Effects of agricultural activities on nitrate contamination of groundwater in a Yellow River irrigated region

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Abstract Agricultural-induced increase of nitrate (NO_3^-) loading in groundwater is a worldwide problem. This study investigates the impacts of agricultural activities on groundwater NO_3^- pollution in a Yellow River irrigated region. The agricultural land use patterns are dependent on the land and water conditions. Besides wheat–maize rotation, the most popular cultivation pattern, other patterns with high production/ income, such as greenhouse vegetables, watermelon–cotton, are also widely adopted. N-fertilizer is excessively applied for all land-use patterns, with the annual amount ranging from 500 to 1420 kg N ha^{-1}. The NO_3^- loading in groundwater has large seasonal variation mainly caused by agricultural activities. Even in the best water quality season, 4 out of 27 samples show NO_3^- concentrations in excess of the drinking water standard, with a maximum NO_3^- concentration in well water of 100 mg NO_3^- L^{-1}. The shallow groundwater of the study region, combined with poor water and NO_3^- management practices, are creating a long-term legacy of contamination.

Key words nitrate leaching; groundwater; irrigation; agriculture; land use; Yellow River

INTRODUCTION

Nitrate (NO_3^-) leaching is a common issue in most irrigated agricultural regions of the world, especially where the crops/grass with high water and nitrogen (N) requirements tend to increase the potential risk of NO_3^- pollution to the groundwater. There is considerable literature that documents the impact of irrigated agriculture on groundwater quality in humid (e.g. Quin & Burden, 1979; Hubbard *et al.*, 1984; Kengni *et al.*, 1994; Kraft & Stites, 2003) and arid regions (e.g. Scepers *et al.*, 1983; Lettey & Pratt, 1984; Sabol *et al.*, 1987; Bustos *et al.*, 1996; Jalali, 2005). The drinking water standard for NO_3^- concentration is set as a limit of 45 NO_3^- mg L^{-1} or 10 NO_3^--N mg L^{-1} by the Environmental Protection Agency of USA (US-EPA). Besides degrading drinking water resources (e.g. Hamilton & Helsel, 1995), NO_3^- leaching to groundwater may also affect aquatic ecosystems when the pollutant-bearing groundwater discharges to surface water.

Due in part to the application of chemical fertilizer as well as irrigation area extension, food production of China has increased in recent decades (e.g. Kaneko *et al.*, 2005). In fact, the fertilizer was over-applied to most fields in China in pursuit of high yields. Zhang *et al.* (1996) has reported that over half of 69 groundwater samples collected in north China exceed the NO_3^- standard for drinking water, and the highest NO_3^- concentration is 300 mg L^{-1} in some intensive vegetable-producing areas, indicating a serious situation of NO_3^- pollution in groundwater. The N or NO_3^- aspects of groundwater contamination caused by agricultural activities in the North China Plain (NCP) has been reported by Chen *et al.* (2002), Tang *et al.* (2003), and Ju *et al.* (2005). Even in the region where the groundwater table is deep, NO_3^- pollution of groundwater has been detected (e.g. Tang *et al.*, 2004).

The Yellow River irrigated regions play an important role in food production in China. In these regions, the groundwater table is always shallow, varying from 1 to 10 m in depth, because of the effective recharge from surface irrigation. This indicates that there is less water shortage in the Yellow River irrigated regions comparing to other places in North China. However, NO_3^- leaching will contaminate the groundwater and cause health problems, particularly in rural areas.

The present research, under the framework of our Weishan Eco-Hydrological Experiments (WEHEX), will demonstrate the impacts of irrigation and agricultural activities on groundwater quality in a Yellow River irrigated region. The goals of WEHEX are to evaluate the regional water conditions of the large irrigation district, including both the physical and chemical aspects, and evaluate the role of human activities in the hydrological cycle of the groundwater–soil–plant–atmosphere systems. Therefore, the objectives of the current study are to evaluate the interrelations among agriculture, irrigation and groundwater and to illustrate the NO_3^- leaching status in the irrigation district.

STUDY AREA

The study area of this research is the whole region of Weishan Irrigation District (WID) located at the left bank of the lower reach of the Yellow River in western Shandong Province, the area between 36.14°–37.01°N and 115.43°–116.51°E (Fig. 1). The altitude of the study area ranges is 24–40 m above sea level with an average gradient of 1:7500, declining slightly from southwest to northeast. WID is the 5th largest irrigation district in China, with a total irrigated area of 310 000 ha, and about 3.8 million people. Agriculture associated land use/cover dominates the landscape of the study area. The GDP per capita was about 3000 USD in 2009, which is ~80% of the average GDP of China. The irrigation infrastructure of WID was constructed in 1958, but irrigation was suspended during 1962–1970. The water diversion has totalled 30.2 billion m^3 since 1970.

The study area has a temperate continental, semi-arid to semi-humid monsoon climate. Annual mean air temperature is 13.1°C, with 200 frost-free days per year. The annual precipitation ranged from 580 to 670 mm in recent years, of which 70% occurred during summer. The soil is a thick sandy-loam composed of Yellow River sediments. Major land use includes farmland, residential, forest and open water. The former two types occupy more than 90% of the total area. The major crops are wheat, maize, cotton, peanut, watermelon, garlic, and other greenhouse vegetables.

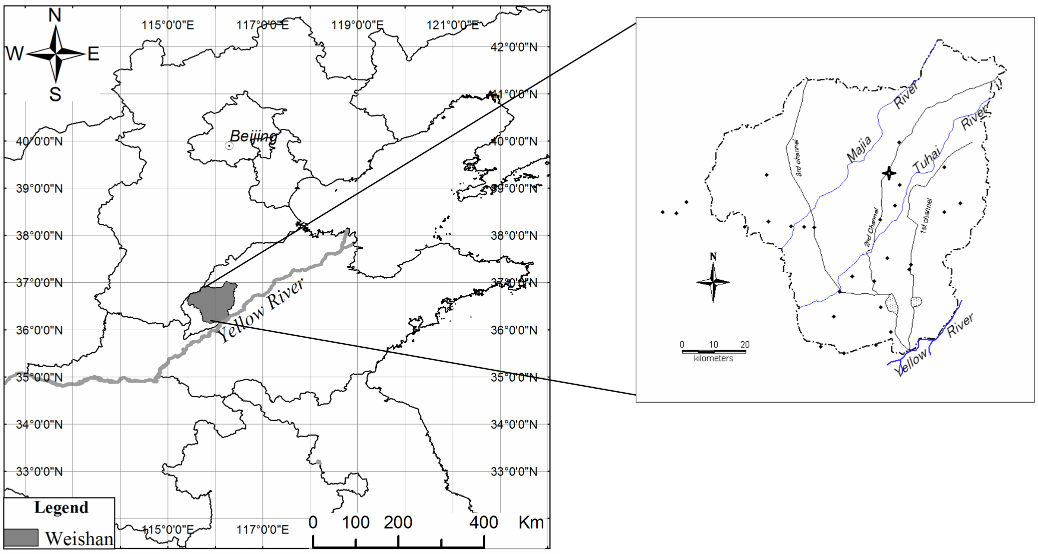

Fig. 1 The Weishan irrigation district. The black points show survey sites and the star shows the position of the long-term gauging station at Gaoying.

FIELD SURVEY

In order to investigate the agricultural water use and its impacts on the hydrology and water environments in the irrigation district, we conducted a field survey during 7–12 March 2006. The period of survey was immediately before the first irrigation phase during the growing season. At this time, the groundwater table was at its lowest position and the groundwater quality was expected to be at its best condition. The survey included agricultural water use, fertilizer practice, yield, cropping system adoption, groundwater depth, water quality, soil wetness, and crop growing status. Table 1 shows the survey content and sample numbers in detail. The position of each water sample site was recorded by using a GPS system. The regularly sampled groundwater from our comprehensive Weishan Eco-Hydrological Experimental Station, called Gaoying site, was used for interpreting the seasonal change of water quality in relation to agricultural activities. Gaoying site, positioned at the central part of WID, was established in March 2005 for integrated study of the eco-hydrological processes in the irrigated agriculture region. In total, the survey collected information on agricultural activities from 38 sites; water samples were collected at 27 of these sites for water quality analysis.

Table 1 Survey content design and number of collected samples.

Survey item	Contents	Investigated/sampled sites
Land use and agricultural practice	Cropping system Crop yield Fertilizer application (type, amount, application time) Irrigation (times, periods, amount) Main irrigation water source	38[a]
Groundwater well	Well depth Used age Groundwater depth Purpose (drinking, washing) Quality (sampling)	27[b]
Soil wetness	Topsoil moisture (0–10 cm)	27

a: Total number of sites investigated; b: including four surface water samples.

RESULTS

Water, land use, and agricultural practices

The land use pattern across the irrigation district is to some extent dependent on land conditions, such as topographical position and soil texture (Fig. 2). In general, wheat and maize are the dominant crops, which are cultivated in rotation in the study area. And, the land with good groundwater conditions has a tendency to be used for vegetable production; while the lowland with salty groundwater or low productivity is likely to be used for cultivating cotton. In addition, there are large areas of watermelon cultivation rotating with cotton, as well as garlic and maize rotation due in part to the local institutional policy. The growing season of the major crops are shown in Fig. 3.

The studies on agricultural water requirement (Liu *et al.*, 2002; Shen *et al.*, 2004; Sun *et al.*, 2006) show that ~350–400 mm irrigation water is needed to keep production high under the current climatic conditions of the North China Plain. Over the study area, the most important irrigation water source is the Yellow River, except for several places that cannot access the diversion water easily due to their high elevation. As an alternative for these areas, groundwater is pumped for irrigation. The groundwater table in the irrigation district is less than 10 m below the land surface, with a seasonal fluctuation of ~1–3 m. However, the groundwater level outside the irrigation district is fairly deep compared. Figure 4 shows the groundwater depth distribution in the surveyed area. There is an obvious groundwater gradient declining to the west from the irrigation district to outside the irrigated area, where groundwater levels are declining due to excessive pumping and lack of recharge from surface water irrigation.

For all types of land use (or cropland), very large amounts of N fertilizer are being applied (Table 2). Particularly for vegetable production and other high-value crops, such as garlic and watermelon, N-fertilizer use is greater than for other cropland. Steinbuch *et al.* (1993) reported that in the suburbs of Beijing, the proportion of excessive N-fertilizer application for vegetable production has reached 86%. Even in cereal cropland, farmers tend to use more N fertilizer than is necessary in order to achieve high levels of food production. The ratio of production to income per

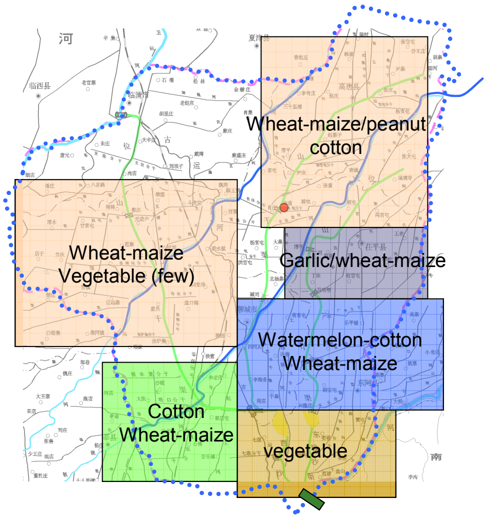

Fig. 2 Distribution of major crop types in the study area.

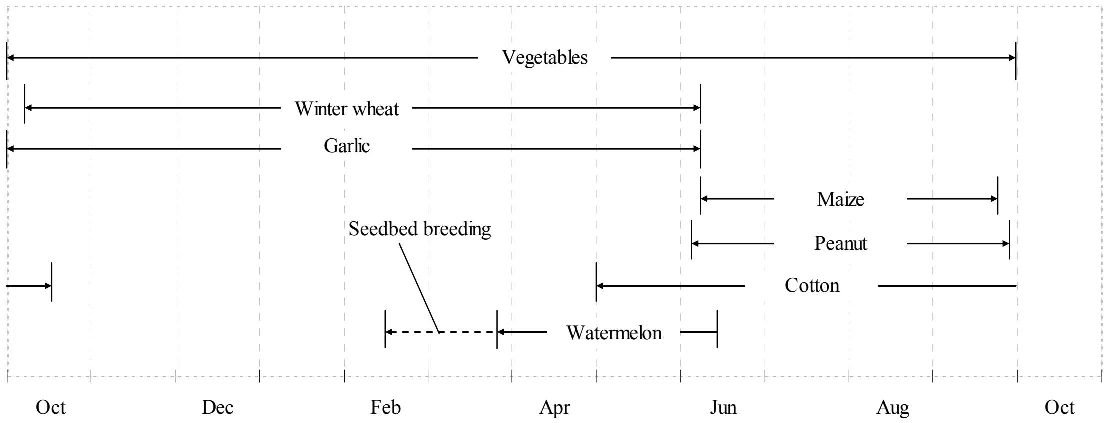

Fig. 3 The growing season of major crops cultivated in the study area.

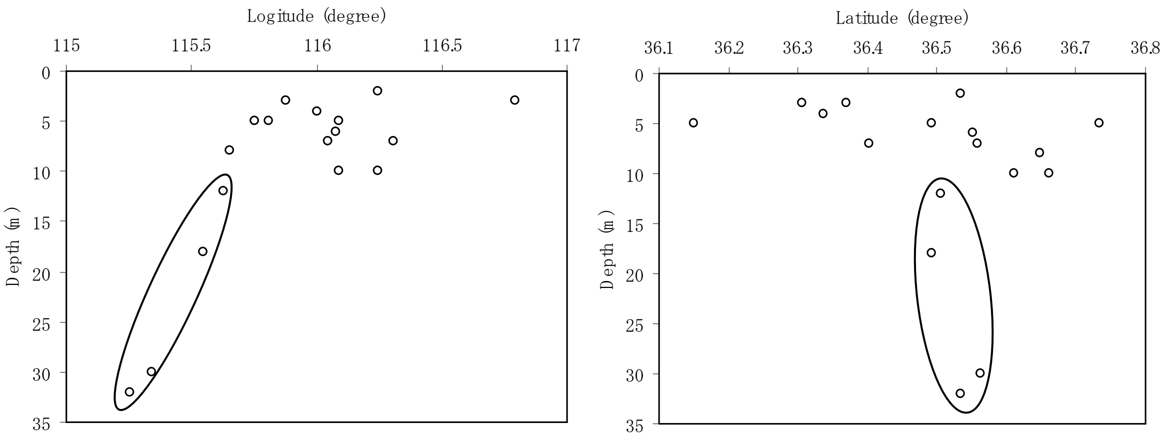

Fig. 4 Groundwater table depth across Weishan district. Ovals signify sites outside of the irrigated zone.

unit area of land listed in Table 2 is fairly high compared to that of other regions in China and other countries. The annual N-fertilizer input ranges from 500 to 1420 kg N ha^{-1}, allowing for the different matching of the cultivation patterns. In the rural areas of China, there is lack of environmental awareness about the harm caused by excessive application of N fertilizer.

Table 2 Agricultural practices and associated information with respect to different land use.

Land use	Growing period	Yield (10^3 kg ha^{-1})	Irrigation[a] (times)	N-fertilizer Type/times	Amount (kg N ha^{-1} $year^{-1}$)
Wheat	Oct. 10–Jun. 10	5.0–7.5	2–3	DAP[b] / 1	127
				Urea / 1-2	280
Maize	Jun. 10–Sep. 25	6.0–9.0	0–2	Urea / 1	140
Cotton	May 15–Oct. 20	2.0–3.0	1–2	Urea / 1	140
Peanut	Jun. 1–Sep. 25	~3.8	1–2	Manure / 1	100
				Urea / 1	70
Garlic	Oct. 1–Jun. 10	6.0–7.5	1–2	DAP / 1	148
				Urea /1	327
Watermelon	Apr. 1–Jun.10	35–50	Frequent	Manure / 1	100
				DAP / 1	159
				Urea / 1	103
Vegetable	All year through	Depending	Frequent	Manure/several	300
				Urea /frequent	1120

[a] The water quantity of each irrigation is approximately 100 mm; [b] diammonium phosphate, $(NH_4)_2HPO_4$.

Nitrate leaching to groundwater

As mentioned above, the survey was conducted before the first irrigation and the groundwater quality was expected to be relatively good. Figure 5 shows the seasonal change of NO_3^- concentration in groundwater at Gaoying site, where we established a comprehensive experimental system on the interactions and processes of the groundwater–soil–plant–atmosphere system. The NO_3^- concentration changes significantly with agricultural activities between the two growing seasons. Fertilizer application causes a large increase in the NO_3^- loading to groundwater and the two peaks of nitrate-NO_3 in June and September reach the allowable limit for drinking water. These facts imply that much N-fertilizer is not used by the crops and leaches into the groundwater via irrigation, causing long-term groundwater contamination.

The change in the vertical profiles of NO_3^- concentration of groundwater before and after irrigation (Fig. 6) shows how NO_3^- leaching associated with irrigation affects groundwater quality. Before irrigation, NO_3^- concentrations are less than 20 mg L^{-1}, and irrigation accompanied with fertilizer application causes NO_3^- concentrations in the upper layers to reach 65 mg L^{-1}. The significant NO_3^- leaching suggests that the irrigation method, i.e. flood irrigation, results in low N-use efficiency, with high risks to the environment.

From the regional survey, 4 of 27 water samples had NO_3^-concentrations that exceeded the allowable limits for drinking water, and the highest NO_3^- concentration was 100 mg L^{-1}. Most samples were collected from domestic wells in vegetable producing areas, except for one sample collected from a sewage channel. Figure 7 shows the distribution of NO_3^- concentrations with depth. It is obvious that shallow groundwater tends to have the highest contamination of NO_3^-, most likely due to leaching of fertilizer applied to the fields in this area. It is, therefore, suggested that drinking water should be abstracted from more than 30 m below land surface. Since the survey was conducted during the season of the best groundwater quality, the NO_3^- loading to shallow groundwater, i.e. less than 10 m below land surface, would potentially exceed the drinking standard if the seasonal variations followed the pattern at Gaoying study site.

CONCLUDING REMARKS

Agricultural groundwater pollution from NO_3^- is a worldwide problem that has economic, ecosystem, and human health impacts. Especially, in sandy irrigated areas, where saturated hydraulic conductivity is high making NO_3^- leaching easier, groundwater is susceptible to NO_3^- contamination.

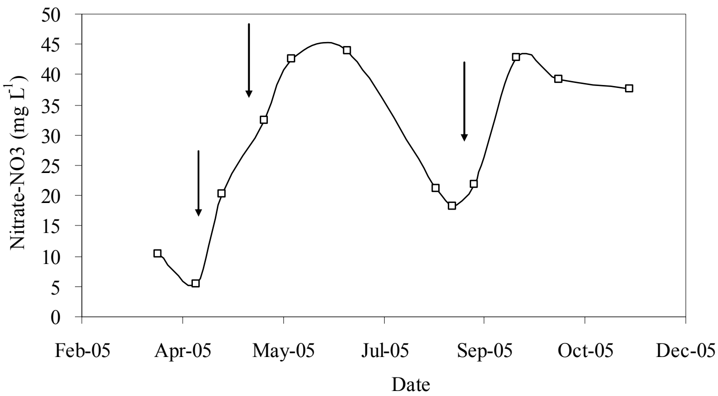

Fig. 5 Seasonal change of NO_3^- concentration of groundwater during 2005 (Gaoying site). The three arrows show the timing of fertilizer (urea) applications.

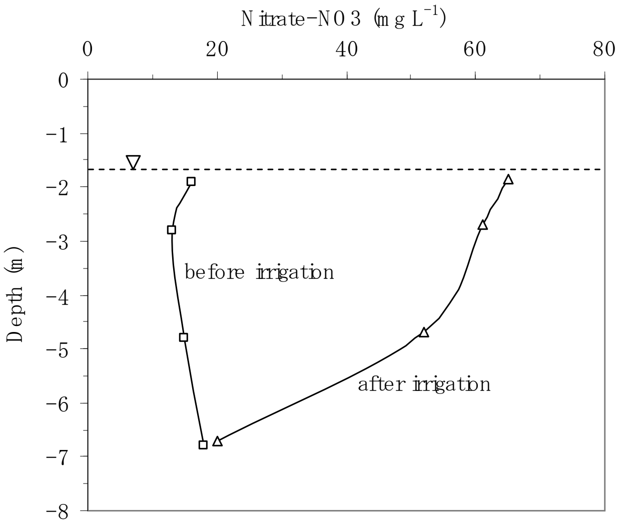

Fig. 6 Nitrate-NO_3 profiles in groundwater before and after irrigation (Gaoying site, March 2006). The dashed line shows the groundwater level position.

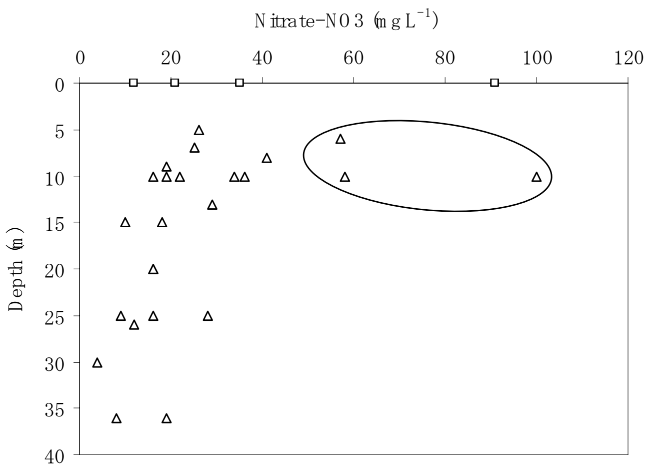

Fig. 7 Nitrate-NO_3 concentrations in groundwater in the Weishan Irrigation District (March 2006).

In the current study, the thick sandy-loam soil composed of Yellow River sediments has a high saturated hydraulic conductivity, 5.66×10^{-5} m s^{-1}, which causes water and fertilizer leaching from the root zone to pollute groundwater. Similar phenomena were reported for the sandy irrigated area in humid region of USA (Massbarger & Yost, 1989). The comparison of the NO_3^- profiles in groundwater before and after irrigation (Fig. 6) shows significant NO_3^- leaching coinciding with the application of irrigation water. Partly due to the lack of technology for precise agricultural water and fertilizer management, the farmers tend to use much more N fertilizer and water than is necessary in China. The result is a low use efficiency of both N fertilizer and water applications.

And from the seasonal change of NO_3^- concentration in groundwater, we conclude that there is a high risk of seasonal groundwater NO_3^- contamination in the study area, particularly during summer.

There are limited options to control NO_3^- loading to groundwater. Because denitrification is a fairly complex process and difficult to implement on a household scale, improved N-fertilizer use efficiency may be a good choice for drinking water protection in rural areas. Traditional strategies such as decreasing fertilization rates, scheduling fertilizer inputs, and optimizing irrigation may have some potential to reduce NO_3^- loading to groundwater in this area, but the effect has limited applicability to high N-demand crops (Kraft & Stites, 2003), particularly if the practice of flood irrigation is not changed. Better control of N application and leaching will require more precise irrigation and fertilization technologies, such as the adoption of spray irrigation, to improve water- and N-use efficiency in North China. In the long run, implementation of N fertilization and irrigation strategy will not only reduce groundwater contamination from NO_3^- leaching but also improve water use for mitigating water stress in the North China Plain.

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