Nitrogen contribution to the river basin from tropical paddy field in the central Thailand

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Abstract

An investigation of nitrogen contribution to river basin from a tropical paddy field was performed using water and nitrogen mass balance analysis. The study was conducted in the acid-sulfate clayey soil in a research field, Pathumthani, Thailand, where fertilizers are being applied according to the local cultivation practice. The nitrogen inflow and outflow from field were measured by direct methods. Inflow of nitrogen consisted of commercial fertilizer, precipitation, irrigation water and soil where as outflow consisted of plant uptake, percolation, surface runoff, retention in soils and loss from the field. Nitrogen leaching was calculated from daily flux of water percolation and soil-water nitrogen concentration extracted by vacuum lysimeter. Results showed that about one third of the water inflow was contributed by precipitation and nearly one third of total outflow by surface drainage. Water balance showed that about two third of water inflow was discharged to the groundwater and surface drainage while one third was utilized by plant as evapotranspiration. It was found that the fertilizer application increased the nitrate nitrogen concentration by five-fold in shallow groundwater. The total nitrogen input including irrigation, precipitation and fertilizer, was 120.07 kg ha^{-1} whereas total nitrogen output including surface drainage, percolation and plant uptake was 103.42 kg ha^{-1}. The difference of total nitrogen in the soil before and after cultivation was not significant and nitrogen loss from the research field was 16.65 kg ha^{-1}. Nitrogen contribution to the river basin systems from the paddy field within the research field was 22.85 kg ha^{-1} which corresponds to about 20% of total nitrogen input. The total nitrogen loss from the paddy field to the water environment and atmosphere accounted 33% of total nitrogen input. These results suggest that the fertilizer nitrogen is one of the major source pollutants in the study area.

Keywords: Mass balance, Nitrogen contribution, Nitrogen leaching, Tropical paddy fields and River basin

Introduction

Agricultural nonpoint pollution source is the leading source of water quality deterioration in rivers and lakes (Galloway et al., 2003; Laegreid et al., 1999). The extent of deterioration is closely related to landuse and rainfall events suggesting agricultural practice is of particular concern. This concern is heightened by the fact that the majority of the population in developing countries receives their drinking water supply from private wells, which are vulnerable to water pollution, especially from nitrogen. Nitrogen has detrimental effects on human health, water related environment and ecosystem (Wolfe et al., 2002). It is believed that elevated level of nitrate is the root cause of methemoglobinemia in infants where as free ammonia imposes stress on aquatic life even at low concentration. Nitrogen is a vital nutrient for eutrophication in natural water bodies, which has been linked to the depletion of dissolved oxygen (DO) that decrease the number of aquatic animal, and then ultimately affects the aquatic ecosystems (Smith et al., 2003). Furthermore, nitrogen loss is economically and environmentally undesirable. Nitrate that leaches below the crop root zone carries valuable nutrient from plant and hence add economic cost to the agriculture. Therefore increased nitrogen in the water bodies can be regarded as chain reaction, each subset of the reaction is detrimental to human life and economy. Unless it is managed very carefully, its positive contribution to agricultural productivity could be negated by its adverse impact in the environment.

Thailand remains as the largest rice exporter in the world (MAC, Thailand, 1991) in terms of both by quantity and by quality. About one third of Thailand's gross area (51million ha) is arable and 52.8% of arable area is used for rice production while 98.3 % of rice field is occupied by paddy field. Rice production requires abundant water, accounting 95% of the total agricultural water demand (Tabuchi and Hasegawa, 1995) and discharges large amount of water. Since most paddy fields are located along the upper sections of natural canals and rivers; the outflow is discharged back into the river systems. Such outflow during the tropical rainstorm is high and significantly increases nitrogen load in the water bodies. Previous studies reported that most of the paddy fields are the source of pollutant while few of them are pollutant sinks, depending on the agricultural practices (Tabuchi and Takamura, 1985; Iwata et al., 1995). Irrigated rice paddy soils produce a specific zone due to the constant flooding of the fields during rice growth (Reddy and Patric, 1984). It also creates high temperature zone with little variation throughout the year in tropical climate. In such soil zones, microbial processes such as mineralization, nitrification and denitrification greatly affect nitrogen dynamics thereby govern the supply of nitrogen to plants and leaching to the groundwater. To reduce the nitrogen output, several approaches such as improving the fertilizer application practice, analyzing soil properties and recycling irrigation facility have been commonly used (Feng et al., 2006). However, nitrogen contribution to the river basin as outflow and leaching from tropical paddy field has been poorly understood Thus, the objectives of this study were to measure the nitrogen loss from a tropical paddy to the river basin and to assess the consequences of agricultural management practices. Among several methods of measuring nitrogen loss such as mass balance (Ahlgren, 1967), ^{15}N isotope pairing technique (Nielsen, 1992) and mathematical model and empirical equation (Jeon et al., 2005; Shiratani et al., 2004, Yoshinaga et al., 2004), mass-balance approach by Ahlgren, (1967) is used in the present study because of its simplicity,and practical usefulness among others

Materials and methods

Site description

This study was conducted in 2001 in a 1600 m^2 research field station within the premise of Asian Institute of Technology, Pathumthani,Thailand. The elevation of the site is 2 to 2.5 m above the mean sea level. The region has a humid climate and the mean annual rainfall of 1300 to1400 mm, 80% of which occurs during rainy season. The average monthly temperature varies from 19 to 35°C and relative humidity fluctuates from 70 to 80%. Groundwater table is usually high and varied from 0.40 to 1.5 m during the crop period with an average GW depth of 0.6 m.

Experimental set up

To evaluate the amount of nitrogen input and output in the field, both the stagnant and flow components of water and nitrogen was measured. Triangular weirs with pressure sensor were installed at the inlet and outlet of the research field to measure the water level and flow rate. Two rain gauges were installed diagonally to the field to catch the precipitation. Lysimeter was installed inside the plot to measure the evapotranspiration from the field and plants. To monitor groundwater level and water quality, eight PVC tube wells at a distance of 4 m and four PVC tube wells at a distance of 80 m away from the field. The depth of water level in the plot was recorded daily by vernier scale installed at two corner of plot and volume of water stored was calculated.

Rice seeds were directly sown on the ground and major components of nitrogen flow had been measured until rice was harvested (Table 1). The local practice in field management and cropping systems were imitated to compare the results to the surrounding area of cultivation.

Three different doses of inorganic fertilizer (Table 1) were supplied during entire cultivation period. As urea is quickly hydrolyzed to NH_4^+-N and subsequently nitrified to NO_3^--N, the amount of nitrogen input through fertilizer during the cultivation period was calculated, which corresponds to about 100 kg N ha^{-1}. Weeds were controlled manually and pesticide was applied occasionally.

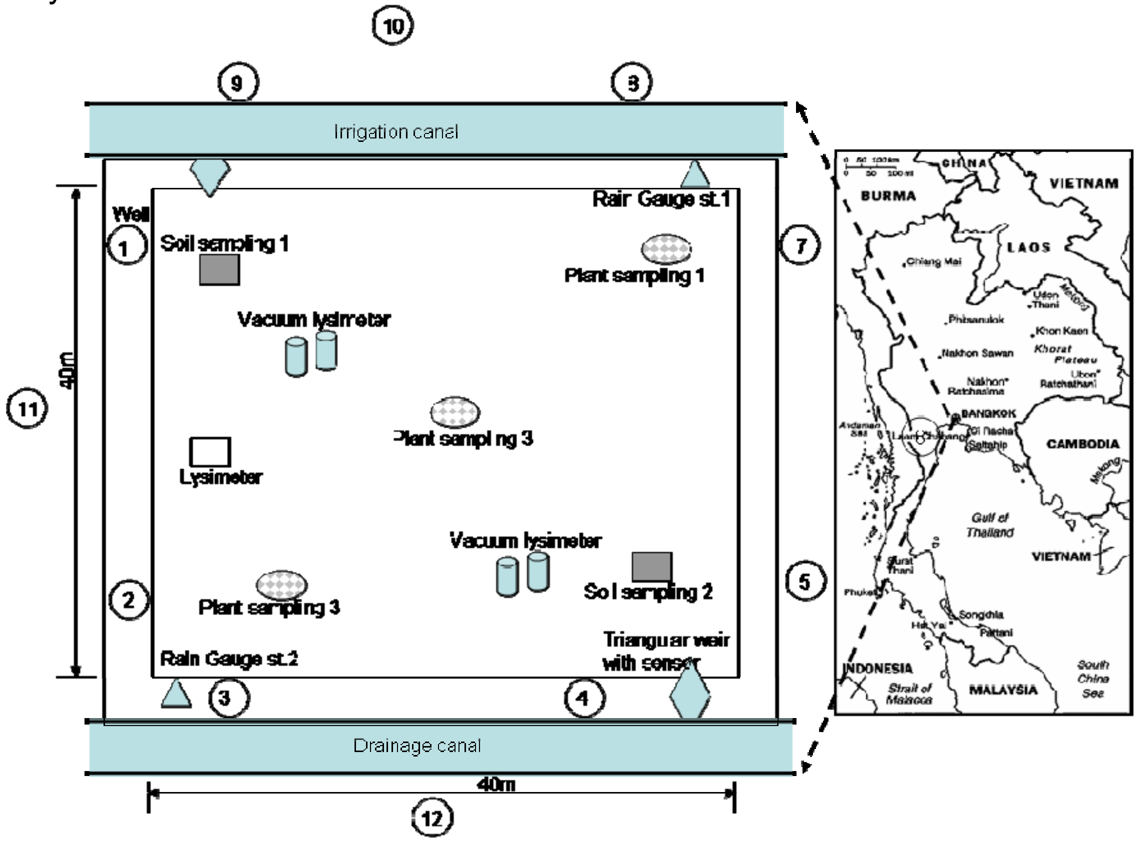

Figure 1 Outline of experiment in the paddy field in the Thailand

Table 1 Major agricultural activity and fertilizer dose during the study period

Date (crop days)	Agricultural activities	Remarks
September 7	Plowing	
September 13	Basal fertilization (Metrophos:30 Kg-N ha^{-1})	
September 14 (1)	Direct rice seeding	Seed name: *Suphan 1*
September 24 (11)	Installation of soil water sampler	
October 13 (30)	Tillering fertilization (Urea: 43 Kg-N ha^{-1})	
November 20 (68)	Panicle fertilization (Urea:27 Kg-N ha^{-1})	
December 24 (102)	Harvest	

* Number in the bracket represents the crop days

Vacuum lysimeters having diameter of 4.8 cm (Model 1900, Soil Moisture Equipment, USA) were washed with dilute acid before using (Litaor, 1988) to avoid possible contamination. Vertical holes of 7.6 cm in diameter were dug at two points on the research field with a hand auger at depth 20 and 60 cm, which corresponded to the limit of root zone and average ground water table respectively. Four vacuum lysimeter were installed just after the emergence of rice plant. To ensure good contact between soil and ceramic soil slurry was added at the bottom side as mentioned by Grossmann and Udluft, (1991). Vacuum pressure of 30 KPa was applied to each sampler before 24 hour of the sampling and disturbance in sampling was avoided.

Samples collection and analysis

Water samples

Irrigation, drainage, precipitation, flood and groundwater samples were collected in clean polyethylene bottles during each event of irrigation and precipitation. Similarly, soil-water samples were collected by suction pump twice a week from each sampler during entire cultivation period. NH_4^+-N, NO_3^--N, and total Kjeldahl nitrogen (TKN) concentration was examined colorimetrically as mentioned in standard method (APHA, 1998).

Soil samples

Soil samples were taken from four distinct soil layers by different double-cylinder cores for bulk density and hydraulic conductivity measurement. Soil sampling was carried out both in pre-cultivation and post harvesting time from four different soil layers using double-cylinder core (see Results and discussions section) to examine the changes in physical and chemical properties of soil. Particle density of the extracted soil was measured by pycnometer method and saturated hydraulic conductivity was measured using falling head method. Separate samples were taken for soil chemical analysis. Soil-water pH, particle size and organic matter were determined by glass electrode method, hydrometer method and dry ash method, respectively. KCl (2.0M) extraction method was used to measure the NO_3^--N in soil. The sphere of one meter soil depth from the soil surface was assumed to consider the amount of nitrogen stored in the soil and was calculated by multiplying the weight of dried soil by the average nitrogen content at each layer of soil. The difference in amount of nitrogen in soil samples before cultivation and after harvesting was considered as the amount of nitrogen in the soil stored in the soil.

Plant tissue samples

Plant tissues (leafs, grain, stem and roots) from three sampling point at the time of harvesting were collected separately and the dry weight of each component was measured. Organic nitrogen faction in each component was measured using standard method. Nitrogen contained in harvested tissues was calculated by multiplying faction of organic nitrogen with dry weight of matter for each component and summed up. Difference of total nitrogen in harvested tissues and initial seed was considered as plant uptake.

Water mass balance

Water mass balance approach was used to determine the deep percolation of water as follows:

$$DPR = I + P - ET - R \qquad (1)$$

Where DRP is the daily water percolation in mm, I is irrigation water applied during the day in mm, P is precipitation in mm, ET is the evapotranspiration in mm and R is runoff from the field in mm. Since polyethylene sheets were set on the levees, the lateral seepage was assumed to be zero. Similarly, leaching at the research field was considered above the groundwater surface; therefore the groundwater outflow was not taken into account. Evapotranspiration was calculated by Penman-Monteith with crop coefficient method and compared with lysimeter result. Secondary percolation was calculated using Darcy method and compared with percolation calculated from water balance.

Nitrogen mass balance

Total amount of nitrogen in input and outs terms were calculated by multiplying the nitrate concentration in each term mentioned in Equation 1 with the volume of water. The nitrogen mass balance in the experimental field can be expressed as

$$N_{loss} = N_{in} - N_{out} - N_{diff\ soil} \qquad (2)$$

Where, $N_{in} = [N_f + N_i + N_p]$, $N_{out} = [N_d + N_l + N_u + N_{loss}]$ and $N_{diff\ soil} = [N_{sf} - N_{si}]$. Suffixes f, i, p, d, u, l, and loss represent fertilizer, irrigation water, precipitation, drained water, leaching to groundwater, uptake by plants and the loss from the research field due to denitrification and anaerobic oxidation of ammonia (anammox), respectively. N_{si} is the amount of nitrogen stored in pre-cultivation soil and N_{sf} is the amount of nitrogen stored in post-cultivation soil. The other minor component of nitrogen speciation such as biological nitrogen fixation, groundwater contribution, ammonium volatilization and weed production were ignored.

Results and discussions

Soil Properties

The vertical soil profile of consisted of four different soil horizons, separated by their distinct color (Table 2). The pore size distribution of the soil profiles was estimated as meso-pores (30 to 100 μm diameter). The soil temperature varied from 21-29°C. Average saturated hydraulic conductivity of the soil before cultivation ranged from 2.951E-06 to 4.478E-04 cm s^{-1} while after cultivation from 9.259E-07 to 3.741E-04 cm s^{-1}. The soil classification based on saturated hydraulic conductivity suggested that the soil was clay (i.e. conductivity less than 2.31E-06 cm s^{-1} Smedema and Rycroft, 1983). Average bulk density varied from 1.18 to 1.35 g cm^{-3} while average particle density was 2.65 to 2.71 g cm^{-3}. The high soil porosity (0.47-0.62) contributed strongly to lower the bulk density of soil. Furthermore, the bulk density also decreased due to cultivation by average of 18 %. Since the pH in all soil layers was <5.0 and contained high percentage of clay, the soil was categorized as acid sulfate (Asadi, 2001). Because of the acid sulfate clayey soil (with pH range from 3.58 to 4.70 in the first layer), NH_3–N losses from these soils were less probable (Mountonnet and Fardeau, 1982). Average organic matters content of soil ranged from 3.45 to 4.84 % and found highest in first the layer.

Table 2 Physical and chemical properties of soil in the experimental field

Depth (cm)	Color	Particle size distribution (%)			Average organic matter content (%)		pH	
		Clay	Silt	Sand	B	A	B	A
0-20	Black	77	11	12	4.4	5.2	4.70	3.58
20-40	Red-brown	71	14	15	4.4	4.2	3.85	3.42
40-60	Yellow-green	80	14	6	4.6	3.6	3.59	3.19
60-120	Brown-gray	79	16	5	3.6	3.3	3.30	3.08

A-after cultivation, B-before cultivation,

Water balance

Total depth of precipitation measured in 37 rainfall events during the study period was 541.1 mm. The total volume of irrigation measured at the inlet of the field was 1480.6 m^3 (925.4 mm) and depth of water in cultivated area varied from 8 to10 cm. Because of heavy rainfall, 15 events of overflow were observed in the experimental period with total volume of overflow of 550.7 m^3 (344.2 mm). It showed that about one third of the water inflow was contributed by precipitation and nearly one third of total outflow by surface drainage. The total amount of evapotranspiration measured by the lysimeter during the cultivation period was 416.75 mm and the average daily evapotranspiration was 4.1 mm. The percolation rates calculated using Equation (1) during the cultivation period ranged from 0 to 13 mm d^{-1} and the average daily percolation was 5.21±3.1 mm. At the end of cultivation the percolation rate was found slightly less than that in other periods. Evapotranspiration calculated by Penman-Monteith method (393 mm) with crop coefficient and lysimeter value (417mm) was nearly same while percolation discharge calculated by Darcy method (406 mm) was slightly lower than mass balance value (476 mm).

Nitrogen in the water and soil-water solution

Total nitrogen in the precipitation varied from 0.8-6.6 mg L^{-1} depending on the amount of rainfall and number of dry days before the rain event. Total nitrogen in irrigation water varied from 0.75 to 2.1 mg L^{-1} while the nitrogen concentration in overflow varied from 1.7 to 24.4 mg L^{-1}. Deviation in mean values of nitrogen concentration (Table 3) in the overflow percolation and groundwater was affected by the application of nitrogen fertilizer. In the beginning of crop period, the rate of nitrate leaching was very low and maximum leaching was found after one week of the second and third dose of fertilizer. The effect of first dose of fertilizer was not observed in detail because soil water samplers were installed only after two weeks of seeding. NO_3^--N concentration in soil water solution after the application of second dose fertilizer showed a significant increase in NO^-_3-N and TN in both 20 and 60 cm depth of soil layers.

Since nitrates are highly soluble salts, the movement of water dissolves some nitrates that are present on the surface of soil. Nitrate ions and clay particles both are negatively charged. Thus nitrate behaves as a conservative solute and moves with water without any sorption to the clay surface, where the sorption phenomenon has largely been found to be electrostatic (Hetzel and Doner, 1993; Jaisi et al., 2006). To the other hand, positively charged ammonium ions sorbes/adheres to the clay particles, therefore protected from leaching. Such phenomenon was clearly observed in this study (Table 3). In addition, nitrate and total nitrogen concentration near the groundwater table (GWT) and in the groundwater was almost equal (Figure 2). However, both nitrate nitrogen and organic matter significantly declined in two lower soil layers suggesting that the nitrogen removal through denitrification. This observation was consistent with Nakasone et al. (2003). Although the nitrogen removal was correlated with the temperature in the paddy field (Tabuchi et al., 2001), such variation was not expected to be high in tropical area such as in central Thailand, where mean soil temperature does not vary among seasons.

Table 3 Total water volume and nitrogen concentration in the experimental plot (n = 9 -11)

Items	Water volume, m^3	Mean nitrogen concentration ($mg\ L^{-1}$)±SD			
		NO_3^+-N	NH_4^+-N	TKN	TN
Irrigation water	1480.6	0.10±0.07	0.21±0.18	1.14±0.42	1.24±0.40
Precipitation	833.4	0.40±0.26	1.37±1.19	2.68±1.74	2.79±1.91
Overflow	550.4	0.54±0.19	1.90±1.84	6.15±7.07	6.70±7.20
Percolation (60cm)	758.6	0.56±0.36	2.37±0.98	2.91±0.69	3.74±0.84
Groundwater		0.77±0.44	0.88±0.81	2.13±0.95	2.97±1.10
Soil (20cm)		*3.04	7.12	10.86	13.90
Soil (60 cm)		*6.05	10.12	10.54	16.60
Evapotranspiration	724.0				

* Unit of post harvesting soil nitrogen is $\mu g\ g^{-1}$, n is the number of samples.

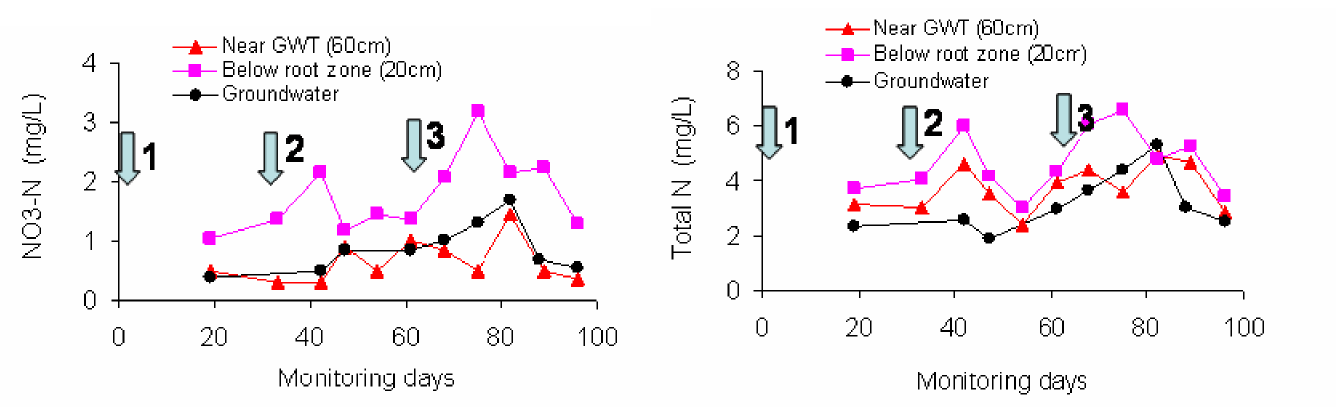

Figure 2 Nitrate and total nitrogen concentration variation in the soil water solution. Arrow with number indicates the dose of fertilizer in basal, tillering and panicle crop stage respectively.

The greatest nitrate nitrogen concentration was measured after the application of third dose of fertilizer and effect was observed after one week just below the root zone and after three weeks at the GWT interface. The delay between two layers was most possibly caused by the low hydraulic conductivity in upper layer. Other factors such as planting method, shallow irrigation, formation of macro pores due to alternate soil wetting and drying, and soil disturbance during weeding operation probably built up the NO^-_3-N concentrations in the soil because these activities encourage better soil aeration for nitrification. It was found that the NO_3-N concentration in shallow groundwater was elevated to five fold after fertilizer application than existing NO_3-N concentration. Although soil thickness, soil type and distance between the root zone and groundwater also determine the vulnerability of an aquifer to pollution, this increment may vary from one place to other even in short distance. However, such increment indeed is detrimental for human health and water environment.

Nitrogen in plant tissue

Average organic nitrogen in harvested grains, stems, leaves and roots were 0.83, 0.26, 0.38 and 0.32% of dried matter, respectively. Nitrogen stored in initial seeds and harvested plant was 3.83±0.2, 84.4±4.7 kg ha^{-1} respectively. Therefore, calculated plant uptake was 80.57 kg ha^{-1}.

Nitrogen in the soil

The measured total nitrogen concentration in pre- and post-cultivation soil was 9,672.3 kg ha^{-1} and 9,673.5 kg ha^{-1}, respectively. It suggests that the there was practically no nitrogen accumulation in the soil. However, the calculation of nitrogen amount in soil may contain considerable error due to the spatial variability of soil properties.

Nitrogen mass balance

The total amount of nitrogen load in irrigation, precipitation, fertilizer, overflow, percolation and plant uptake were 9.22, 10.85, 100, 4.65, 18.20, and 80.57 kg ha^{-1}, respectively. Since, the amount of total nitrogen in the soil before and after cultivation was not significant, it was taken as constant value. Sum of nitrogen loss calculated from the nitrogen mass balance model (Equation 1) was 16.7 kg ha^{-1} (Figure 3) which corresponds to the 13% of total nitrogen input. Similarly, the total nitrogen contribution to the river basin systems (surface and groundwater) from the paddy field was 22.85 kg ha^{-1} which accounted 20% of total nitrogen input. Comparing with total nitrogen input about one third of nitrogen was lost from the experimental field. Nitrogen load runoff measured in this study (4.65 kg ha^{-1}) was between results observed by Kim et al. (2006) for Korean paddy field (1.9-3.7 kg ha^{-1}) and Tekeda and Fukushima et al. (2006) for Japanese paddy field (13.1 kg ha^{-1}). As compared to the study of Jeon et al. (2005) [2.12-5.29 kg ha^{-1}], nitrogen load percolated to the groundwater in this study was significantly high. This difference was probably due to fertilizer application rate and local water management practice as reported by Randal et al. (1990). Although errors are anticipated, the margin of error is expacted to be low because of direct measurement of nitrogen components.. These results, however, have been assumed highly beneficial for finding better management of extraneous use of nitrogen and therefore creating another chain of problem in water and environment.

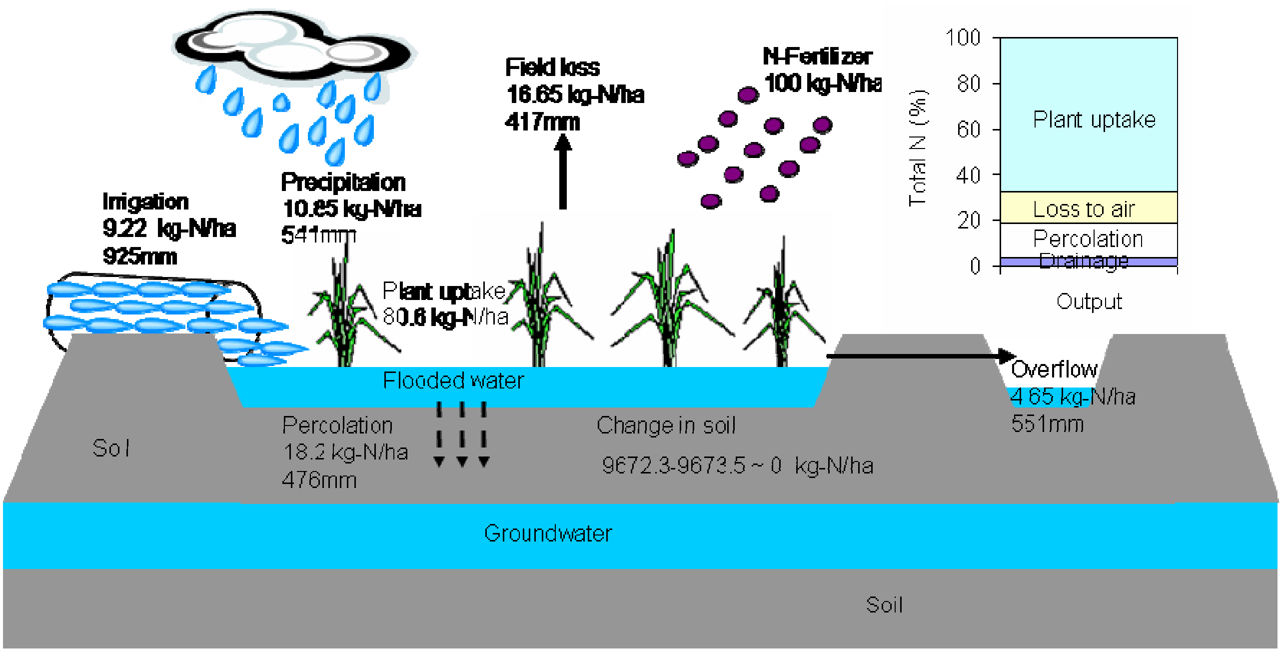

Figure 3 Water and nitrogen mass balance in the research field

Conclusions

Mass balance analysis showed that 66% of water discharged to the water bodies whereas 22.85 kg ha^{-1} of nitrogen which corresponds to the 20% of input nitrogen was added the river basin systems through surface drainage and percolation. It was measured that fertilizer application increased the NO_3-N concentration in the shallow groundwater from 0.4 mg L^{-1} to 1.62 mg L^{-1} which corresponds to 460% increment. Although, the NO_3-N concentration in groundwater is below the world health organization (WHO) threshold value (10 mg L^{-1}) for the drinking water, such increment in nitrate level pose a serious threat to the future water quality and aquatic ecosystems as these increment continue in future. Since the nitrogen concentration is strongly influenced by fertilization and surface drainage runoff during heavy rainfall, reducing surface drainage, percolation and decrease in flooded water depth are suggested to reduce the nitrogen loss. However, lowering fertilization rate may negate the rice yield. Therefore, the crossover point of better rice yield and acceptable level of nitrogen contamination is seems urgent to develop on site by site by basis for better future.

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