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GROUNDWATER DYNAMICS AND QUALITY UNDER INTENSIVE CROPPING SYSTEMS

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SUMMARY

A study was conducted from October 1994 to March 1996 to assess groundwater dynamics and quality in relation to landuse and farm input of nitrogen fertilizer in a highly diversified and intensive agricultural area at Magnuang, Batac, Ilocos Norte. Monthly groundwater depths, nitrate-nitrogen (NO_3-N), chloride (Cl^-), bicarbonate (HCO_3^-), electrical conductivity (EC) and pH were determined in 19 agricultural and domestic wells. In the dry season, sweet pepper (*Capsicum annuum*) had a higher irrigation requirement and caused more groundwater level decline than other crops. EC (700–3000 μmho cm^{-1}) and HCO_3^- (90–500 ppm) in all wells exceeded the FAO threshold quality for irrigation but were not related to farm management practices. Eight wells showed near or above the World Health Organization NO_3-N limit (10 ppm) for drinking water. High nitrogen fertilizer input increased the mean NO_3-N ($r^2 = 0.45$, $p < 0.002$). The percentage of the wells' service area under rice cultivation in the wet season accounted for 84% ($p < 0.001$) of the variation in NO_3-N among the wells. The mean NO_3-N declined as the percentage of service area under rice increased. This was related to the denitrification process in the flooded fields and the lower levels of nitrogen fertilizer for rice compared with other crops.

INTRODUCTION

Rainfall is the primary water source in rainfed lowland rice ecosystems. However, in Batac, in the Philippines, rainfall is barely sufficient to sustain rice production during the wet season and is unavailable during the dry season. In areas like this, groundwater (available from shallow tubewells) is an important source of supplemental irrigation for wet season rice during periods of no rain and for sustaining upland crop production during the dry season.

Problems of groundwater depletion have been experienced after short periods of withdrawal in the Indian state of Tamil Nadu, in Northern Africa and in the high plains of Texas. Significant deterioration in groundwater quality has been observed in many developed nations due to leaching of fertilizer salts from agricultural land, from domestic contaminants, and as a result of marine incursions (McDonald and Kay, 1988).

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Leaching of fertilizer salts from agricultural land contributes significantly to groundwater pollution, especially nitrate pollution (Bajwa *et al.*, 1993). Wherever there is a source of nitrogen and an excess of water applied to the soil, nitrates have the potential to reach groundwater (Jury and Nielsen, 1989). It has been reported that drinking water containing more than 10 ppm nitrate-nitrogen causes methemoglobinemia or 'blue baby' syndrome in infants and stomach cancer in adults (McDonald and Kay, 1988).

The potential for pollution of agricultural areas varies depending on landuse and fertilization history, position relative to the stream or water table, underlying geology, hydrologic, chemical and physical soil properties, and the climatic conditions in the area (Rogowski, 1990). The type of crop is also important in determining the amount of nitrate leached (Nielsen and Jensen, 1990). Under shallow-rooted and heavily fertilized vegetable crops, nitrate losses as a result of leaching can be very large (Bajwa *et al.*, 1993). Much less literature is available about the effects of high rates of nitrogen fertilizer on the quality of groundwater in land used for growing rice. Castaneda and Bhuiyan (1991) observed a lower concentration of nitrate-nitrogen in the groundwater underneath rice fields during the wet season than during the dry season in rainfed areas, and they attributed this to dilution during the wet season when there is an abundant supply of rainfall.

In Magnuang, Batac, Philippines, most farmers grow rice during the wet season and almost all farmers grow upland crops during the dry season. Applications of nitrogen (N) fertilizer are as much as 120 kg N ha^{-1} for rice and 340 kg N ha^{-1} for upland crops (Tripathi *et al.*, 1997). Irrigation for dry season crops comes from shallow tubewells alone. Under such conditions, nitrate can be leached and can contaminate the shallow aquifer which is also a source of drinking water. Extensive pumping of water from tubewells may also deplete the groundwater reserves resulting in them being recharged with poor quality water. There has not been a systematic assessment of the water quality in the area and there is still a lack of understanding of the dynamics of nitrate contamination in small farm holdings under diverse cropping systems, as in Magnuang. This knowledge is important for future land-use planning and for management options to mitigate pollution and health hazards. We hypothesized that the degree of nitrate pollution may vary over short distances and that at each location, it depends on the prevailing land-use pattern and the management of the well service areas. Areas with a greater proportion of land under rice during the wet season may contribute less nitrate leaching because of the denitrification process in lowland rice culture (Buresh and De Datta, 1990) and because N input for rice is less than for upland crops. This study was conducted, first, to quantify seasonal and spatial changes in groundwater level and groundwater quality and, second, to relate these changes to landuse and farm input.

MATERIALS AND METHOD

Study site

A watershed with an approximate area of 265 ha located at Magnuang, Batac, Ilocos Norte (lat 18°3′N, long 120°33′E) was selected as the study site (Fig. 1). Its land and land-use pattern are typical for most of the rainfed areas in the whole province. The area under cultivation is flat to almost flat (slope 0–2%) and the climate is classified as Type I (Coronas, 1920) characterized by two distinct seasons, a wet season (WS) from May to October and a dry season (DS) for the rest of the year. The annual rainfall in 1995 was 1432 mm and the average over the past 10 years was 2000 mm. The predominant cropping pattern was wet season rice followed by upland crops such as sweet pepper (*Capsicum annuum* L.) or

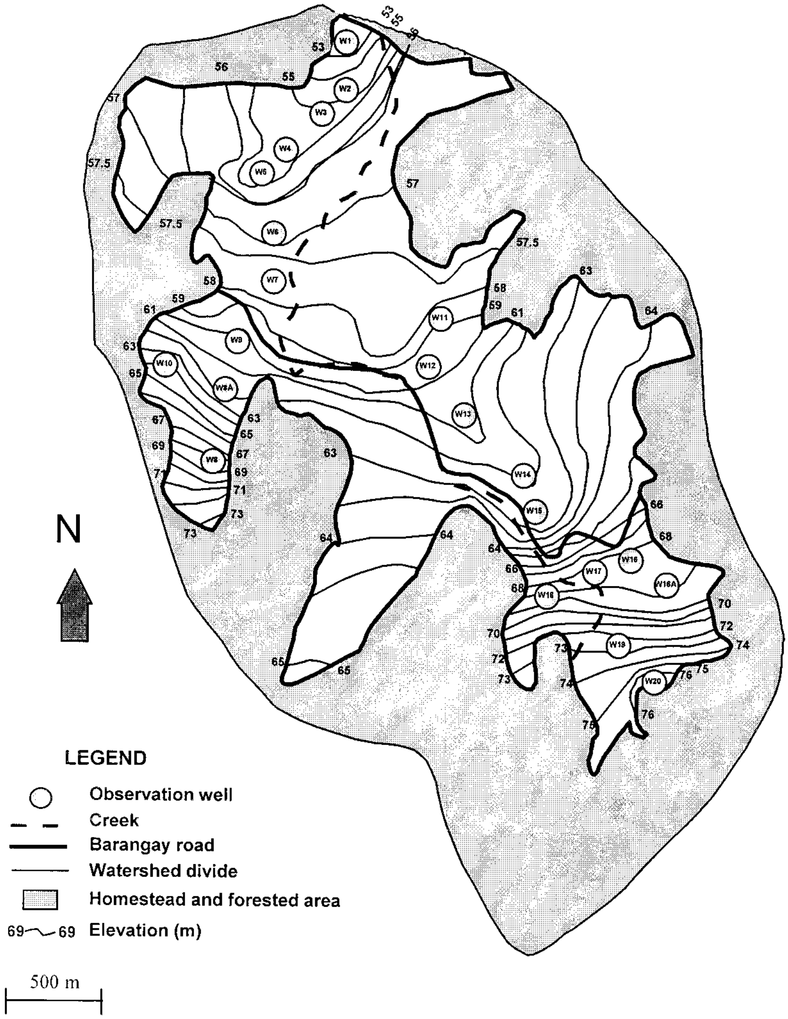

Fig. 1. Map of the study area showing the elevation and location of observation wells.

mungbean (*Vigna radiata* L. Wilczek) in the dry season, but a considerable number of farmers were growing two seasons of upland crops.

Network of observation wells

Nineteen existing agricultural and domestic tubewells (7 cm in diameter, 5–6 m in depth) were selected as observation wells. They were distributed uniformly in different land-use/cropping patterns. Each well was equipped with a PVC casing 3 m in length and 7 cm in diameter extending to a depth of 2.7 m. At the soil surface the casing was anchored by a cement base measuring 0.5 m × 0.5 m × 0.2 m, which protected the wells from contamination with surface runoff. The coordinates and elevation of each observation well were determined through stadia surveying, using a theodolite.

Land-use and management practices

Parcels of land and the area being irrigated by each well were identified. For each parcel, data on cropping patterns and management practices including the crops planted, dates of planting and harvest, rates and dates of fertilizer application and irrigation practices from October 1994 to March 1996 were collected. From these data, the percentages of the area serviced by the well which were under different cropping patterns could be calculated. Monthly applications of nitrogen fertilizer for the areas irrigated by each well were computed as:

$$N_{ij} = \frac{\sum f_{kij}}{\sum a_{kij}}$$

where N = kg N ha^{-1}, f = kg N per parcel, a = area (ha), i = well number, j = month and k = parcel number.

The depth of irrigation water from a well was estimated for a given month by multiplying the pumping rate by the total irrigation time for that particular month and crop, divided by the area planted with each crop. Irrigation rates were measured directly in the field using a pre-calibrated V-notch weir.

Groundwater levels and quality

From October 1994 to March 1996, groundwater levels and quality were monitored. Groundwater depths in all observation wells were measured weekly using a groundwater level indicator. Samples of groundwater measuring about 1 L were collected monthly from each observation well using a portable water sampler after the well had been purged. This involved pumping the 'dead water' from the well prior to sampling for 10 minutes. Electrical conductivity (EC) and the pH of the water were measured directly in the field using portable meters. Samples were sealed, placed in an iced box, and transported to the Mariano Marcos State University laboratory and refrigerated until further chemical analyses could be carried out. Chloride (Cl^-) and bicarbonate (HCO_3^-) were determined by the titration method (PCARRD, 1980), and nitrate-nitrogen (NO_3-N) using the cadmium reduction method (Keeney and Nelson, 1982).

Statistical analyses

A complete linkage, tree-joining cluster analysis using Statistica (Statsoft, 1994) was performed on the data for groundwater NO_3-N, Cl^-, EC, HCO_3^-, pH and depth collected from different wells on a monthly basis from October 1994 to March 1996. The purpose was to classify the wells into groups and to determine whether grouping according to one parameter was associated with another parameter or management factor (for example, % of total area under rice and N input). Correlation analyses between the different chemical parameters, groundwater depths and management factors were carried out.

RESULTS AND DISCUSSION

Cropping pattern and management practices

The main cropping pattern was lowland rice–upland crop (RU), although an upland crop–upland crop sequence (UU) was also practiced on 12.8% of the total area (Table 1). In the RU pattern, rice was transplanted towards the end of July and harvested in late October. Upland crops, primarily pepper but also garlic (*Allium sativum*), mungbean and other cash crops, were planted from late November to January and some lasted until April or May. Fertilizer-N input for pepper was high compared with the other crops (Table 2). Farmers used tubewell water to irrigate the rice crop when there was insufficient rainfall, especially during land preparation and transplanting. Tubewells were also used extensively for upland crops. Pepper was irrigated weekly with a total irrigation per crop season amounting to 51 cm water depth.

In areas where the UU crop sequence was practised, upland crops (mostly pepper and garlic) were planted as early as September and harvested from December to February. After this crop, most farmers grew another upland crop which lasted until May, while some planted a relay crop (either maize or mungbean) from December or January to March. A fallow period of four to six months (March or May to August) was common in this area. The fertilizer management for upland crops in this cropping pattern was the same as for the RU cropping pattern.

Groundwater levels

Cluster analysis showed two large groups of wells differentiated according to groundwater depths (Fig. 2). Groundwater levels in Group 1 wells were significantly deeper than those of Group 2 wells during the dry season (Fig. 3). The difference in the dry season groundwater level between the two groups can be related to the difference in their land-use patterns. The pepper and garlic (P + G) area irrigated by Group 1 wells from January until May was significantly greater ($p < 0.02$) than the P + G area irrigated by Group 2 wells. Pepper and garlic had

Table 1. Area (ha) under different land-use systems irrigated by 18 wells in 1995 in Magnuang, Batac, Ilocos Norte.

		January–May 1995			June–September 1995		October–December 1995		
Well number	Service area	Pepper + garlic	Other crops	Fallow	Rice†	Fallow‡	Pepper + garlic	Other crops	Fallow
W1	3.2	1.8	1.4	0.0	3.2	0.0	1.9	1.3	0.0
W2	2.3	1.1	0.4	0.7	2.2	0.1	0.0	1.1	1.2
W3	1.2	1.1	0.1	0.0	1.2	0.0	0.0	1.2	0.0
W4	1.1	0.4	0.4	0.3	1.1	0.0	0.1	0.6	0.4
W5	0.6	0.2	0.4	0.0	0.6	0.0	0.0	0.6	0.0
W6	0.6	0.3	0.3	0.0	0.6	0.0	0.0	0.6	0.0
W7	0.9	0.1	0.8	0.0	0.9	0.0	0.0	0.8	0.1
W8	3.0	0.3	2.8	0.0	3.0	0.0	0.3	2.8	0.0
W8A	0.4	0.0	0.4	0.0	0.4	0.0	0.0	0.4	0.0
W9	2.2	0.1	1.8	0.3	2.2	0.0	0.0	2.2	0.0
W10	1.7	0.0	1.6	0.1	1.7	0.0	0.1	1.2	0.4
W12	0.8	0.3	0.0	0.5	0.6	0.2	0.0	0.3	0.5
W13	1.2	0.4	0.8	0.0	0.9	0.3	0.3	0.9	0.0
W15	1.1	0.7	0.2	0.2	0.2	0.9	1.0	0.1	0.0
W16	1.4	0.3	1.2	0.0	1.0	0.5	0.3	0.9	0.2
W16A	0.2	0.1	0.0	0.1	0.1	0.1	0.1	0.0	0.0
W19	1.0	0.0	1.0	0.0	0.4	0.6	0.7	0.4	0.0
W20	0.9	0.0	0.7	0.1	0.4	0.4	0.4	0.1	0.4
Total area	23.7	6.9	14.4	2.4	20.7	3.1	5.3	16.3	3.2
Percentage of total area	100.0	29.1	60.9	10.0	87.2	12.8	22.2	64.5	13.3

†Area planted with rice during this period followed rice–upland crop sequence; ‡area fallowed during this period followed upland crop–upland crop sequence.

Table 2. Fertilizer nitrogen (N) application rates (kg ha^{-1}) and irrigation practices on rice and some upland crops grown at Magnuang, Batac.

	N-fertilizer application per season			
Crop	Rate	Number of applications	Number of irrigations per season	Total irrigation per season (cm water)
Rice	63 (46)†	1–2	0–1	6
Pepper	356 (43)	2–4	16–20	51
Garlic	91 (33)	1–2	4–5	20
Tomato	75 (63)	1–3	3	9
Tobacco	50 (15)	1	2–3	4
Maize	38 (7)	1	2–3	5
Mungbean	2 (2)	1	1–2	3

†Standard deviation in parentheses.

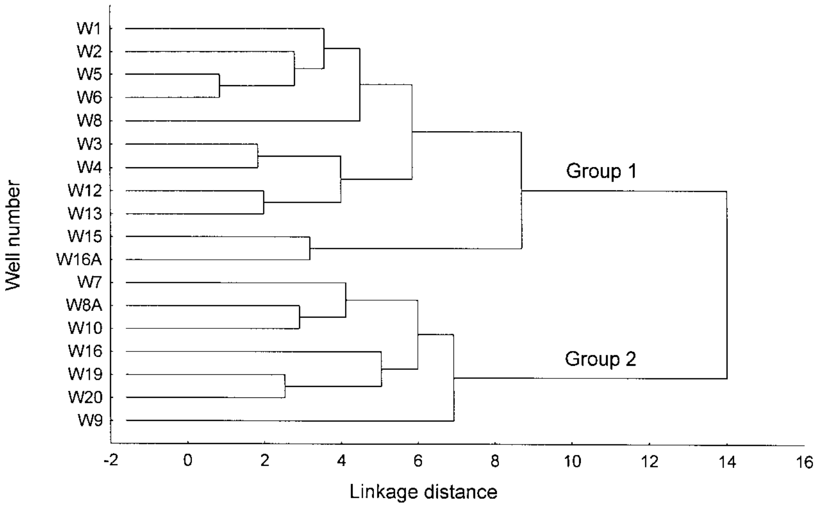

Fig. 2. Dendrogram showing well groups according to monthly groundwater depths (GWD) from October 1994 to March 1996. GWD of Group 1 wells was 6–7 m and of Group 2 wells 4–6 m.

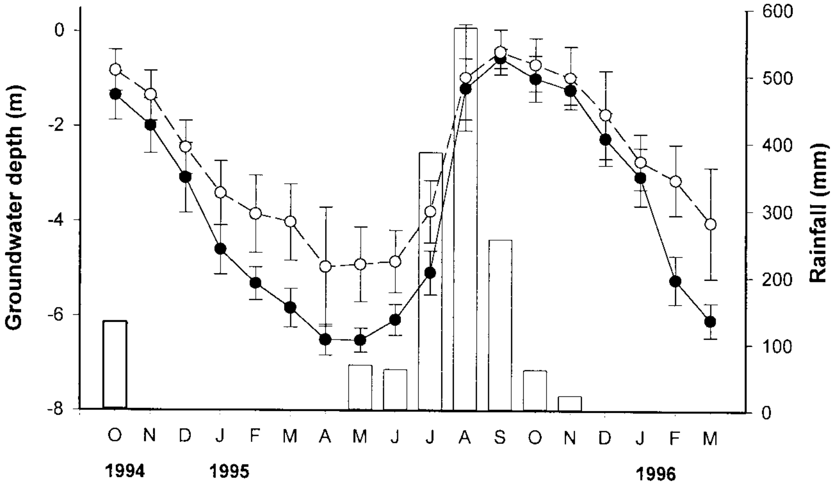

Fig. 3. Monthly rainfall (bar graph) and groundwater depths for 11 Group 1 wells (—●—) and 7 Group 2 wells (– –○– –). Vertical bars represent 95% confidence interval.

a much greater demand for irrigation than other crops such as maize and mungbean (Table 2).

At the onset of the rainy season, groundwater levels began to rise in all wells and were nearest to the ground surface towards the end of the rainy season in September. There was no significant difference between the two groups for the highest groundwater levels reached between August and November. Groundwater levels in October 1995 were at the same level as in October 1994. The data showed that the aquifer was fully recharged, irrespective of the decline during the dry season. This recharging of the wells by rainfall occurred even though the annual rainfall of 1432 mm in 1995 was less than the mean of 2000 mm for the past 10 years. The data implied no overdrafting of the groundwater resources during the observed period, though longer time-series data are needed for any conclusions on whether groundwater depletion exists in the study area.

Seasonal variation in groundwater chemical properties

Electrical conductivity (EC) was generally high, and in most wells ranged from 600 to >1000 μmho cm^{-1} (Fig. 4). A decline in EC was noted during the start of

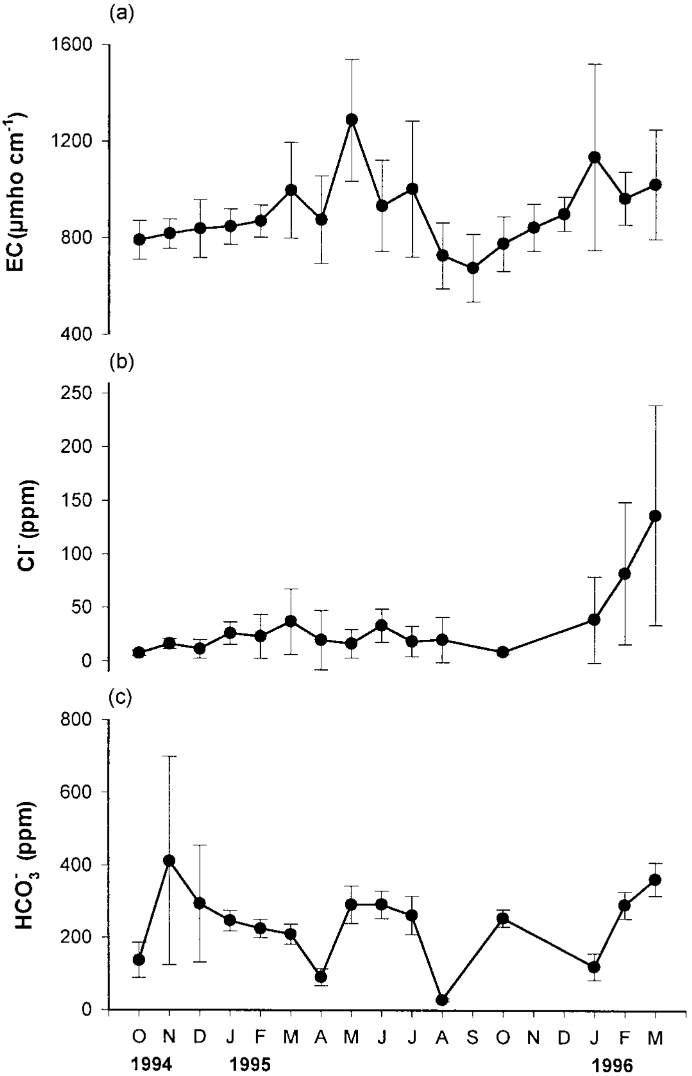

Fig. 4. Seasonal variation of (a) electrical conductivity (EC), (b) chloride (Cl^-) and (c) bicarbonate (HCO_3^-) in the groundwater from October 1994 to March 1996. (Means of 19 wells; vertical bars represent 95% confidence interval.)

the wet season and EC increased again at the end of the season. A higher variability in EC among the different wells during the dry season was observed. Lower concentrations in the rainy season might have been due to dilution of the different chemical components by rain water which infiltrated and raised the groundwater level during this time.

Cluster analysis of monthly Cl^-, EC, HCO_3^- and pH did not show any particular pattern of grouping. Cluster and correlation analyses also failed to detect any correspondence between management factors and EC, Cl^-, HCO_3^- and pH (data not shown).

Nitrate pollution

Nitrate in groundwater. Cluster analysis of monthly NO_3-N concentrations in groundwater showed three distinct groups of wells (Fig. 5). Group I wells had mean values of <5 ppm NO_3-N, Group II wells from 8 to 11 ppm NO_3-N and Group III wells >15 ppm NO_3-N. According to the World Health Organization standard, water in Group I wells was safe for drinking but in Group II wells (already at the maximum limit of 10 ppm for drinking water) it should be used with caution. In Group III wells it was unsafe for human consumption.

It was noted that there was a correspondence between the NO_3-N grouping of wells and the land-use pattern in their service area (Fig. 6). In the service area 95% of the wells in Group I (lowest nitrate level) were under the RU cropping pattern, with rice grown during the wet season. Wet season rice occupied 35–80% of the area serviced by wells in Group II. In well W15 (Group III), only 20% of the area serviced by the well followed the RU cropping pattern.

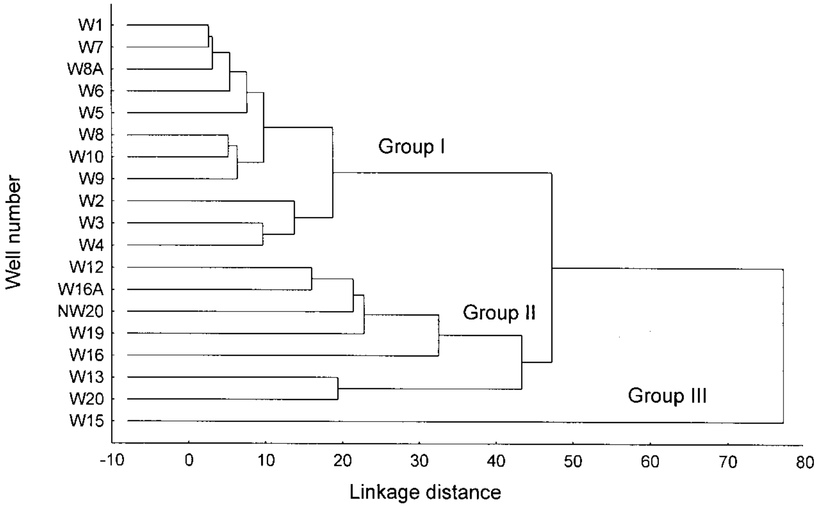

Fig. 5. Dendrogram showing well groups according to monthly nitrate-nitrogen (NO_3-N) concentration in the groundwater from October 1994 to March 1996.

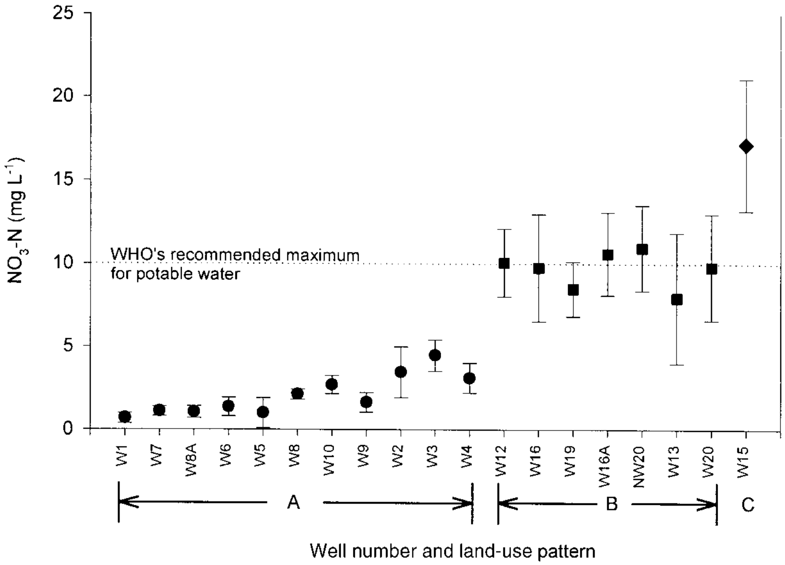

Fig. 6. Correspondence between the nitrate-nitrogen (NO_3-N) concentration in the groundwater of Group I wells (●, mean NO_3-N <5 ppm), Group II wells (■, mean NO_3-N 8–11 ppm) and Group III wells (◆, mean NO_3-N >15 ppm). Vertical bars represent 95% confidence intervals. Land-use pattern A: $>95\%$ of area under wet season rice; B: 35–80% of area under wet season rice; C: $<20\%$ of area under wet season rice.

Effect of cropping pattern and management on nitrate pollution. The correspondence between the grouping of wells by cluster analysis and the land-use pattern (Fig. 6) suggested that the cropping system might be a major factor influencing nitrate pollution in the groundwater. A significant relationship ($r^2 = 0.841$, $p < 0.001$) between the mean groundwater nitrate concentration in a well and the percentage of the well's service area under rice cultivation during the wet season was also obtained (Fig. 7). (Note, however, that there were big gaps in the scatterplot and the high r^2 may be due to clustered data.) The data may suggest that growing lowland rice during the wet season could reduce the amount of nitrate leached to the shallow aquifer. Fig. 8 also showed that the groundwater nitrate concentration in the wells where wet season rice occupied $> 95\%$ of the service area declined from July to October, which corresponded with the growth of the rice crop. This decline occurred despite the applications of N fertilizer during the same period. For the same study site, Tripathi *et al.* (1997) showed that soil NO_3-N at a soil depth of 0–50 cm in the RU cropping pattern could be as high as 167 kg ha^{-1} at the start of the rice season, but only 14–20 kg ha^{-1} at 15–20 d after rice was transplanted in July. Low nitrate in the soil profile and hence low nitrate pollution in the groundwater were related to the denitrification and volatilization losses of N (Buresh and De Datta, 1990) and low nitrification was associated with flooded rice fields.

In contrast, the groundwater nitrate in wells with a lower percentage of land under rice (Groups II and III) increased or remained high with fertilization

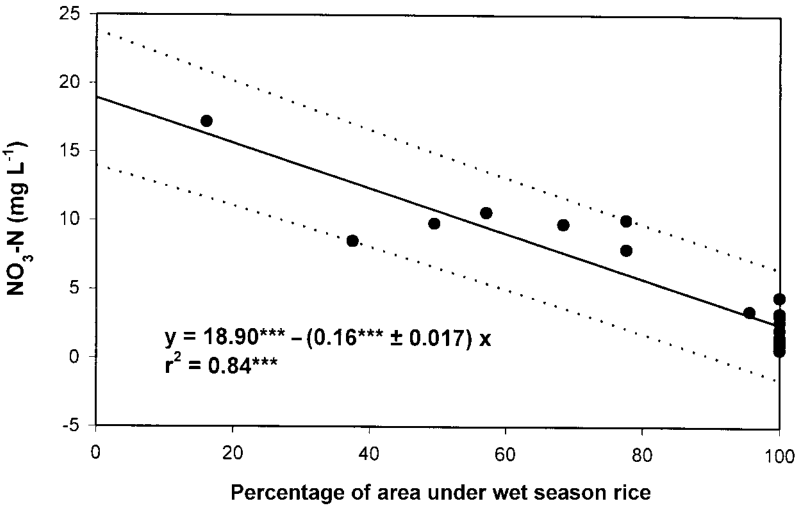

Fig. 7. Relationship between mean groundwater nitrate-nitrogen (NO_3-N) from October 1994 to March 1996 and the wet season rice area expressed as a percentage of the total area serviced by wells. The dotted lines represent 95% prediction interval; *** indicates significance at $p < 0.001$.

during the wet season (Fig. 8). With a high rate of N fertilizer especially for pepper (Table 2) in combination with high rates of percolation during the rainy season, excessive losses of NO_3-N through leaching may have occurred. In aerobic soils or soils under upland cultivation, fertilizer applied as urea or ammonium is converted rapidly into the nitrate form which is very susceptible to leaching. And, since the land in the UU crop sequence was left fallow for a longer period (4–6 months) than that in the RU sequence (2–3 months), there was more time to build up soil nitrate through mineralization in UU than in RU. Consequently, when there was enough percolation water (through rainfall or irrigation), the soil nitrate may easily have been leached into the groundwater.

Linear regression analysis also showed that the total amount of N-fertilizer input (from October 1994 to March 1996) accounted for 45% of the variation in groundwater NO_3-N (Fig. 9). The total application of fertilizer N in areas with a UU cropping sequence was significantly higher (544 kg N ha^{-1}) than in areas with a predominantly RU sequence (329 kg N ha^{-1}).

CONCLUSIONS

The study site was characterized by highly intensive cropping systems with the availability of supplemental irrigation from shallow tubewells and high fertilizer inputs (especially N) for the diverse, dry season, non-rice crops. Sustaining the quantity and quality of groundwater resources is of prime importance for maintaining crop productivity and protecting the health of farmers and their families. Our study indicated that slight to moderate restrictions should be posed on irrigation with water from all the wells studied because of the relatively high

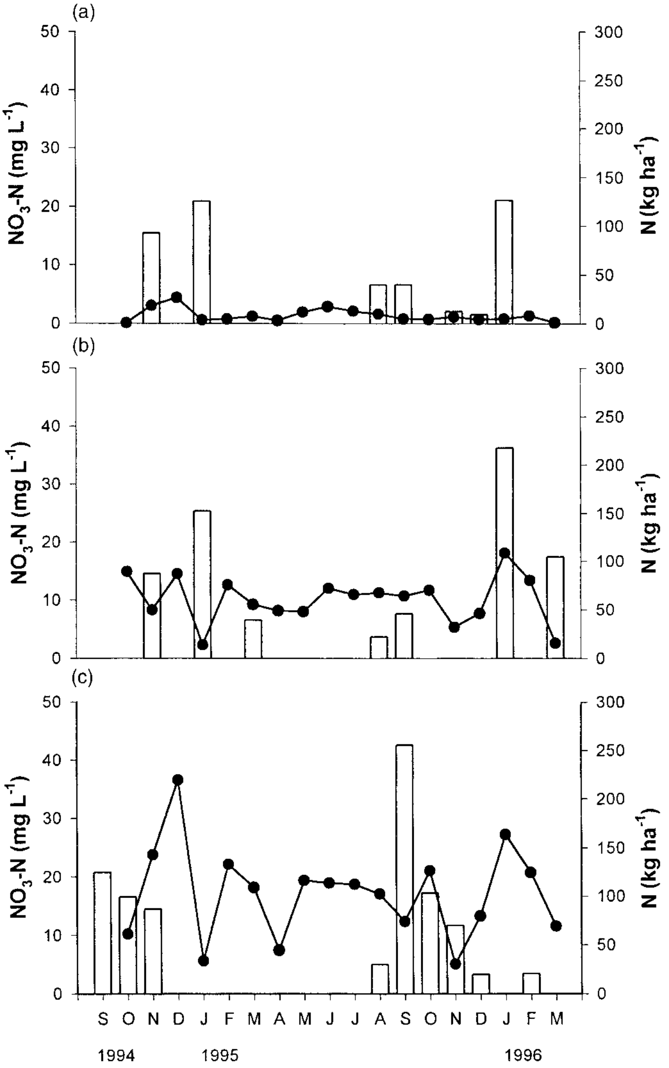

Fig. 8. Monthly input of fertilizer nitrogen (N) (bar graphs) and groundwater nitrate-nitrogen (NO$_3$-N, —●—) concentration in selected wells (a) W6 where >95%, (b) W12 where 35–80% and (c) W15 where <20% of the area serviced by the well was under wet season rice.

EC (700–3000 μmho cm^{-1}) and HCO$_3^-$ (90—500 ppm) levels, which exceeded the FAO's threshold values (Ayers and Westcot, 1985). The levels of Cl$^-$ and pH were still within safe limits except for W7 (Table 3).

Groundwater levels were lowest towards the end of the dry season (April–May) and the decline was more pronounced in wells irrigating pepper. There was no indication of groundwater depletion during our study period as the groundwater levels in all wells rose to the same level (about 1 m below the ground surface) at the end of the rainy season.

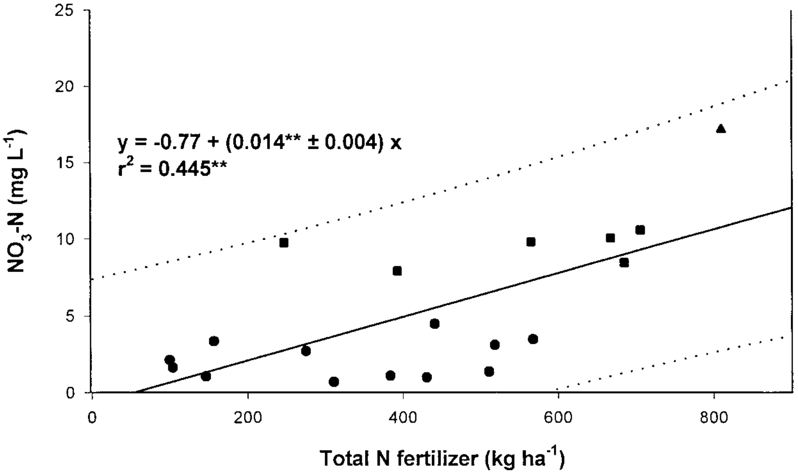

Fig. 9. Relationship between total nitrogen (N) fertilizer and mean groundwater nitrate-nitrogen (NO_3-N) between October 1994 and March 1996 where >95% (●), 30–85% (■) or <20% (▲) of the area serviced by wells was under wet season rice. The dotted lines represent 95% prediction intervals; *** indicates significance at $p < 0.01$.

Table 3. Electrical conductivity (EC, μmho cm^{-1}), chloride (Cl^-, ppm), bicarbonate (HCO_3^-, ppm) and pH of water from 19 wells at Magnuang, Batac from October 1994 to May 1996.

	EC		Cl^-		HCO_3^-		pH	
Well number	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.
W1	877	463	28	26	250	144	7.18	0.33
W2	913	312	20	18	289	172	7.10	0.22
W3	758	282	12	11	230	124	7.10	0.20
W4	714	195	10	11	206	83	7.15	0.30
W5	805	317	27	30	273	117	7.04	0.21
W6	981	416	59	141	258	120	7.05	0.20
W7	1875	852	301	313	269	121	6.98	0.25
W8	820	77	17	15	244	125	7.08	0.18
W8A	1185	912	90	148	272	116	7.11	0.26
W9	1383	892	32	26	253	127	7.35	0.31
W10	1030	230	28	30	312	126	7.24	0.28
W11	842	190	35	31	242	134	7.06	0.32
W12	960	58	17	17	225	127	6.93	0.30
W13	821	63	17	15	180	72	7.05	0.20
W15	977	132	29	25	188	91	6.86	0.20
W16	696	74	22	33	191	75	7.10	0.27
W16A	1002	267	41	41	240	115	6.99	0.21
W19	921	114	21	14	218	101	6.88	0.24
W20	767	36	12	14	160	102	6.93	0.27
NW20	912	56	26	18	188	84	6.74	0.16
FAO criteria for irrigation water quality:								
No restriction on use	<700		<142		<90		6.5–8.4	
Slight to moderate restriction on use	700–3000		142–355		90–500		na	

Groundwater in the study area was heavily polluted with NO_3-N. The mean nitrate level in eight, and the maximum in nine, of the 19 monitored wells were near or above the WHO limit for drinking water. Groundwater NO_3-N pollution was related to land-use pattern and input of fertilizer N. Growing rice during the wet season seems to reduce the leaching of N due to denitrification and volatilization losses of N in lowland rice areas. The input of fertilizer for rice was also less than for pepper, another major crop grown towards the end of the wet season.

This study was an example of the trend in Asia towards substantially increased crop intensification in the rainfed lowland rice ecosystem, especially in areas where shallow aquifer water is present. Although farmers benefit economically from the vegetable cash crops such as pepper, current management practices used for these crops may pollute the environment and affect human health. The pollution also indicates low nitrogen use efficiency. A better understanding of the N requirements of the crops and the optimum timing of N application are necessary to avoid excessive losses of N and to maintain sustainability and environmental quality. Alternatively, planting a suitable nitrate catch crop after pepper may reduce the amount of NO_3-N leached into the groundwater.

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REFERENCES

Ayers, R. S. & Westcot, D. W. (1985). *Water Quality for Agriculture. FAO Irrigation and Drainage Paper 29 Rev. 1.* Rome: Food and Agriculture Organization of the United Nations.

Bajwa, M. S., Singh, B. & Singh, P. (1993). Nitrate pollution of groundwater under different systems of land management in the Punjab. In *First Agricultural Science Congress, 1992 Proceedings*, 223–230 (Ed. Prem Narain). New Delhi: National Academy of Agricultural Sciences.

Buresh, R. J. & De Datta, S. K. (1990). Denitrification losses from puddled rice soils in the tropics. *Biology and Fertility of Soils* 9:1–13.

Castaneda, A. R. & Bhuiyan, S. I. (1991). Nitrate-nitrogen concentrations in shallow groundwater underneath ricefields. *Philippine Journal of Crop Science* 16:57–62.

Coronas, S. J. (1920). *The Climate and Weather of the Philippines, 1903 to 1918.* Manila, Philippines: Bureau of Printing.

Jury, W. A. & Nielsen, D. R. (1989). Nitrate transport and leaching mechanisms. In *Nitrogen Management and Ground Water Protection*, 139–156 (Ed. R. F. Follett). Amsterdam: Elsevier Science Publishers BV.

Keeney, D. R. & Nelson, D. W. (1982). Nitrogen – inorganic forms. In *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*, 643–698 (Eds A. L. Page, R. H. Miller & D. R. Keeney). Madison: American Society of Agronomy and Soil Science Society of America.

McDonald, A. T. & Kay, D. (1988). *Water Resources: Issues and Strategies.* Harlow, UK: Longman Scientific and Technical.

Nielsen, N. E. & Jensen, H. E. (1990). Nitrate leaching for loamy soils as affected by crop rotation and nitrogen fertilizer application. *Fertilizer Research* 26:197–207.

PCARRD (1980). Standard methods of analysis for soil, plant tissue, water, and fertilizer. Los Baños, Laguna, Philippines: Philippine Council for Agricultural Resources Research and Development.

Rogowski, A. S. (1990). Estimation of the groundwater pollution potential on an agricultural watershed. *Agricultural Water Management* 18:209–230.

Statsoft (1994). *Statistica/W. Volume 2.* Tulsa: Statsoft, Inc.

Tripathi, B. P., Ladha, J. K., Timsina, J. & Pascua, S. R. (1997). Nitrogen dynamics and balance in intensified rainfed lowland rice-based cropping systems. *Soil Science Society of America Journal* 61:812–821.