Using geoinformatics to estimate nitrate leaching to groundwater in the Azraq Basin in Jordan due to human activities

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Abstract During the 20th century, the Bedu's environment was fragmented to form parts of Jordan, Syria, Iraq and Saudi Arabia. This process has restricted their nomadic way of life. In Jordan, the Bedu were encouraged to settle in newly built towns on the edge of the desert and to exercise irrigated agriculture. Groundwater contamination has recently been recognized as a problem in Jordan. This paper attempts to estimate nitrate leaching to groundwater in part of the Azraq Basin using Geoinformatics. Data were gathered from fieldwork, secondary sources and remote sensing. GIS was used to estimate nitrate leaching to groundwater from cesspools and agriculture. Estimated leaching from cesspools ranged from approx. 800 to 1990 kg year^{-1} (approx. 0.3 to 0.7 kg per household per year). The estimated loss from agricultural land was from approx. 222 600 to 358 800 kg year^{-1}. In Jordan, water resources are scarce and are being degraded, while the demand for water use is increasing. This study indicates the urgent need to manage the expansion of agriculture in the region.

Key words Azraq Basin, Jordan; cesspools; geoinformatics; groundwater; nitrate leaching

INTRODUCTION

For centuries, the nomadic people of Arab descent, the Bedu, dominated the Middle East desert, The Badia. The Bedu were practically self-sufficient and were reliant on wild natural grass for animal feed. The Bedu survived the hostile environment by migrating to find pastures and water for their herds of camels, sheep and goats in the Badia region, which now forms part of Jordan, Syria, Iraq and Saudi Arabia (Al-Oun, 2001; Baban *et. al*, 2003). The geographical division of Arabia into small states, particularly since the end of the First World War, resulted in the Bedu being separated from their land and other Bedu populations (Fig. 1) (Al-Rabia, 1974). Restrictions on movement have since played a key role in the decline of pastoral nomadism in the region. Consequently, the pressure on the environment and its resources has intensified in many parts of the Badia as traditional nomadic people have settled in small towns and villages (Baban *et al.*, 2003). The study area is located in the northern part of the Azraq Basin, Jordan, which lies within the basalt aquifer (Fig. 1). The area under investigation covers 867.4 km^2, which comprises around 18% of the total basalt aquifer area. This area was settled in the early 1990s by approx. 14 300 inhabitants who lived in 32 towns, villages and small settlements. The population of the study area is expected to exceed 28 000 in the year 2013 based on a 3.3% annual rate of growth (BRDP, 1994). The projected growth in population will continue to put pressure on the local natural resources. Irrigated agriculture in the study area began to expand in the early 1990s after a government decision to support irrigated agriculture as a form of employment (Al-Oun, 2001). All irrigation wells are drilled in the upper aquifer of the Azraq Basin (Dottridge, 1998; Al-Hussein, 2000). The majority of farmers cultivate crops such as tomatoes and watermelons, while other farmers cultivate olives and fruit trees (Waddingham, 1998; Al-Hussein, 2000). The irrigated agriculture season for vegetables starts in April and ends in late November, with only two months with no irrigation (December and January) (Waddingham, 1998; Millington *et al.*, 1999; Al-Hussein, 2000). Drip irrigation is the only method of distributing water to the crops in the study area (Waddingham, 1998). Farm size varies from around 10 ha to around 50 ha (Al-Hussein, 2000), while the size of the farms growing olives and fruit trees ranges from around 100 trees to more than 40 000 trees. The study area is classified as semiarid. Summer maximum daily temperatures often reach 35–38°C in August but rarely exceed 40°C. In winter, temperature rarely falls below freezing (Allison *et al.*, 1998; Millington *et al.*, 1999). Average precipitation varies between 50 mm in the south to 200 mm in the north and it occurs mainly between November and May (Al-Ansari & Baban, 2001). The study area is entirely within the basalt plateau which covers an area of 11×10^3 km^2 in the Northern Badia (Allison *et al.*, 1998). Soils in the study area include well developed xerochrepts on older basalt flows, with gypsitic and calcitic horizons, and weakly developed xerothents on the recent basalt flows and in the wadis (Allison *et al.*, 1998). Groundwater in the Azraq Basin, occurs in three aquifer complexes; Upper, Middle and Lower (Dottridge, 1998). The Azraq Basin supplies water for both domestic and agricultural sectors from the upper complex. It supplies Amman, Zarqa and Irbid, as well as villages within the Azraq Basin with drinking water (Al-Kharabsheh, 2000). Currently water withdrawal is well above the safe yield of 129%, leading to a decline in the water table (Gibbs, 1993; Al-Kharabsheh, 2000). These declines have increased the dissolved solids concentrations, causing an upward migration of more highly mineralized water into the aquifer (USGS, 2000). In the central part, water in the Amman-Wadi Sir system is mineralized and sulphurous and of generally poor quality, with total dissolved solids concentrations ranging between 800 and 2500 mg L^{-1}. In the western and northwestern part of the basin in the basalt system, the quality is good with total dissolved solids concentrations between 200 and 500 mg L^{-1} (USGS, 2000).

DATA COLLECTION

Fieldwork was carried out in late April 2000 to survey the existing agricultural activities and collect groundwater samples from wells in the study area. Information was also collected on the application of inorganic and organic fertilizers (i.e. sheep and chicken manure) (Al-Adamat, 2002).

Secondary data collected included:

(a) A digital elevation map with a 10 m interval contour interval at a scale of 1:50 000 obtained from the Jordan Badia Research and Development Programme (BRDP).

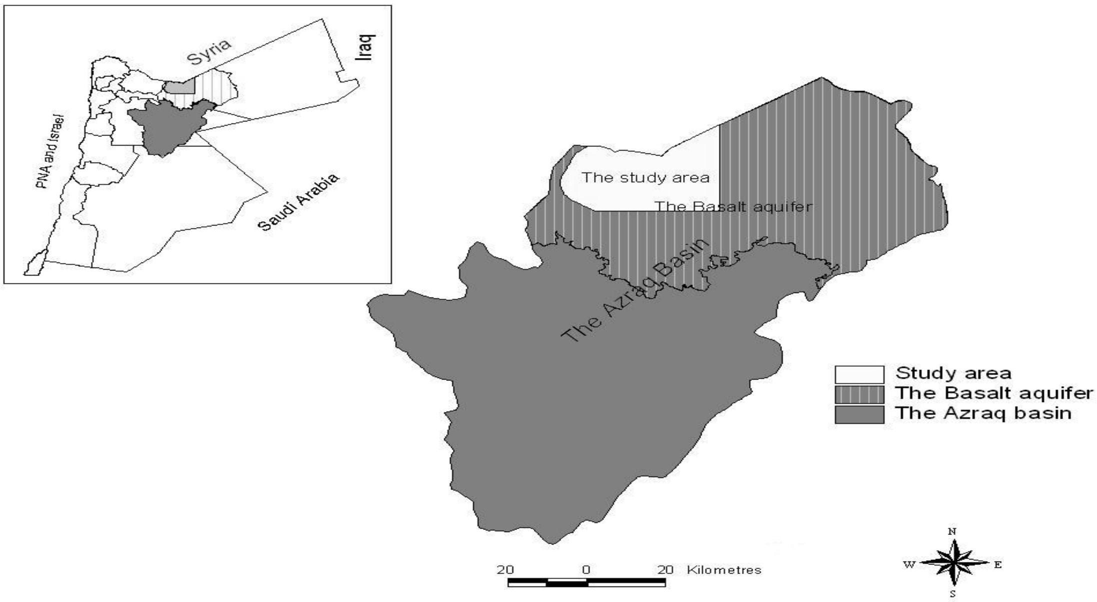

Fig. 1 The study area.

(b) A digital soil map at a scale of 1:50 000, obtained from BRDP.
(c) Depth to groundwater, obtained from the Water Authority of Jordan.
(d) A digital rainfall map, obtained from Jordan Ministry of Agriculture.
(e) A land use map dated 2000 and developed by using aerial photographs in an earlier study (Al-Adamat *et al*., 2004) (Fig. 2).

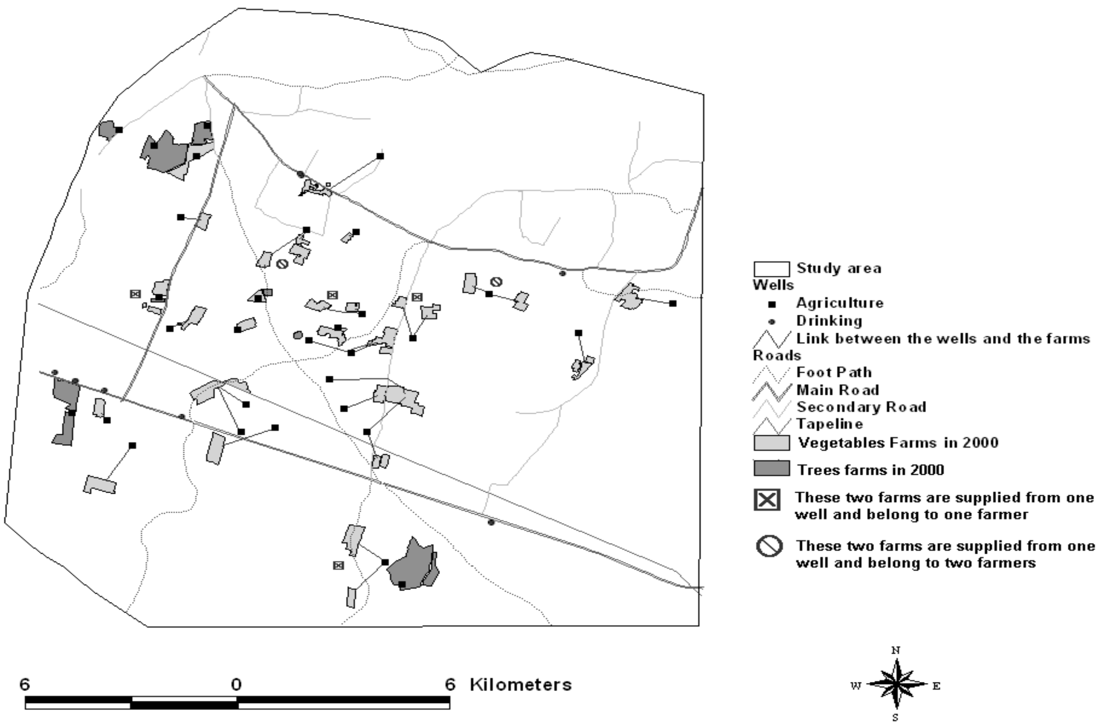

Fig 2 The agricultural activities in 2000 (after Al-Adamat *et al.,* 2004).

ANALYSIS AND RESULTS

A basic model was developed to estimate nitrate leaching based on that described by Gusman & Marino (1999). The model takes into consideration all potential sources supplying nitrate to the soil (rainfall, irrigation water, fertilizer application, cesspools), existing NO_3 in the soil before cultivation, and all nitrate losses (leached, plant uptake, nitrate decay, denitrification and volatilization) that occur in the environment. The model was based on the concept that the nitrate input (sources) should equal the nitrate output (losses)):

$$NO_3\,L = \{NO_3\,R + NO_3\,IR + NO_3\,SBC + NO_3\,F\} - \{NO_3\,PU + NO_3\,D\} \qquad (1)$$

where: *L*, leached; *R*, rainfall; *IR*, irrigation water; *SBC*, soil before cultivation; *F*, fertilizers (organic and inorganic); *PU*, plant uptake; and *D*, decay (denitrification and volatilization).

In the case of cesspools, equation (1) is modified as follows:

$$NO_3\,L = NO_3\,CP - NO_3\,D \qquad (2)$$

where: *CP*, cesspools; *D*, denitrification.

This modification results from the fact that in the study area, cesspools have an estimated depth of 2 m below the ground surface and, being below the rooting zone of most crops including grass, nitrogen is not available for plant uptake (Jordan *et al.*, 1994).

A conceptual model was developed to estimate nitrate leaching to groundwater from agricultural sources (Fig. 3). The nitrate amount (kg ha^{-1}) supplied by rainfall was calculated from equation (3) (modified from Jordan *et al.*, 1994).

$$NO_3(R) = \frac{NO_3(CR) \times R}{100} \text{ (kg ha}^{-1}\text{)} \ldots\ldots\ldots\ldots (3)$$

where *CR* is concentration of NO_3 in rainwater (mg L^{-1}), and *R*, rainfall amount (mm).

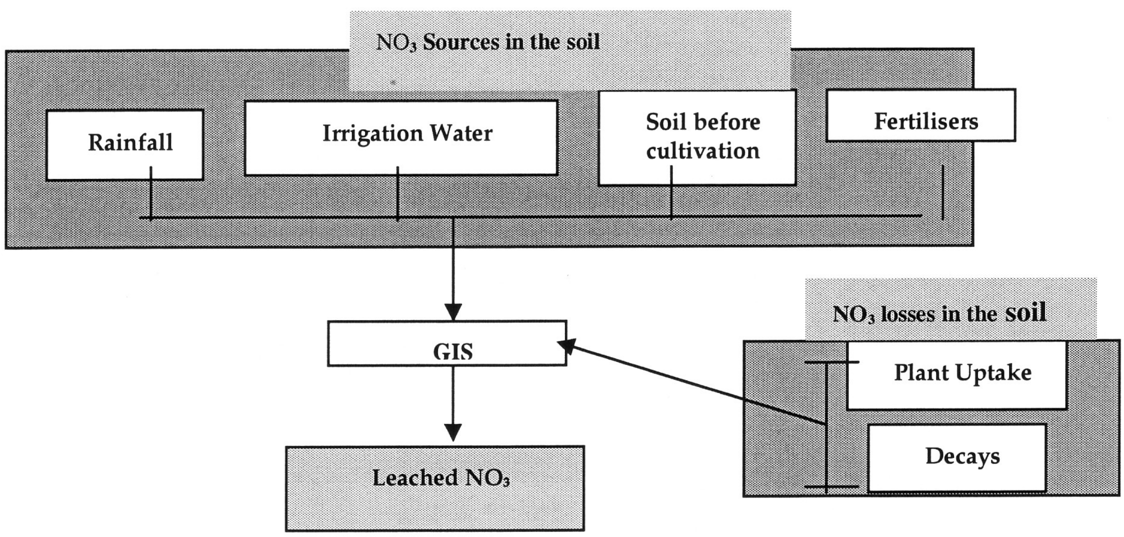

Fig. 3 The conceptual model used to estimate nitrate leaching from agricultural land.

Rainfall data for the period from April 2000 to May 2001 were calculated from data for the three stations covering the study area. Areal rainfall was calculated using the Areal Rain Extension in ArcView GIS, which uses the Thiessen method (Ward & Robinson, 2000). Equation (3) was then applied to the attribute file of this map. The amount of nitrate (NO_3) in the study area derived from rainfall was estimated to be between approx. 5.5 kg ha^{-1} and 6.75 kg ha^{-1}.

Since all farming activities in the study area depend on groundwater for irrigation, the nitrate concentration in the water was assumed to be one of the major sources of nitrate in the soil that might be leached back to groundwater. The NO_3 concentrations (mg L^{-1}) for irrigation wells were measured on field samples. Waddingham (1994) estimated the amount of water abstracted in 1994 for irrigation was approx. 6.3×10^6 m^3 which was used to irrigate 482 ha (approx. 13 070 m^3 ha^{-1}). It was also estimated that the cultivated area needed only 3.8×10^6 m^3 (approx. 7884 m^3 ha^{-1}) if farmers used the optimum amount of water for irrigation. In this research, both values were used to estimate the amount of nitrate from irrigation water based on optimum and excessive water usage. The amount of nitrate (kg ha^{-1}) supplied by irrigation water was calculated using equation (4):

$$\mathrm{NO}_3(IR) = \mathrm{NO}_3(CIR) \times IR \times 10^{-3} \;\; (\text{kg ha}^{-1}) \qquad (4)$$

where *CIR*, concentration of NO_3 in irrigation water (mg L^{-1}); *IR*, amount of irrigation water (m^3 ha^{-1}).

The agriculture map for 2000 (Fig. 2) was updated with both estimates of irrigation water (m^3 ha^{-1}) and the nitrate concentrations of the well water that supplied each farm in 2000. Equation (4) was then used to calculate the nitrate volume added to the soil (kg ha^{-1}) based on the estimated optimum usage of irrigation water (Fig. 4) and the nitrate added if farmers had used excessive irrigation as estimated by Waddingham (1994). The latter showed a range of values of 64.4–274.6 kg ha^{-1}.

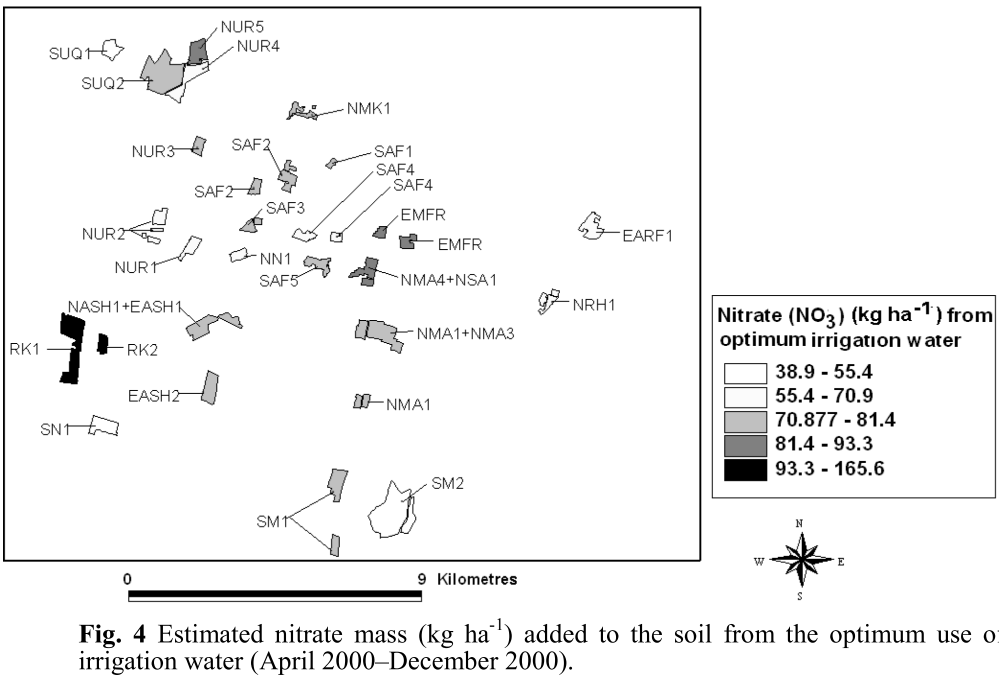

Fig. 4 Estimated nitrate mass (kg ha^{-1}) added to the soil from the optimum use of irrigation water (April 2000–December 2000).

The amount of nitrate in the topsoil before cultivation was calculated as follows:

$$NO_3(SBC) = NO_3(CSBC) \times B \times 10^4 \text{ (kg ha}^{-1}\text{)} \quad (5)$$

where *CSBC* is concentration of NO_3 in the soil before cultivation (kg kg^{-1} soil) and *B* is bulk density of the soil (kg m^{-3}).

The nitrate (NO_3) concentrations in water extracted from two soil sampling sites were used in equation (5). Both samples represented natural soil (uncultivated before). One was located in a silt loam soil and the other in clay loam soil. In ArcView GIS, the attribute file of the soil map was updated with bulk density values and nitrate concentrations (kg kg^{-1} soil) based on the assumption that all soil units that have a silt loam texture had 0.4 mg L^{-1} of nitrate if sampled for the topsoil and all soil units that have a clay loam texture had 1.7 mg L^{-1} of NO_3 in the topsoil. The results map showed that available NO_3 in the topsoil before cultivation was between approx. 1.3 and 5.7 kg ha^{-1}. The amount of nitrate from the application of fertilizers was estimated from interviews with local farmers. Nitrogen N in applied inorganic fertilizers has three forms, N, NO_3 and NH_4. In this model, it was assumed that the total amount of nitrogen (Nt) had been transformed to nitrate. Once more, the agriculture activities map of 2000 was updated with the nitrate estimates in the applied fertilizers and results ranged from 156 to 3685 kg ha^{-1}. The amount of organic fertilizers (e.g. sheep and chicken manure) used by each farm was also obtained from interviews. Assuming that only one third of the nitrogen found in organic manures was transformed into nitrate and made available for plant uptake, the nitrogen values were calculated for each farm. The range relating to sheep manure was 3448–16 000 kg ha^{-1}, while that derived from chicken manure ranged from 1700 to 10 000 kg ha^{-1}.

Plant uptake was based on values taken from Finck (2000) where the estimated nitrate uptake by plants was found for several crops (e.g. tomato and watermelon). Based on the data collected about crop type in the study area for each farm, the average plant uptake was calculated using equation (6):

$$APU = \frac{\sum_{n=1}^{N} A_n \times PU_n}{A} \text{ (kg ha}^{-1}\text{)} \quad (6)$$

where *APU*, average plant uptake; A_n, area of crop n (ha); and PU_n, plant uptake for crop (in kg ha^{-1}).

Equation (6) was applied to the farm map after updating its attribute file with crop type, crop area and plant uptake for each crop. The results indicated that the average plant uptake of NO_3 (kg ha^{-1}) for farms growing olives and fruit trees ranged from 68 at farm RK1 to 429 at farm SM2, while average plant uptake of NO_3 (kg ha^{-1}) for vegetable farms ranged from 331.4 at farm EMFR to 821 429 at farms NMA4 and NSA1.

Denitrification and volatilization were assumed to be the only decay processes affecting inorganic fertilizers in the agricultural lands. Table 1 illustrates the denitrification rates from the applied fertilizers as estimated in a review published by Rolston (1981). Based on these data, it was assumed that the denitrification rate in the study area was approx. 20%, which is approximately the average value from these estimates. This percentage was subtracted from the applied inorganic fertilizers within the GIS. The volatilization rate for three types of fertilizers used in the study area. was also estimated from FAO (2001) statistics as shown in Table 2.

Table 1 Estimated denitrification rates (based on Rolston, 1981).

Denitrification value (%)	Notes
10–30	
22	If applied fertilizer is 224 N kg ha^{-1}
45	If applied fertilizer is 300 N kg ha^{-1}
15	If applied fertilizer is 335 N kg ha^{-1}

Table 2 Estimated volatilization losses (based on FAO, 2001).

Fertilizer name	Estimated volatilization losses (%)
UREA ($(NH_2)_2CO$)	10
MAP (mono ammonium phosphate)	15
NH_4NO_3 (ammonium nitrate)	2

The estimated nitrate leaching from agricultural lands was based on having two scenarios. These scenarios take into consideration the fact that there are two irrigation water schemes: optimum (SA1) and excessive (SA2). All nitrate inputs and losses were calculated in ArcView GIS to produce the estimated nitrate leaching to groundwater in both the tree and vegetable farms as shown in Tables 3 and 4. Based on a field survey, Waddingham (1994) estimated the actual per capita water demand for the study area of approx. 115 l day^{-1}. It was estimated in an earlier study (Al-Adamat *et al*., 2003) that the average family size in the study area is approx. six, which gives a

Table 3 Estimated nitrate leaching from the tree farms (kg ha^{-1}).

Farm code	Scenarios SA1 (kg ha^{-1})	SA2 (kg ha^{-1})	Farm code	Scenarios SA1 (kg ha^{-1})	SA2 (kg ha^{-1})
NUR4	144	187	SM2	25	61
NUR5	277	333	SUQ1	644	669
RK1	865	974	SUQ2	97	151

Table 4 Estimated nitrate leaching from the vegetable farms (kg ha^{-1}) (*S5 soil sample location; †S1 soil sample location).

Farm code	Scenarios SA1 (kg ha^{-1})	SA2 (kg ha^{-1})	Farm code	Scenarios SA1 (kg ha^{-1})	SA2 (kg ha^{-1})
EARF1	3116	3162	NUR2†	295	341
EASH2	2729	2780	NUR3	765	812
EMFR	4598	4659	NUR4	2608	2651
NASH1+EASH1	1453	1501	NUR5	384	440
NMA1	356	407	RK2	1483	1570
NMA1+NMA3*	685	737	SAF1	351	404
NMA2	2046	2095	SAF2	743	793
NMK1	1202	1250	SAF3	1362	1412
NN1	1926	1968	SAF4	1735	1780
NRH1	895	938	SAF5	2126	2178
NSA1+NMA4	277	334	SM1	3309	3357
NUR1	2973	3015	SN1	121	158

daily water consumption of approx. 690 L per family. It was assumed that only approx. 10% of that water would reach the cesspool on a daily basis. This meant that the water input to the cesspool is approx. 4 m^3 $month^{-1}$. It was also identified that the estimated cesspool size is approx. 8 m^3, which means that without drainage or evaporation the cesspool would be full in two months. For this research, evaporation was assumed negligible as the ventilation hole in the cesspools is too small (approx. 10 × 10 cm) to have a major evaporation loss. Equation (2) was modified to estimate nitrate leaching to groundwater based on the period needed to empty the cesspool:

$$\mathrm{NO_3}(L) = \frac{\mathrm{NO_3}(C) \times NC \times (NM - 2) \times 48 \times 10^{-3}}{NM} \quad (7)$$

where *L*, leached; *C*, concentration in sewage (mg L^{-1}) after denitrification, *NC*, number of cesspools and *NM*, number of months needed to empty the cesspools.

The constant (48) is the estimated consumed water that can reach the cesspool in a 12-month period. This equation is valid only when the period needed to empty the cesspools is 3, 4, 6 or 12 months. It appears from this equation that if the house owner emptied the cesspool every two months, there would be little or no nitrate available for leaching. It would be assumed that the difference between the cesspool size and the water that goes into the cesspool in any period spent after the two months is groundwater recharge (together with its nitrate).

Three scenarios were evaluated in this research project using equation (7). These were a low, medium and high risk scenario, where it is assumed that the cesspool will be emptied every three months, every six months and once every year, respectively. The total nitrogen in sewage before treatment is approx. 40 mg L^{-1} of which 15 mg L^{-1} is organic N and the remaining 25 mg L^{-1} is ammoniacal (NH_4+NH_3) nitrogen and there is no nitrate nitrogen (Schroeder, 1981). Schroeder (1981) explained the absence of nitrate in sewage as a result of the lack of oxygen in the sewer system and the short reaction times. In Jordan, the only available data for nitrate levels in sewage was for the Aqaba Treatment Plant (ATP). According to Salameh & Bannayan (1993) the nitrate concentration at the inlet of the ATP was approx. 11.2 mg L^{-1}. The maximum concentration recorded in this plant during the treatment process was approx. 34 mg L^{-1}, which might have resulted from the nitrification process. It was also found that the nitrate concentration at the outlet of ATP was approx. 18 mg L^{-1}, which could result from denitrifying the nitrate in the plant. In this research project, it was assumed that the nitrate concentration in the cesspools after denitrification was approx. 18 mg L^{-1}. In order to apply equation (7), Fig. 2 was updated with the estimated nitrate concentration in sewage and the estimated number of cesspools in each village. In ArcView GIS, equation (7) was applied to calculate the volume of nitrate available in each village based on the above scenarios. The results of this operation are shown in Table 5. The total estimated amount of leached nitrate in the study area supplied from cesspools was estimated to lie between approx. 796 and 1989 kg $year^{-1}$ (approx. 0.3 to 0.7 kg $household^{-1}$ $year^{-1}$). Table 6 shows that the highest estimated nitrate leaching occurred in Abu Al-Farth, Al-Mukayfita, Ar-Rifa'iyyat, Qasim, Dayr Al-Kahf, Jubaya and Um Al-Quttain in the northern part of the study area. In the southern part also (on the main Road to Baghdad), villages like Rahbat Racad, Nifeh, Al-Sa'ada, Al-Manareh, Hulaywat Al-Masarheh, Hamra Al-Suhaym and Al-Bishriyya have a high value of

Table 6 The estimated leached nitrate (kg year^{-1}) in each village based on three scenarios; SC1, cesspool is emptied every 3 months; SC2, cesspool is emptied every 6 months and SC3, cesspool is emptied every 12 months.

Village name	Scenarios			Village name	Scenarios		
	SC1	SC2	SC3		SC1	SC2	SC3
Abu Al-Farth	32.3	64.5	80.6	Dayr Al-Qinn	7.8	15.6	19.4
Al-Ashrafiyya	35.1	70.3	87.8	Gadir Al-Naqa	0.9	1.7	2.2
Al-Bishriyya	42.6	85.2	106.6	Hamra Al-Suhaym	25.6	51.3	64.1
Al-Hashimiyya	2.3	4.6	5.8	Hulaywat Al-Masarheh	36.0	72.0	90.0
Al-Jada'a	5.8	11.5	14.4	Jubaya	32.8	65.7	82.1
Al-Ma'azula	5.8	11.5	14.4	Khisha'a Al-Qinn	7.5	15.0	18.7
Al-Manareh	43.2	86.4	108.0	Manshiyyat Al-Qin	12.1	24.2	30.2
Al-Mansura	2.6	5.2	6.5	Midwar Al-Qinn	8.4	16.7	20.9
Al-Mukayfita	96.2	192.4	240.5	Mithnat Rajil	8.6	17.3	21.6
Al-Munaysa	11.8	23.6	29.5	Nifeh	30.2	60.5	75.6
Al-Muraygip	2.3	4.6	5.8	Qasim	26.2	52.4	65.5
Al-Sa'ada	25.9	51.8	64.8	Rahbat Racad	23.3	46.7	58.3
Al-Suwaylima	1.2	2.3	2.9	Tall Al-Rimah	16.4	32.8	41.0
Ar- Rifa'iyyat	30.8	61.6	77.0	Um Al-Quttain	150.9	301.8	377.3
Ar-Rifa'iyyat Ash-Shamalyya	6.9	13.8	17.3	Um Hussein	7.8	15.6	19.4
Ar-Rnibat Al-Na’yemat	2.9	5.8	7.2	*Min.*	1.2	2.3	2.9
				Max.	96.2	192.4	240.5
Ath-Thalaj	4.3	8.6	10.8	*Mean*	22.3	44.6	55.7
Dayr Al-Kahf	49.2	98.5	123.1	*SD*	25.0	50.0	62.5

estimated nitrate leaching to groundwater. The distribution of these villages over a large area increases the risk of having both chemical and biological groundwater contamination problems.

CONCLUSIONS

Nitrate leaching to groundwater was investigated and two sources of nitrate were examined; cesspools and irrigated agriculture. In the agricultural lands, the estimated amount of leached nitrate from several sources was evaluated. This included rainfall as well as irrigation water under optimum and excessive use by farmers. These sources of nitrate also included what existed in the soil before cultivation. Organic manure and inorganic fertilizers, together with the irrigation water, were found to be the major sources of nitrate in the study area. The nitrate losses in this model included denitrification, decay through volatilization and plant uptake. The outcome showed that the estimated nitrate leaching from the agricultural lands ranges between 121 and 4598 kg ha^{-1} if farmers used an optimum amount of irrigation water and between 158 and 4659 kg ha^{-1} if farmers used an excessive amount of irrigation water. Nitrate leaching from cesspools was examined on the basis of three scenarios. The results showed that the estimated nitrate loading from cesspools varied from one village to another in conjunction with the population density. Estimates varied between 1.2 and 240.5 kg year^{-1}. It was also found that nitrate leaching from agricultural lands was much higher than that predicted from the cesspools.

In conclusion, it seems that both agricultural lands and cesspools pose a threat to future groundwater quality in the study area. Although in watersheds A, B and C, the estimated nitrate leaching from the agricultural sources is very high when compared to the leaching from the cesspools, the cesspools are also considered a high risk to groundwater quality especially because biological (bacterial/viral) contamination could also result from this source. Fertilizer application is not supervised by any advisory services. Finally, although the groundwater is relatively deep, care should be taken when siting developments in these areas due to the importance of the basalt aquifer as a groundwater resource for drinking water supply for the local population and the major cities of Jordan.

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