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Management of Nitrate in Groundwater: A Simulation Study

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إدارة النترات في المياه الجوفية عن طريق النمذجة الرياضية

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خلاصة: أثبتت الدراسات أن النشاطات الزراعية يمكن أن تتسبب في دخول النترات و بعض المواد الكيميائية الأخرى إلى المياه الجوفية. يعتبر تواجد النترات في مياه الشرب خطراً على الصحة. لقد أجريت هذه الدراسة لتقييم دور الزراعة في تلوث المياه الجوفية بالنترات وتقييم مدى إمكانية استعمال نموذج LEACHN لادارة دخول النترات للمياه الجوفية للأراضي الزراعية في منطقة الباطنة باعتبارها أهم منطقة زراعية بالسلطنة. تم جمع و تحليل عينات من المياه الجوفية لتقيم المشكلة والاتجاهات الممكنة. كان الهدف من جمع وتحليل العينات هو معرفة الفروقات في تركيز النترات في التربة الزراعية وغير الزراعية. ولقد تم عمل استبيان لجمع معلومات عن الممارسات الزراعية وكمية المخصبات المضافة وما إذا كانت هناك أية مصادر أخرى للتلوث بالنترات. أظهرت النتائج أن ٢٣ % من عينات المياه الجوفية تحتوى على تركيز ١٠ ملغم / لتر من النترات – نيتروجين و ٣٤% تحتوى على تراكيز أكثر من ٨ ملغم / لتر. ولقد لوحظ أن التربة الزراعية تحتوى على تراكيز أعلى من النترات عن التربة الغير الزراعية. وقد أظهرت الدراسات أن مستويات النترات في المياه الجوفية تشكل اتجاها خطرا. و أوضحت الدراسة أن نموذج LEACHN يمكن استخدامه كأداة إدارية لتقليل كمية النترات المتسربة للمياه الجوفية عن طريق تقنين كمية الأسمدة و المياه المضافة.

ABSTRACT: Agriculture may cause nitrate and other chemicals to enter into groundwater systems. Nitrate in drinking water is considered a health hazard. A study was conducted to assess the extent of nitrate pollution of groundwater caused by agriculture and to evaluate the possibility of using the LEACHN model to manage nitrate entry into groundwater of agricultural areas of Al-Batinah, which is the most important agricultural region of Oman. Groundwater samples were collected and analyzed to assess the problem and to detect possible trends. Soil sampling and analyses were done to demonstrate the difference in the nitrate concentration in agricultural and non-agricultural soils. A questionnaire survey was conducted to gather information on agricultural practices, fertilizer input, and other possible sources of nitrate pollution. Results from the study show that 23% of groundwater samples have a concentration of of nitrate-N concentration of 10 mg/l and 34% samples exceed 8 mg/l. Agricultural soils have higher levels of nitrate compared to non-agricultural soils. Results also demonstrate that nitrate levels in groundwater in Al-Batinah are rising. Application of the 'LEACHN' model demonstrated its suitability for use as a management tool to reduce nitrate leaching to groundwater by controlling fertilizer and water input.

Keywords: groundwater, management, nitrate, simulation, agriculture.

Nitrate contamination of groundwater is a common occurrence in many parts of the world. This issue is the subject of extensive research because of its potential to harm human health (Chettri and Smith, 1995). In many places agriculture has been identified as a major cause of nitrate and other chemicals in groundwater. Nitrate in groundwater originates primarily from fertilizers, septic systems, and manure storage or spreading operations (McCasland *et al.*, 1998). No effective means exists to prevent nitrates from migrating to groundwater or to remove them from a contaminated aquifer. Best management practices have been identified to minimize nitrate pollution resulting from application of nitrogen fertilizer. But

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crops such as vegetables present special problems because farmers often apply excess water and fertilizer. to assure high yields of marketable quality product. In addition, vegetables often are grown on sandy soils which permit easier movement of nitrates to groundwater. The nitrogen in the soil-plant-water system undergoes numerous interactions and transformations. In general, nitrogen, which is applied as fertilizer, is taken up by the plants, volatilized, carried away by surface runoff, and leached to the groundwater in the form of nitrate. To reduce the cost of agricultural production and for the protection of groundwater, it is of utmost importance that leaching of nitrate beyond the root zone be minimized.

THE STUDY AREA: The Batinah plain is the most important agricultural area in Oman. It stretches along the Gulf of Oman from Muscat in the south to Khatmat Malaha at the border with the Emirate of Fujeirah. To the south and the west the Batinah plain is bordered by the Hajjar mountains (MAF, 1993). In this study, most of the groundwater samples were collected in the vicinity of Seeb and Barka towns within a 20 kms stretch. The mean annual temperature in this area is 28.6 °C, relative humidity is 58%, wind speed is 221 km/day, sunshine hours is 9.7 hours/day and rainfall is 81.4 mm/yr (based on 18 years of climatic data at the weather station at Seeb Airport). Like most arid areas, rainfall is very irregular from year to year and some months can be totally dry. The study area is comprised of very thick alluvial, marine and aeolian sediments (MAF, 1993).

Traditional agriculture has been practiced in this area for centuries. The last 25 years have seen tremendous growth of modern irrigated agriculture. Groundwater is used extensively for irrigation. Excessive usage of groundwater resulted in seawater intrusion into the coastal aquifers that led to increased salinity of groundwater. Use of saline groundwater for irrigation has caused the problem of soil salinity in many parts of the Batinah plain. According to MAF 1993) study, 50 % of the agricultural area in the South Batinah is slightly to extremely saline (EC_e of >4 dS/m). Soils are deep, topsoil is generally coarse textured and infiltration rate is moderately rapid to very rapid in most of the farms. Crops grown in the study area include date palm, lime, alfalfa, vegetables, fruits, and fodder.

The objectives of our study were to assess the extent of nitrate pollution of groundwater caused by agriculture in rural areas so that strategies can be developed leading to sustainable agriculture. A further objective was to apply computer models for the simulation of nitrate and water movement in agricultural fields, and to apply a model to optimize water and fertilizer input for selected crops in soils to reduce the potential for groundwater pollution.

Methodology

Forty-four (44) groundwater samples from agricultural farms were collected over a period of two years (during the months of January- March in 1997 and 1998). Farms were chosen based on their accessibility and ease of collecting water samples. Water samples were collected from tubewells supplying water for irrigation. The samples were collected and stored following standard procedures. A nitrate electrode was used for measuring nitrate in the water. A questionnaire survey was conducted to gather information on agricultural practices, fertilizer input, and other sources of nitrate pollution. Soil samples from different depths were collected from agricultural and non-agricultural areas. Only a limited number of samples were collected. Four cores were taken (two each from agricultural and non-agricultural, and at seven different depths). Soil extracts from these samples were analyzed for nitrate. Extracts were obtained by mixing equal amounts of soil and water (100 gms) and then filtering the solution through filter paper. Composite nitrate concentrations from agricultural and non-agricultural soil samples at various depths were calculated and plotted on a single figure (Figure 1). Historical data (1992-98) on groundwater nitrate concentration in some selected farms were collected from the records kept by the farm owners (Figure 2). For model application, soils from a typical farm in the study area were sampled from different depths and characterized with regards to their physical and hydraulic properties. The following properties were measured: particle size distribution, bulk density, soil moisture-tension relationship and hydraulic conductivity. For model testing, an experiment was conducted in the laboratory using soil columns to measure nitrate movement. Climatic data were gathered from published sources.

MODEL CALIBRATION AND APPLICATION: The behavior of nitrogen (N) in the soil-plant-water system is very complex. Models are useful tools for integrating different processes involved in N transport in soil and can be used in forecasting the behavior of a system without actually making measurements in the physical system (Tanji and Gupta, 1978). In recent years development and application of models to predict soil water transport, N transformation and N transport have received wide acceptance. LEACHN developed at the Department of Agronomy, Cornell University, USA, is

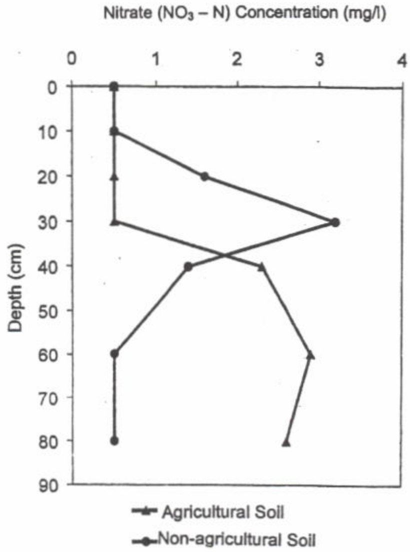

Figure 1. Nitrate (NO3-N) concentration in soil extracts from different depths from agricultural and non-agricultural soils.

a model that can be used to simulate field-scale N transformations and movement in the unsaturated zone of soil profiles (Hutson and Wagenet, 1995).

LEACHN can be used for the simulation of leaching of nitrate (and ammonium) from the plant root zone, which is of much concern to the agriculturists and environmentalists. Once beyond the root zone, N is no longer available to plants and thereby has the potential to pollute groundwater (Ahmed *et al.,* 1996).

In LEACHN, soil-water flow is computed using the Richards equation, which is a second order partial differential equation describing the flow of a fluid in a porous medium. Solute movement is calculated using the advection-dispersion equation which includes adsorption, dispersion and advection terms. The finite difference method is used for solving the differential equations describing water and solute transport. The LEACHN model includes N transformation processes such as mineralisation, nitrification, denitrification and surface volatilisation. The rate constants, which control these processes, are dependent on temperature and soil water.

The LEACHN model was first applied with experimental data obtained from a soil column study conducted in the laboratory. A cylindrical PVC column, 50 cm long and 9.4 cm inside diameter was used. The length of the soil column was 30 cm. The cylinder was lubricated with vaseline, which proved to be efficient for sandy soils by eliminating any possibility of solute movement through the sides. Two grams of urea (46% N) was placed on top of the soil column. The experiment was performed inside a laboratory at a temperature of 20 °C. Soil physical and hydraulic properties were measured. Urea fertilizer and water were applied on top of the soil column. Leachate at the bottom of the column was collected and the amount and concentration of nitrate in the leachate were measured.

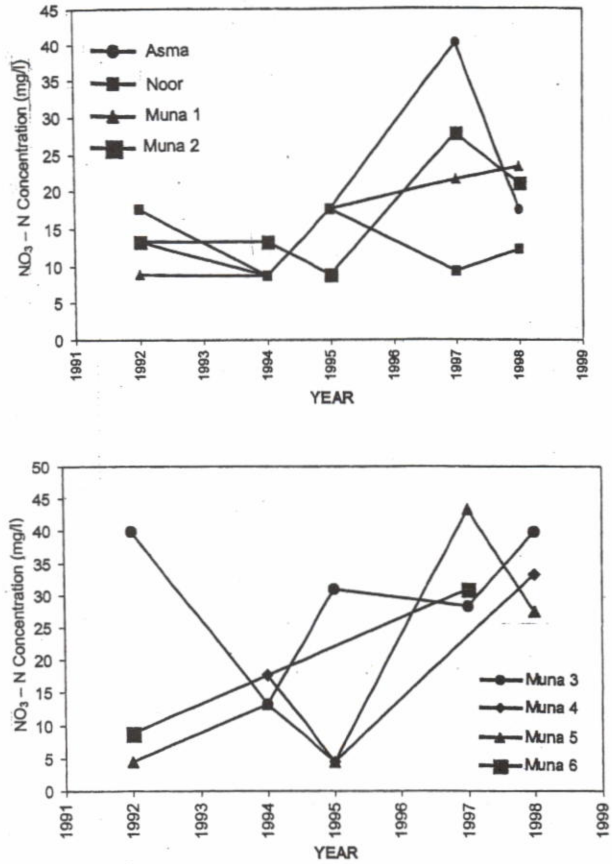

Figure 2. Time series of nitrate (NO3) concentration in groundwater samples in Barka.

The input rate constants and several other parameters in the model were adjusted to get reasonable fits for cumulative leachate (mm), cumulative nitrate loss through drainage (kg/ha) and nitrate concentration (mg/l) (Table 1). The model was then applied to simulate field conditions. Some of the input data used is as follows: Location: Barka (in the study area), Period: 04 Jan – 08 Feb, 1998, Depth of the Soil profile: 1000 mm, Crop: Alfalfa, Type of soil: Sandy loam, Initial moisture content: Dry, Crop cover at maturity: 0.7, Root depth: 500 mm, Initial nitrogen content: Low, Potential Evapotranspiration (PET): 36 mm/week.

TABLE 1

Input data used in the simulation study.

Depth (mm)	Clay (%)	Silt (%)	Organic Carbon (%)	Bulk Density (gm/cm^3)	Campbell' s parameter Alpha	Campbell' s parameter Beta	Saturated Hydraulic Conductivity (mm/day)
0-200	5.5	19.7	1.0	1.55	-1.0	3.06	1090
200-400	11.4	28.6	1.0	1.55	-1.13	3.05	895
400-600	8.6	24.7	0.5	1.42	-1.19	3.25	835
600-800	8.6	24.7	0.5	1.35	-0.85	3.55	930
800-1000	7.4	19.0	0.5	1.325	-0.79	3.76	1040

SOIL PHYSICAL AND HYDRAULIC PROPERTIES: Soil samples were collected at different depths (up to one meter). Undisturbed soil columns were also collected to obtain information on the hydraulic parameters of the soil and soil bulk density. Measurements of the hydraulic conductivity at saturation (Ks) were carried out using the constant head method, which is based on the direct application of Darcy's equation to a saturated soil column of uniform cross-sectional area. Soil water characteristics curve (relationship between moisture content and suction) was obtained using standard soil moisture suction table for low-pressure potentials and pressure plate method for medium to high-pressure potentials. Campbell's (1974) parameters (alpha and beta) relate the volume fractional water content, pressure potential and hydraulic conductivity. Alpha and beta were obtained by the curve-fitting method. The LEACHN model uses functions based on these parameters to predict the soil water retention and the hydraulic conductivity. The RETFIT subroutine was used to calculate these parameters where the matric potential and the corresponding water content obtained from the soil moisture characteristics curve were fed as input data.

NITROGEN PARAMETERS: These parameters describe the interactions, transformations and fate pathways of nitrogen in the soil profile. They vary quite distinctively according to the type of soil and depth, climate and temperature. As such, it is difficult to measure site specific rate constants. In the absence of any related field data, rate constants used in the study by Johnsson *et al.* (1987) were emphasized as guideline values with modifications for the higher temperature in Oman. Although there were differences in the study conducted by Johnsson, *et al.* (1987) and the present study, especially the climatic conditions and the length of study, it was observed that for short duration simulation the rate constants are rather robust. Sensitivity analysis showed that drastic reductions in rate constants (Table 2, simulations 1 and 6) did not produce significant difference in nitrogen loss from the field in a 35-day simulation period.

Results and Discussion

SURVEY RESULTS: Forty-four (44) groundwater samples were collected for nitrate analysis. About 23% of the samples were found to have a level of NO_3-N concentration exceeding 10 mg/l (Figure 2). World Health Organization (WHO) has set a limit of 10 mg/l of NO_3-N in drinking water mainly based on the possible formation of methaemoglobin in red blood cells as a consequence of nitrate conversion to nitrite by bacteria in the gastrointestinal tract (Van Dijk-Looyaard and Montizaan, 1990) at higher concentrations. Table 3 shows the NO_3-N concentration distribution in the samples.

TABLE 2

Water and nitrate simulations for an irrigated farm in Al-Batinah using LEACHN model.

Simulation No.	Comments	Water Application (mm)	Drainage (mm)	Urea Application (kg/ha)	Plant Uptake NO_3-N (kg/ha)	Plant Uptake NH_4-N (kg/ha)	NO_3-N in Drainage (kg/ha)
1	Field data	558	236	20	10.6	3.1	5.5
2	Double the amount of fertilizer applied	558	236	40	20.9	5.5	11
3	Reduce the amount of fertilizer applied	558	236	5	2.8	0.8	1.6
4	Fertilizer applications in two times	558	236	10 + 10	10.9	4.6	3.7
5	Increase rooting depth from 0.5 m to 1m	558	236	20	14.3	3.6	2.4
6	Decrease rate constants by 50%	558	236	20	9.3	4.6	5.2
7	Decrease the water application by 35%	364	47	20	16.3	3.4	0.29
8	Decrease the water application by 50%	279	No Leachate	20	14.9	3.4	No Leachate

Data on nitrate concentrations in groundwater for years 1992-1998 were available for eight farms. Figure 2 shows that nitrate levels on the average have a rising trend. It was not possible to gather precise information from expatriate farm-workers in the field. In the absence of data and information on irrigation practices, cropping patterns, and water table fluctuations, for the period 1992-1998, it is difficult to explain the variability of nitrate levels in groundwater. Although 1997 and 1998 were wet years in terms of rainfall (meaning more than annual average rainfall), this alone is not likely to cause more leaching of nitrate

TABLE 3

NO_3-N concentration distribution in collected samples.

Concentration (mg/l)	No. of Samples	%
0 - 5	15	34
5 - 8	14	32
8 - 10	5	11
> 10	10	23
Total	44	100

from the soil profile. Farmers tend to over irrigate which is substantially higher than the rainfall amount. It is more likely that variation in fertilizer input may have caused such variability. Fertilizer application varies due to change of crops and the farmers' tendency to apply more fertilizer than needed. Over irrigation after fertilizer application can also carry nitrates rather quickly to groundwater instead of it being made available to crops. Limited data on nitrate concentrations in soil extracts from different depths of agricultural and non-agricultural soils (Figure 1) clearly show that non-agricultural soils have moderate levels of nitrate in the top 40 cm of the profile, whereas from 40-80 cm depth agricultural soils have higher concentration of nitrate. This is probably due to the leaching effect in agricultural soils. As irrigation water is applied, nitrate is leached downwards in agricultural soils. From the questionnaire survey it was found that groundwater in many farms is used as drinking water especially by the expatriate farm-workers. It was also observed that most of the farms have domestic animals. Animal wastes are kept on farm to be used as organic fertilizers. Most farms grow date palms. Bananas, mangoes and vegetables are also widely grown. Flood irrigation is the preferred method of irrigation and application rates are highly variable. Many farms have active septic tank systems.

POTENTIAL SOURCES OF NITRATE: Nitrogen fertilizers, soil organic nitrogen, sewage, and excrements from animal (Dudley, 1990) are possible sources of nitrogen in agricultural areas. During the field visits it was observed that in most farms fertilizers are used in excess of the requirement of the plant. Soils in the area are usually sandy. Irrigation water is also applied, in many instances in excess of the required quantities. All these factors combined will produce higher nitrate levels in groundwater in comparison to natural background levels.

Some of the farms had livestock although not in large numbers. A significant number of farms also had septic tanks. There are also other potential sources of nitrate. Septic tanks, depending on their distances from wells, have been found responsible for elevated nitrate levels in many countries (Sharma *et al.*, 1994). In many places, microbial nitrification of soil organic matter at high levels of soil organic matter may be another possible factor contributing to the nitrate build-up over time (Chettri and Smith, 1995). In the study area, the soils do not have high organic matter content. As such it is unlikely that high nitrate levels are caused by such a process.

SOIL COLUMN STUDY: The column study in the laboratory was done to see whether the model is capable of predicting water and nitrate movement in the soil profile under controlled conditions. Some parameters were adjusted through trial and error to obtain reasonable fit for the amount of water leached, the amount of nitrate leached and the concentration of nitrate in the leachate at different times (Figures 3-5). During the experiment two grams of Urea (46% N) was placed in the soil column with 1200 mm of total water applied in 11 days period. Leachate from the soil profile was then measured and analyzed for nitrate content at different time steps. The following parameters were used to obtain the reasonable fits shown in Figures 3-5: Saturated hydraulic conductivity = 85 mm/day, Campbell' s parameters alpha and beta of -0.183 and 0.478 and bulk density of 1.6 gm/cm^3.

The soil column study clearly demonstrated that the LEACHN model is capable of simulating water movement fairly well although its performance with regards to nitrogen movement can be judged as adequate. When nitrogen load leached is fitted, the peak

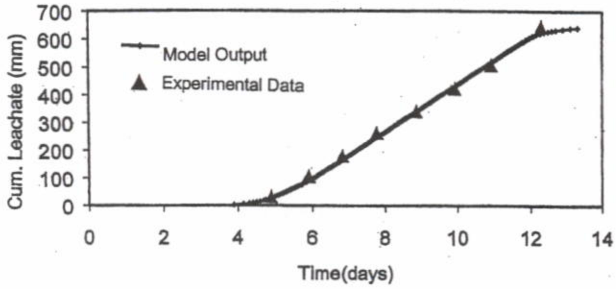

Figure 3. Cumulative leachate vs. time plot for experimental and model data.

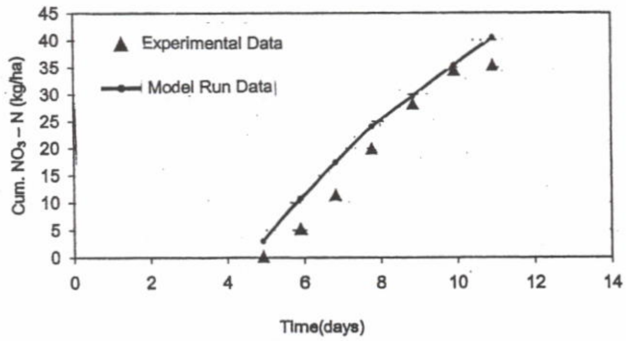

Figure 4. Cumulative nitrate vs. time plot for experimental and model data.

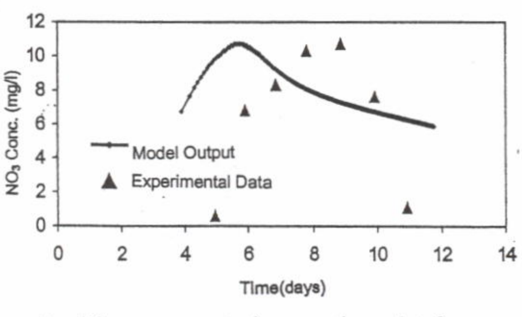

Figure 5. Nitrate concentration vs. time plot for experimental and model data.

nitrate concentration is similar to but arrives earlier than occurs in the experiment. As expected, model output is sensitive to input parameters.

SIMULATION STUDY: Eight (8) different simulations were performed using the LEACHN model. The objective was to assess different management options with regards to their effectiveness in reducing nitrate loss through drainage. The basic model input parameters were discussed previously (Table 1). The irrigation schedule as applied by the farmer was used (for simulation 1 - 6). For simulation 1, a single application of 20 Kg/ha of Urea was assumed. This resulted in 5.5 Kg/ha of nitrate loss in drainage. Table 3 shows that the increase (decrease) of fertilizer input results in the increase (decrease) (although not proportionately) of nitrate loss in drainage water. Drainage water here refers to the water that drains out from the bottom of the 1 m profile. One possible way to reduce nitrate loss is to apply the total amount of fertilizer (20 kg/ha) in two equal applications instead of one. This reduced nitrate loss by 33% in comparison to single application situation. By increasing the rooting depth of plants from 0.5 to 1 m, nitrate loss can also be reduced by 56%. However, by far, the best results can be achieved by decreasing water application. A 35% reduction in water application reduced nitrate loss by 95% whereas 50% decrease in water application resulted in no drainage and consequently no nitrate loss. However, this would not be sustainable as salts would accumulate in the root zone.

POTENTIAL FOR USING ELECTROKINETICS FOR NITRATE MANAGEMENT: Greater attention now is focused on discovering ways to maintain agricultural production while minimizing undesirable environmental consequences. One of the avenues scientists are examining is the use of an electrical potential to manage chemical movement in soil. Electrokinetic processes have been found effective in removing chemicals from soils in research investigations and have also been used in commercial decontamination applications (Probstein and Hicks, 1993). Concentration and removal of nitrates from soils by electrokinetics depends on process effectiveness in moving nitrate ions to or retaining them near the anode (Acar *et al.*, 1992). In field lysimeter studies with a sandy loam soil Cairo *et al.* (1996) reported that nitrates were attracted towards the anode. In laboratory tests involving solute flow through sand columns, electrokinetics effectively attracted nitrates to the anode in saturated sand even with solution flow towards the cathode (Eid *et al.*, 1999).

A field study was recently conducted which developed in-situ electrochemical technique for managing nitrate movement in soils irrigated by a buried drip irrigation systems (Al-Rawahy *et al.*, 1999). The goal was to develop and test an electro-drip irrigation system which retained nitrate near the irrigation tube located just below the anode, thus maximizing nitrate utilization by crop (barley) while minimizing nitrate leaching into the groundwater. A secondary benefit of the system includes increased acidity and thus increased nutrient availability in the region near the drip tube. The system consisted of a buried drip irrigation tube with an embedded electrode (anode) and two cathodes that were equidistant from the anode and a DC power source. Tests compared plant nutrient uptake, and nitrate and pH distributions in the soil in replicated outdoor tests in 0.5 m^3 lysimeters. The results showed a greater nitrate content near the anode during the first month but the effect diminished during second and third months. The soil pH was lower near the anode during the second month. Similar studies are now being conducted in our laboratory. It is expected that this type of research will result in better nitrate management guidelines.

Conclusions

In the survey of groundwater wells, one third of the samples had high levels of NO_3-N. This indicates a serious pollution problem which is likely to be a health hazard for the people living in these areas who use groundwater as a source of drinking water. It was also found from a limited number of cores that agricultural soils have higher levels of nitrate compared to non-agricultural soils especially at lower depth. In selected wells, NO_3-N levels show on the average a rising trend. Considering the land use pattern and agricultural practices (high fertilizer and irrigation water usage), it is likely that agriculture may be the reason for the elevated levels of nitrate in groundwater. The LEACHN model can be used as a management tool to reduce nitrate leaching to groundwater. Reduction in fertilizer and water input, split application of fertilizers and cultivation of crops with higher rooting depth are some of the options that can be employed to reduce nitrate leaching.

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