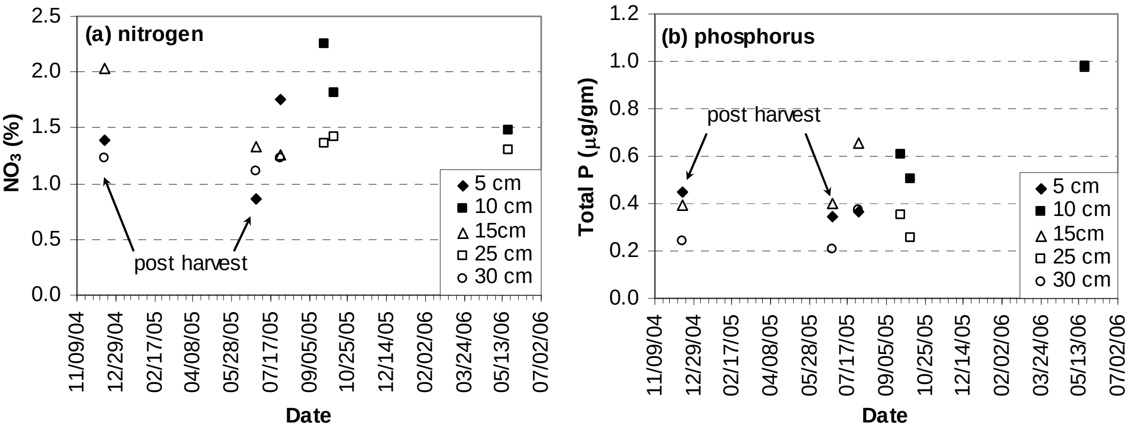

Fig. 5. Nitrogen and phosphorus contents in soil

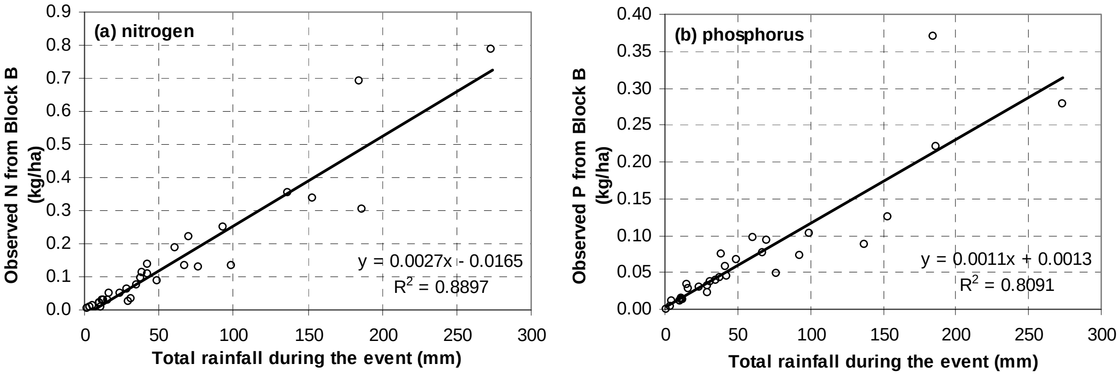

Fig. 6. Observed nutrient load and rainfall in Block B

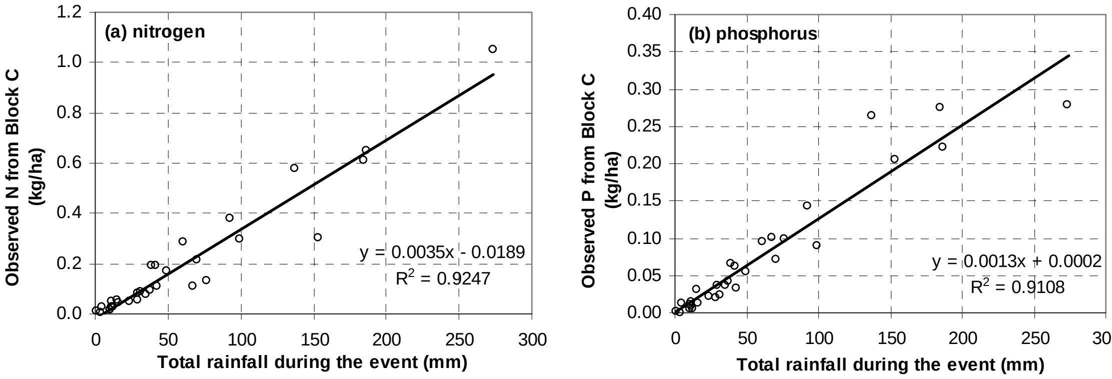

Fig. 7. Observed nutrient load and rainfall in Block C

5. Conclusion

Loss of N and P to water bodies has been monitored during 2 consecutive crop seasons, Aman and Boro, in an intensively rice-cultivated farmland. Surface water flow and quality, and groundwater level and quality have been monitored in 2 drainage compartments or Blocks of the study site. The maximum observed concentration of 1.3 mg/L NO_3-N, equivalent to 5.8 mg/L NO_3, in surface water is within the allowable limit of 10 mg/L NO_3-N for drinking water. PO_4 concentrations are also within the allowable limit of 6 mg/L PO_4 at almost all locations. Because of an approximately 140-ft thick upper clay layer, the risk of groundwater contamination from nutrient leaching is very low at the farm. N and P concentrations in groundwater are found to meet the drinking water standards. Supplementary lysimeter experiments show that after a rapid initial decline, the N and P concentrations in the leachate approach constant levels of 0.25 mg/L NO_3-N and 0.6 mg/L PO_4, respectively. However, these water quality observations in a controlled experimental setting should be carefully extrapolated to other areas, since the actual fertilizer application rate in practice by the farmers may vary significantly.

On an average 80, 60 and 40 kg/ha of N, P and K fertilizers, respectively, are applied at the site during each crop season. From soil and plant sample analyses, the N recovery rate at the site is found to be 34.8%, which confirms a previous estimate of BRRI. An estimated overall nitrogen balance at the site shows that of 80 kg/ha N applied, 27.84

kg/ha are used by the rice plants, while 5.15 kg/ha are lost to the surface water bodies. The remaining 47.01 kg/ha N are either transported with infiltration or interflow, or adsorbed to the soil.

Field observations show that approximately 4.53 kg/ha and 6.00 kg/ha N are transported to the receiving surface water bodies from the 2 Blocks during the Aman season in an average-rainfall year. Corresponding, P loads are 2.16 kg/ha and 2.35 kg/ha, respectively. Characteristic relationships are found to exist between event rainfall amounts and observed nutrient loads. These relationships provide a basis to estimate the nutrient load from observed rainfall data.

Acknowledgement

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