Modelling Nitrate Leaching in the Azraq Basin/ Jordan Using GIS

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Abstract

Jordan is a country that faces "absolute water scarcity" and may not be able to meet its water needs by the year 2025. Groundwater is the major water resource for many areas of the country and the only source of water in some areas. Most of the groundwater basins in Jordan are already exploited beyond their estimated safe yield. Total safe yield for all basins was estimated to be *ca.* 418.5×10^6 m^3 yr^{-1} yet the consumed water from these basins was 479×10^6 m^3 yr^{-1}. Groundwater is the second largest contributor to the irrigation sector at 258.4×10^6 m^3 yr^{-1} and it is the largest source for domestic consumption at 182.8×10^6 m^3 yr^{-1}.

A variety of human activities stemming from agricultural, industrial, community and residential sources, as well as the misuse of groundwater resources, have contributed to the deterioration of groundwater quality in Jordan. Since the early 1990's, the Jordanian government has encouraged drilling private wells in the Northern part of the Azraq basin to irrigate agricultural land by providing low cost loans to farmers.

Focusing on this area, this paper attempts to produce a GIS-based model to estimate nitrate leaching from cesspools and agricultural land. It was found that nitrate leaching from agricultural sources was much higher than that derived from cesspools. It was estimated that *ca.* 0.3 to 0.7 kg $household^{-1}$ $year^{-1}$ could leach to groundwater from cesspools in the study area. The estimated nitrate leaching from agricultural sources could reach up to 483,281 kg $year^{-1}$.

Several management scenarios were implemented within a GIS environment to minimise nitrate leaching from both cesspools and agricultural fields. It was estimated that emptying the cesspools on regular basis (*ca.* 2 months) could minimise or eliminate nitrate leaching from this source. Farmers could use information on available nutrient concentrations in the soil, irrigation water and organic manures to estimate the optimum fertiliser requirement. This scenario could reduce nitrate leaching by up to 99%.

Other scenarios were suggested in order to minimise nitrate leaching from cesspools that included better design criteria and the possibility of constructing a local sewage treatment plant in the area.
Keywords: Jordan, Groundwater, Nitrate, GIS, Modelling

Introduction

Jordan is a country that faces "absolute water scarcity" and may not be able to meet its water needs by the year 2025 (Al-Adamat, 2002). Groundwater is the major water resource for many areas of the country and the only source of water in some areas. Most of the Groundwater basins in Jordan are already exploited beyond their estimated safe yield. Total safe yield for all basins was estimated to be *ca*. 418.5×10^6 m^3 yr^{-1} yet the consumed water from these basins was 479×10^6 m^3 yr^{-1}. Groundwater is the second largest contributor to the irrigation sector at 258.4×10^6 m^3 yr^{-1} and it is the largest source for domestic consumption at 182.8×10^6 m^3 yr^{-1}. The Azraq basin is one of the largest groundwater basins in Jordan with an area of more than 12,000 km^2. It supplies fresh drinking water to the major cities in Jordan and towns within the basin.

A variety of human activities stemming from agricultural, industrial, community and residential sources, as well as the misuse of groundwater resources, have contributed to the deterioration of groundwater quality in Jordan. There are three types of pollution that affect groundwater (i) use and overuse of biocides and fertilisers and irrigation return flows, (ii) cesspools in towns, villages and refugee camps and (iii) use of vehicles with oil spills, lead and corroded particles (Al-Adamat ,2002) .

Nitrate is often considered to be a major threat to groundwater quality because nitrate dissolves freely in water and is not held on the soils particles (Addiscott *et al.*, 1991) due to its negative charge (Stauffer, 1998). Therefore, nitrate is most likely to leach into groundwater (Stauffer, 1998) by rain or irrigation water passing through the soil down to the groundwater (Addiscott *et al*., 1991).

The major sources of nitrate in groundwater include soil nitrogen, nitrogen–rich geologic deposits, and atmospheric deposition (Evans and Maidment, 1995). Nitrate could also be sourced in groundwater from fertilisers, septic tank drainage, feedlots, dairy and poultry farming, land disposal of municipal and industrial wastes, dry cultivation of mineralized soils, and the leaching of soil as a result of the application of irrigation water (Evans and Maidment, 1995). During the last two decades, many cases of groundwater contamination from extensive application of fertilizer in watershed developed for agricultural purposes have been reported worldwide (Shamrukh, *et al*., 2001). According to Supalla *et al*., (1995), nitrate pollution from agricultural fertilisers is the most serious and widespread threat to groundwater quality. There are several types of inorganic fertilisers on the market these days, which provide farmers a wide range of choice that suite their crops, soil type and environment. These fertilisers have been developed in order to meet the high nutrient requirement of crops and to supplement available soil nutrients (Finck, 2000).

The use of GIS technology covers a wide range of applications such as agricultural, land use planning, municipal applications, global scale applications (Ahn and Chon, 1999), and Modelling and management of the natural environment (Burrough, 1986). GIS has been used in many aspects of groundwater management and Modelling (Merchant, 1994). According to Mitasova and Mitas (2002), the use of GIS for environment Modelling has increased over the last few years, moving from research to routine applications. The combination of map algebra operations and GIS functions make it relatively easy to implement simple models within GIS. Such an advantage in GIS has made it possible for several research projects to investigate and quantify nitrate leaching to groundwater from various sources in many parts of the world. For example, GIS was used to assess the spatial variability of NO3 leaching from the root zone from fertilizer applications in Rhode Island, USA (Görres and Gold, 1996), to predict nitrate leaching to groundwater in southern Germany (Rodda, et al., 1999) and to estimate nitrate leaching from agricultural lands and septic tank systems in Northern Ireland (Jordan *et al,*. 1994). The researchers argued that their research had demonstrated the application of GIS to predict nitrate leaching to groundwater.

This paper is an attempt to develop a methodology for estimating nitrate leaching to groundwater in the Northern part of the Azraq basin from both agriculture sources and cesspools using GIS techniques. Also, this paper will be an attempt to suggest sound management scenarios to minimize the possibility of groundwater contamination.

The Study Area

The study area is located in the Northern part of the Azraq basin with an area of 867.4 km^2 (Figure 1). In 1993, the total population of the study area was 13,189 living in 33 towns, villages and small settlements (BRDP, 1994) (Figure 2). The population is expected to be 21,464 and 25,247 in the years 2008 and 2013 respectively, based on a 3.3% annual population growth rate (Maani, Hunaiti, & Findlay, 1998).

The climate of the study area is generally characterized by its hot dry summers and cold winters. The area is classified as semi-arid based on its climatic characteristics (Salameh, *et a*l., 1997). It falls within an area recognized to be a transition zone between the environment of the Jordan valley and the arid interior desert areas of eastern Jordan. Also, it is characterized by low precipitation and high potential evaporation (Allison *et al*, 1998). The duration of rainfall in winter is short with high intensity that mainly generates runoff (Al-Adamat, 2002).

The study area is located within the Basalt area of the Northern Badia of Jordan. The basalt eruptions in the Northern Badia are of different ages and appear on the surface in the north and northeast and extend northwards to cover an area of 11×10^3 km^2 (Allison *et al*., 1998, Al-Tarawneh, 1996). The basalt eruptions from what is known as the "Basalt Plateau", which is related to the North Arabian Volcanic province (Al-Adamat *et al*., 2004).

The soils in the study area (Figure 3) are in general characterized by being shallow and saline with little organic material and are associated with the North Jordan basalt plateau. Soils 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 (Al-Adamat, 2002, Al-Adamat *et al*., 2004). The percentage of clay in all soil units in the study area varies between 25.9 and 26.7%, silt percentage is between 44 and 50.2% and sand is between 21.3 and 28.7%, while the organic matter varies between 1.21 and 1.22% (Al-Adamat, 2002, Al-Adamat *et al*., 2004).

Irrigated agriculture in the study area started in the early 1990's after a government decision to allow wells to be dug in order to start cultivating the land in areas close to the Syrian borders (Kirk, 1998). All irrigation wells in the study area are drilled in the upper aquifer of the Azraq basin and within the basalt area (Dottridge, 1998, Al-Hussein, 2000). The majority of farmers cultivate vegetables such as tomato and watermelon, as they claim that it generates a rapid profit (Kirk, 1998), while other farmers cultivate Olive and fruit trees (Waddingham, 1998; Al-Hussein, 2000). The irrigated agricultural season (vegetables only) starts in April and end in late November with only two months with no irrigation (December and January) (Al–Hussein, 2000; Millington *et al*., 1999; Waddingham, 1998). Drip irrigation is the only method used to distribute water to the crops in the study area (Waddingham, 1998). Farm size varies from one farm to another where vegetable farms range from *ca*. 10 ha to *ca*. 50 ha (Al-Hussein, 2000); while the size of the tree farm range from *ca* .100 trees to more than 40,000 trees (Figure 4).

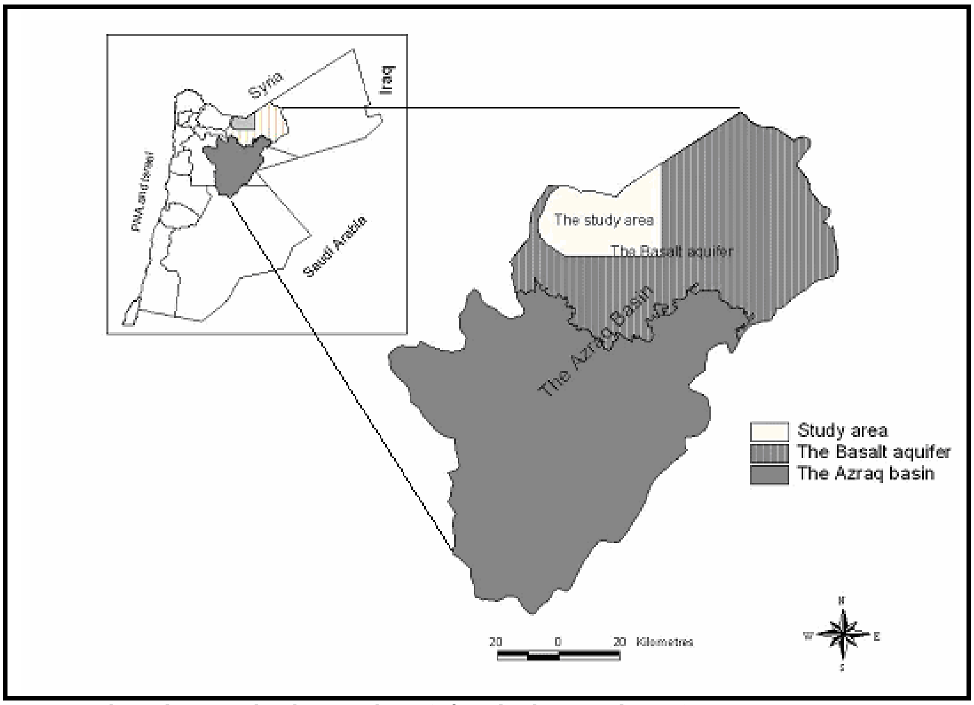

Figure 1. The study area within the Azraq basin (After Al-Adamat, et al., 2004)

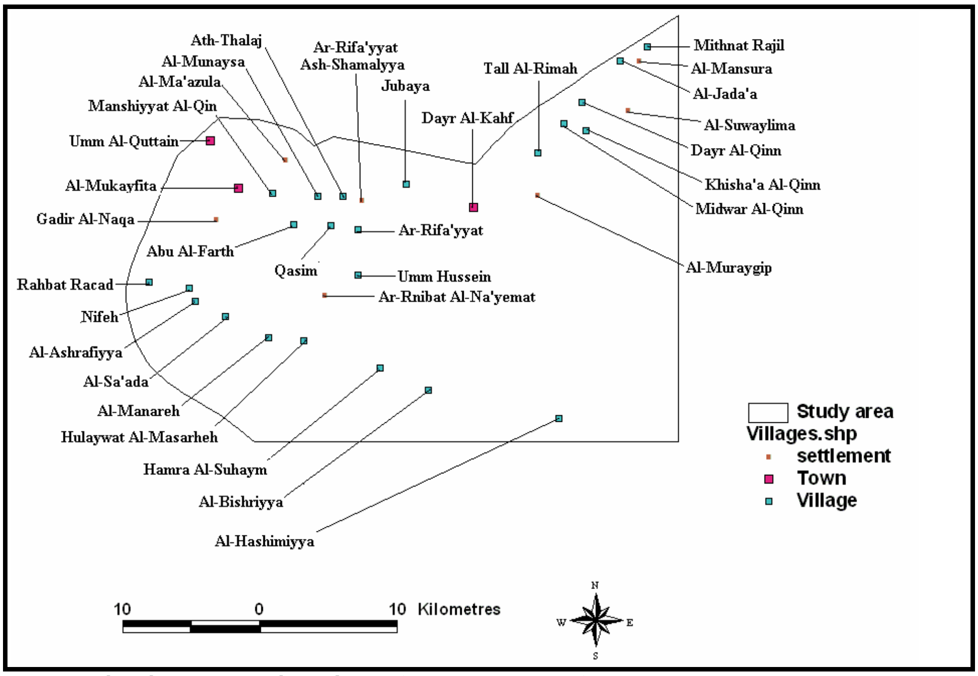

Figure 2. The urban centres in the study area (Source, BRDP, 1997)

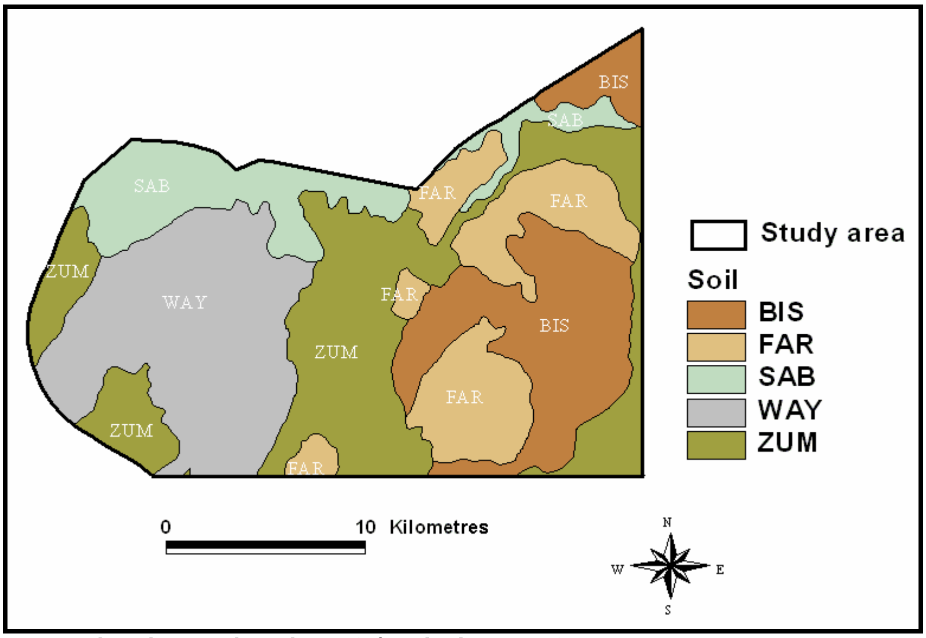

Figure 3. The soil units in the study area (After Al-Adamat, 2002).

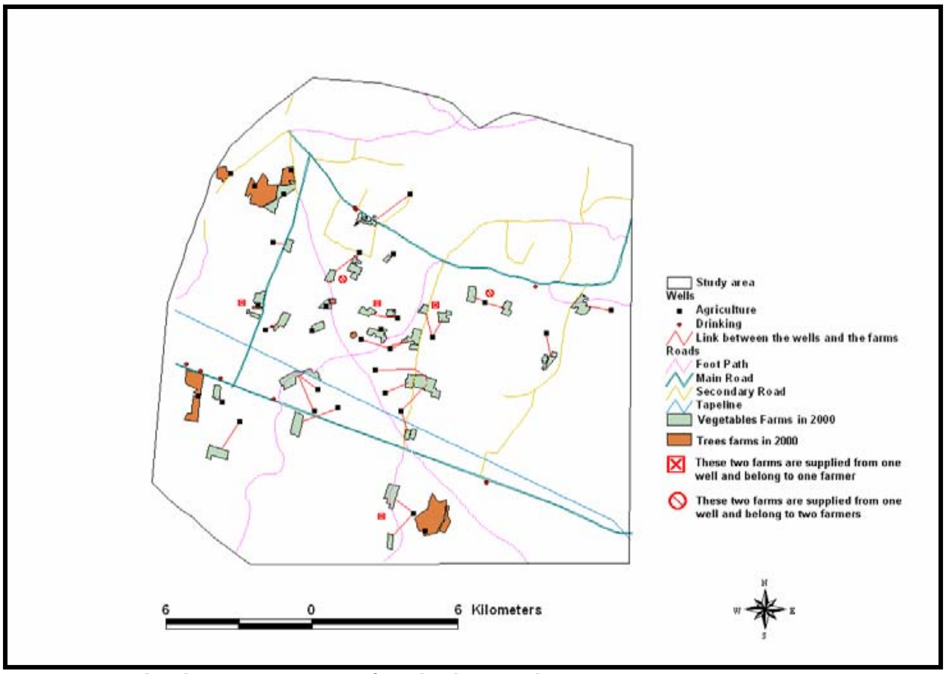

Figure 4. Agricultural activities in 2000 (After Al-Adamat et al., 2004)

Model Design

The model was based on design described by Gusman and Marino (1999). The model takes into consideration all potential sources supplying nitrate to the soil and all nitrate losses that occur in the environment. These sources include:

(1) Rainfall,
(2) Irrigation water,
(3) Fertilizer applications,
(4) Existing NO_3 in the soil before cultivation (The existing NO_3 in the soil before cultivation represents the amount of organic-N that had been converted to nitrate through the process of mineralization) and
(5) Cesspools

Losses of nitrate were defined as:

(1) Leashed,
(2) Plant uptake, and
(3) Nitrate decay (denitrification and volatilization).

The model was based on the fact that the nitrate input (sources) should equal the output (losses) (Equation 1: For agricultural lands: After Al-Adamat, 2002).

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

Where: L: Leached, R: Rainfall, IR: Irrigation water, SBC: Soil before cultivation, F: Fertilisers (organic and inorganic), PU: Plants Uptake, and D: Decay (Denitrification and volatilization).

Figure 5 illustrates the conceptual model designed to estimate nitrate leaching to groundwater from agricultural sources.

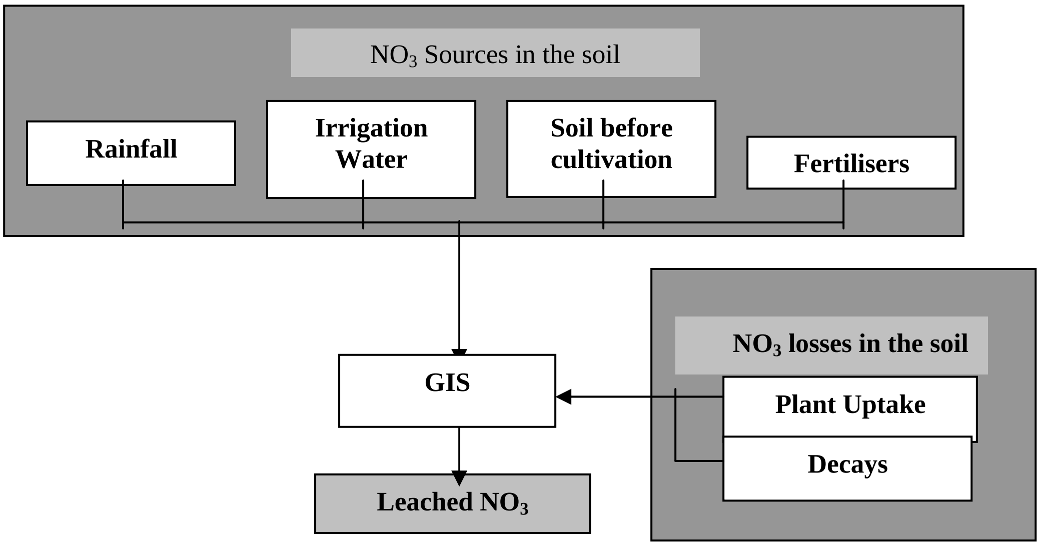

Figure 5. The conceptual model used to estimate nitrate leaching from agricultural land.

In the case of Cesspools, Equation 1 was modified as follow in Equation 2 (After Al-Adamat, 2002):

$$NO_3L = NO_3CP - NO_3D \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where CP: Cesspools, D: Denitrification

This modification results from the fact that cesspools have an estimated depth of 2m below the surface (Figure 6) and, being below the rooting zone of most crops including grass, nitrogen is not available for plant uptake (Jordan *et al.* 1994).

Data Collection

In order to provide quantitative information to estimate the nitrate leaching to groundwater, a fieldwork was carried out to collect groundwater samples from all wells used for irrigation purposes to find their nitrate concentration in April, 2000. Also, in May ,2001 another fieldwork was conducted to collect soil samples from six different locations in the study area (two in uncultivated lands , two in abandoned farms and two in existing farms in 2001), were nitrate level was measured for three different depths (0-10 cm, 40-50 cm and 90-100 cm). A rainwater sample was collected from a rainfall event that occurred during April, 2001 and it was also subject to chemical analysis to find the nitrate concentration. Farmers were interviewed to collect information about crops they cultivate, the amounts and types of organic and inorganic fertilisers used in their farms. Chemical fertilisers producers and dealers were interviewed to collect the required information about the chemical composition of their products. Other data such as the agricultural land use, rainfall and soil maps were acquired from Al-Adamat, (2002), Al- Adamat, *et a*l., (2004) and the Royal Jordanian Geographic Centre (1994) (Table 1).

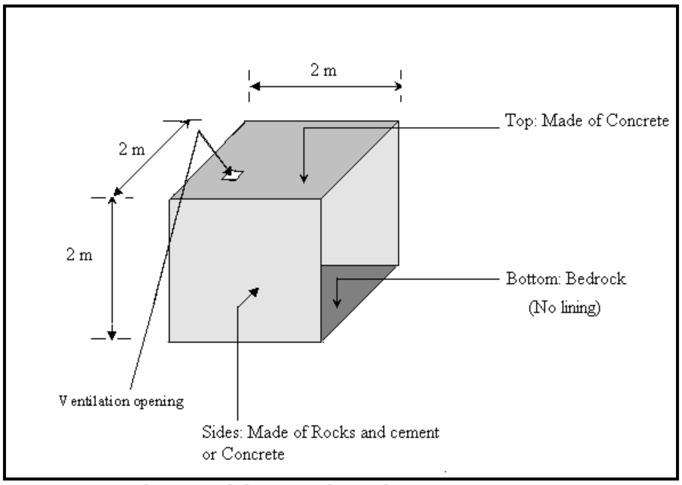

Figure 6. Typical Cesspool design in the study area

Table 1. The secondary data used in this research

Map type	Year of survey	Format	Original scale	Source
Agricultural land use	2000	GIS	1:25,000	Al-Adamat,(2002), Al-Adamat, *et al.*, (2004)
Soil map	1994	GIS	1:50000	Royal Jordanian Geographic Centre
Rainfall data	2001	Excel		Al-Adamat, (2002)

GIS Analysis
1. Nitrate input in agricultural lands
1.1. Rainfall

The nitrate volume (kg ha^{-1}) supplied by rainfall was calculated from Equation 3 (modified from Jordan *et al.* 1994).

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

Where CR: concentration of NO_3 in rainwater (mg l^{-1}), and R: Rainfall amount (mm)

Rainfall data were available from two daily weather stations and three TOTALISER rain gauges (Al-Adamat, 2002) (Figure 7). The rainfall data needed to use this model was for the period from April 2000 to May 2001. Unfortunately, rainfall data were not available from the Dayr Al-Khaf station for this period. Data from the Um Al-

Quttain station covered only the first three months of 2000 (January to March). The other three stations at Abu Al-Farth, Al-Bishriyya and Mathnat Rajil covered the period from April 2000 to April 2001. Rainfall in the area falls in the months of October, November, December, January, February, March and April (Al-Adamat, 2002) which means that these three stations covered the required period. An assumption was made to estimate the rainfall at the Dayr Al-Kahf station based on the locality of this station in relation to the three other stations. The location of Dayr Al-Khaf is between Mathnat Rajil to the north east (*ca.* 17 km) and Abu Al-Farth to the west (*ca.* 13 km) and Al-Bishriyya to the south (*ca.* 14 km). The rainfall at this station was assumed to be the average rainfall value of these three stations (*ca.* 93 mm). The rainfall amount at the Um Al-Quttain station for the period April 2000 to May 2001 was assumed to be equivalent to the amount of rainfall at Abu Al-Farth (*ca.* 8 km to the East). This gave Um Al-Quttain station an estimated rainfall for the whole period of *ca.* 82 mm.

The methodology of mapping the rainfall distribution for the study area was based on the Thiessen method. According to Ward and Robinson, (2000), the Thiessen polygon method is better than the mean for calculating the areal rainfall because it allows for a non-uniform distribution of rainfall gauges by assigning weights to the measured depths at that gauge. This method involves the connection of the stations on the map by lines. Perpendicular bisectors are drawn to the lines connecting the stations, which generate polygons around each station. Each polygon represents the effective area of each station (ISESCO, 1997).

The ArealRain Extension (downloadable at http//:www.esri.com) in ArcView GIS was used to calculate precipitation for the area using the Thiessen Polygon method. Equation 3 was then applied to the attribute file of this map. The outcome of this operation is shown in Figure 8, which shows that the amount of nitrate (NO_3) in the study area from rainfall varied between *ca.* 5.5 kg ha^{-1} and 6.75 kg ha^{-1}.

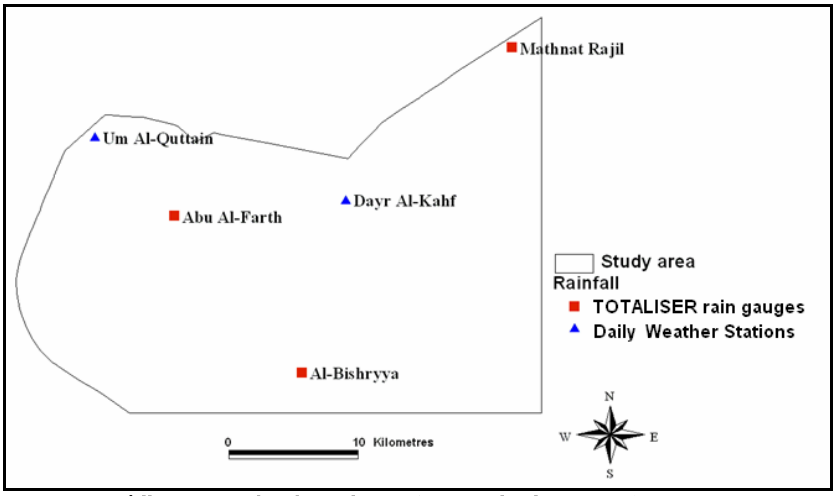

Figure 7. Rainfall stations within the study area (Source Al-Adamat, 2002)

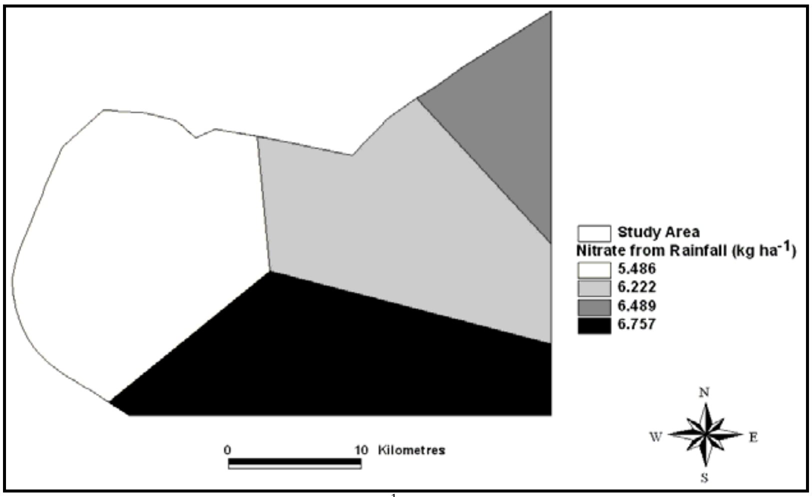

Figure 8. The amount of nitrate (NO_3) (kg ha^{-1}) derived from rainfall in the study area (April 2000 – May 2001)

1.2. Irrigation water

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 to groundwater. The NO_3 concentrations (mg l^{-1}) for irrigation wells were known from the field work of April 2000.

Waddingham (1994) estimated the amount of water abstracted in 1994 for irrigation purposes as *ca.* 6.3 $\times 10^6$ m^3 used to irrigate 482 ha (*ca.* 13,070 m^3 ha^{-1}). This figure was estimated after interviewing 26 farmers in the study area. It was also estimated that the cultivated area needed only 3.8×10^6 m^3 (*ca.* 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 mount 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 (After Al-Adamat, 2002).

$$NO_3(IR) = NO_3(CIR) \times IR \times 10^{-3} \text{ (kg ha}^{-1}\text{)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where CIR: concentration of NO_3 in irrigation water (mg l^{-1}), IR: amount of irrigation water (m^3 ha^{-1}).

The agriculture activities map of 2000 (Figure 4) was updated with both estimates of irrigation water (m^3 ha^{-1}) and the nitrate concentrations of the well(s) that supplied each farm with irrigation water in 2000. Equation 4 was then applied to calculate the nitrate volume added to the soil (kg ha^{-1}) (Figures 9 and 10). These two figures show the estimated nitrate contributed to the soil through irrigation water. Figure 9 represents the minimum nitrate volume added to the soil (kg ha^{-1}) based on the estimated optimum usage of irrigation water, while Figure 10 represents the nitrate (kg ha^{-1}) added if farmers had used excessive irrigation as estimated by Waddingham (1994).

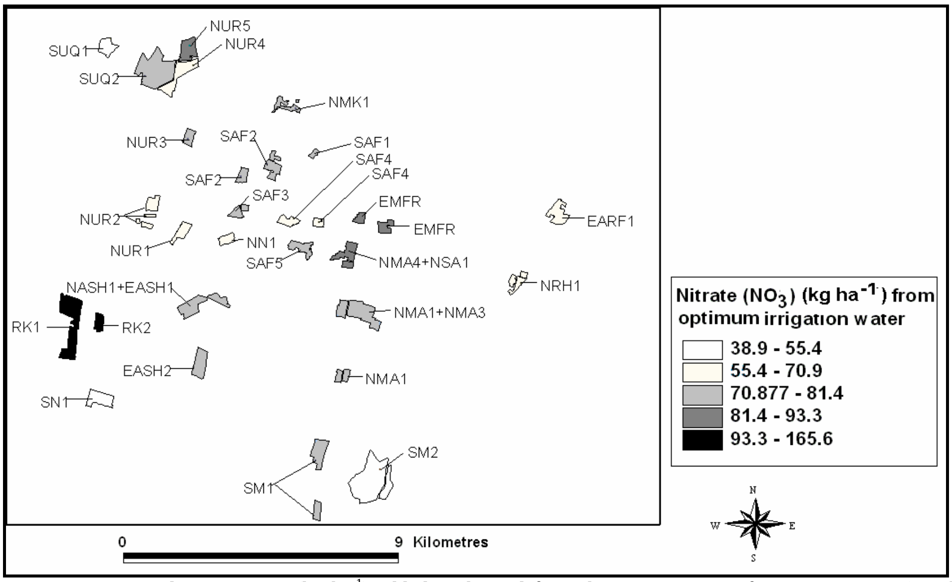

Figure 9. Estimated nitrate mass (kg ha-1) added to the soil from the optimum use of irrigation water (April 2000 – December 2000)

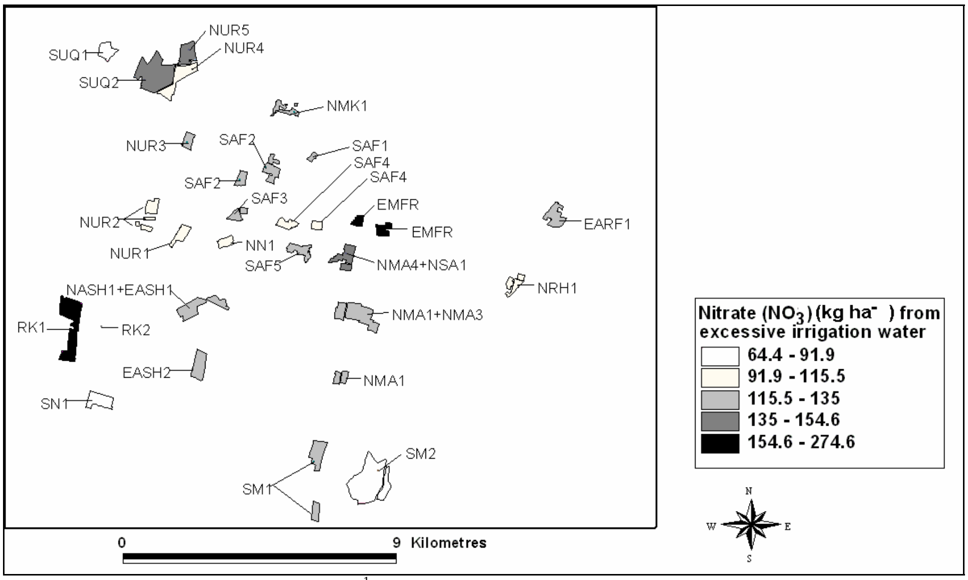

Figure 10. Estimated nitrate mass (kg ha-1) added to the soil from an excessive use of irrigation water (April 2000 – December 2000)

1.3. Soil before cultivation

The amount of nitrate in the topsoil before cultivation was calculated as follows (Equation 5: after Al-Adamat, 2002):

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

Where CSBC: concentration of NO_3 in the soil before cultivation (kg per kg of soil) and B: bulk density of the soil (kg m^{-3}).

The nitrate (NO_3) concentrations from two soil sampling sites (S3 and S6) were used in Equation 5. Both samples represent natural soil (uncultivated before) and it has been assumed that the NO_3 concentration found in these soils is what would be found in the farming areas before cultivation. S3 was located in a silt loam soil while S6 was located in a clay loam soil. Nitrate (NO_3) concentrations from both sampling sites were given in mg l^{-1} which meant that this measure had to be transformed to kg (nitrate) per kg soil. In the soil sampling procedure, 10 g of soil were made up to 25 ml (1/40 litre) of soil-water extracts. In order to convert the nitrate concentration (mg l^{-1}) to nitrate per gram of soil, the nitrate concentration was divided by 400 which, when multiplied by 10^{-3}, produced an estimate nitrate concentration in kg per kg of soil.

In ArcView GIS, the attribute file of the soil map (Figure 2) was updated with the bulk density values and the nitrate concentration (kg per kg of soil) based on the assumption that all soil units that have a silt loam texture had a 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 resulting map is shown in Figure 11. This figure shows that the available NO_3 in the topsoil before cultivation was estimated at between *ca.* 1.3 and 5.7 kg ha^{-1}.

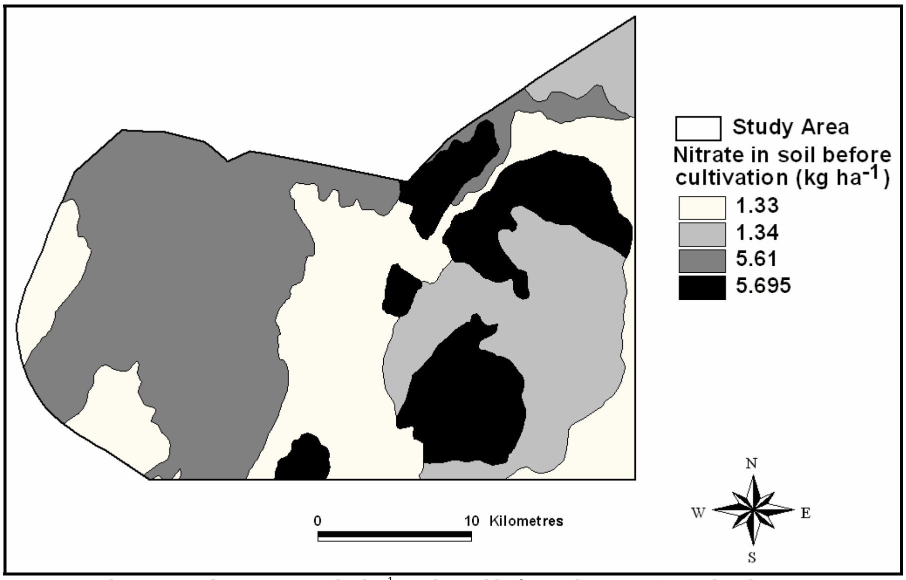

Figure 11. The estimated nitrate mass (kg ha^{-1}) in the soil before cultivation (natural soil)

1.4. Inorganic fertilisers

The amount of nitrate from the application of fertilisers was known through the field work of April 2000. Each farm was visited during that fieldwork where types and amounts of each commercial fertilizer had been documented. Nitrogen N in applied inorganic fertilisers has three forms; N, NO_3 and NH_4. In this model it was assumed that the total amount of nitrogen (Nt) has been transformed to nitrate. Once more, the agriculture activities map of 2000 (Figure 4) was updated with the nitrate estimates in the applied fertilisers as shown in Figure 12.

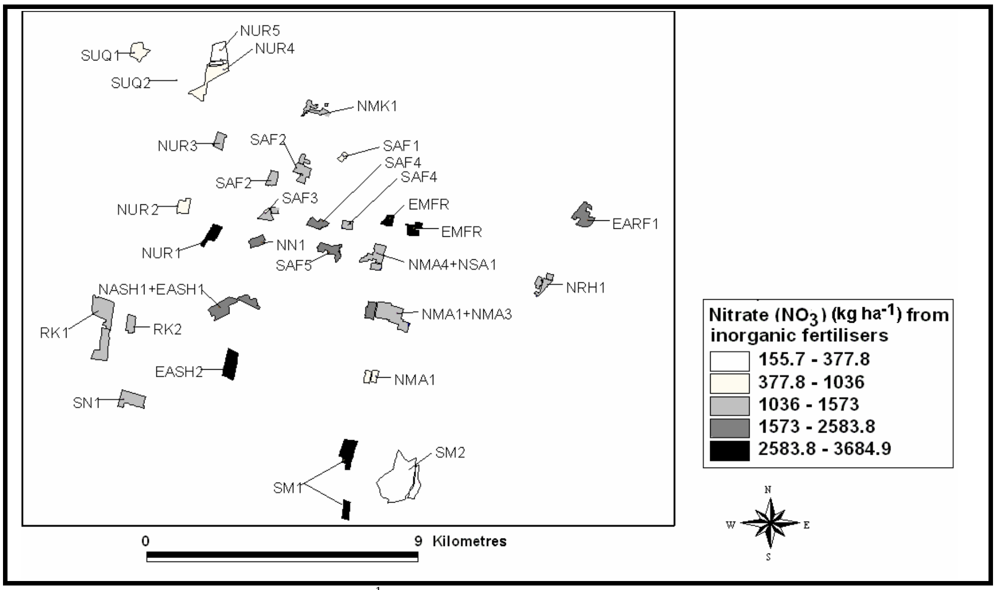

Figure 12. Estimated nitrate mass (kg ha^{-1}) added to the soil from inorganic fertilisers (April 2000 – December 2000)

1.5. Organic manures

There are two types of organic manures used by farmers in the study area (a) chicken manure and (b) sheep manure. Farmers who grow vegetables usually use chicken manure, while farmers who grow fruit and olive trees use sheep manure. The amount of organic fertilizer used was determined from interviews with farmers. Tables 2 and 3 summarize the amount of both chicken and sheep manure used by farmers in the study area.

Table 2. The amount of chicken manure used by vegetable farmers in the study area

Farm Code	Chicken manure (kg ha^{-1})	Farm Code	Chicken manure (kg ha^{-1})
NUR1	5000	NMA1-NMA3	7142.8
NUR2	3980.9	RK1	5000
NUR3	3000	NASH1-EASH1	4909
NUR4	15000	EASH2	8250
NUR5	7000	SM1	9157
SN1	5384.6	EMFR	4000
NN1	5102	NMK1	1700
NSA1-NMA4	8000	EARF1	7142.9
NMA1	5000	SAF3	10000
NMA2	6800	SAF4	5000
SAF1	3000	SAF5	7142.8
SAF2	5000	NRH1	8000

Table 3. The amount of sheep manure used by tree farmers in the study area.

Farm Code	Sheep manure (kg ha^{-1})
NUR4	3448.3
NUR5	9194.3
SUQ1	5970
SUQ2	2395.3
NSA1-NMA4	12000
RK2	10000
SM2	16000

Various authors have discussed the chemical composition of manure. Table 4 summarises the chemical composition of organic manure.

Table 4. The N, P and K percentages in chicken and sheep manures as estimated by various authors.

(%)	Chicken	Sheep	Source	Comments
N	0.9	1.5	Lekasi *et al.*, (2001)	Chicken manure was mixed with goat manure.
P	0.24	0.33		
K	0.45	1.35		
N	4.3	4.0	James, (1993)	Too high: N, P and K composition of manures is highly variable (James, 1993).
P	1.6	0.6		
K	1.6	2.9		
N	1.6	1.4	Cooke, (1982)	USA and UK
P	0.4	0.2		
K	0.4	1		
N	3.77	3-5	Parsad and Power, (1997)	P and K for chicken manure given as P_2O_5 and K_2O respectively. In general the percentages could be considered high for the study area.
P	1.89	0.4–0.8		
K	1.76	2-3		

Based on Table 4, the percentages given by Cooke (1982) were used as an indication of the chemical composition of organic manures used in the study area. The percentages given by Lekasi *et al*. (2001) are for chicken and goat manure mixed together which was not applicable to this research. James (1993), and Parsad and Power (1997) gave a high percentage of N, P and K, which could give an over-estimate of the NPK percentages in chicken and sheep manure in Jordan. This is due to the fact that sheep manure has lower percentages of N, P and K if the animal diet is poor (Cooke, 1982) which could be assumed in the study area.

In manures, about one third of the nitrogen is released quite quickly, but much is very resistant and persists for a long time in the soil (Cooke, 1982). In this study, it was assumed that only one third of the nitrogen found in organic manures was transformed into nitrate and made available for plant uptake in the study area. Based on that and using the percentages provided by Cooke (1982), it was estimated that the sheep manures had added to the soil in the tree farms, nitrate values of 33.5, kg ha^{-1} as a minimum value at SUQ2 farm up to 224 kg ha^{-1} at SM2 farm as shown in Table 5. In the vegetable farms (Table 6), the chicken manure had supplied the soil with nitrate ranging from 27.2 kg ha^{-1} at NMK1 farm to 240 kg ha^{-1} at NUR4 farm.

Table 5. The estimated NO_3 loading contributed by sheep manure in the tree farms

Farm Code	NO_3 (kg ha^{-1})
SUQ2	33.5
NUR4	48.3
SUQ1	83.6
NUR5	128.7
RK2	140
NSA1-NMA4	168
SM2	224

Table 6. The estimated NO3 loadings contributed by chicken manure in the vegetable farms

Farm Code	NO3 (kg ha^{-1})	Farm Code	NO3 (kg ha^{-1})
NMK1	27.2	SAF4	80
NUR3	48	NN1	81.6
SAF1	48	SN1	86.15
NUR2	63.7	NMA2	108.8
EMFR	64	NUR5	112
NASH1-EASH1	78.6	EARF1	114.3
NUR1	80	SAF5	114.3
NMA1	80	NRH1	128
SAF2	80	EASH2	132
RK1	80	SM1	146.5
NSA1-NMA4	128	SAF3	160
NMA1-NMA3	114.3	NUR4	240

2. Nitrate losses from agricultural land

2.1. Plant uptake

Plant uptake was based on values taken from the published literature where the estimated nitrate uptake by plants was found for several crops (e.g. Tomato, watermelon). The plant uptakes were estimated from Finck (2000) as shown in Table 7.

Table 7. The estimated plant uptake (kg ha^{-1}) for vegetables and trees in the study area (Based on Finck, 2000)

Vegetables	NO_3 (kg ha^{-1})	Trees	NO_3 (kg ha^{-1})
Tomato	1741	Apple	92
Water Melon	696	Peach	149
Melon	696	Olive	531
Beans	572	Grapes	97
Aubergine	1285	Other fruits	92
Cabbage	536		
Peppers	1772		
Onion	514		
Cucumber	222		
Cauliflower	775		

Based on the data collected about crop type in the study area during the farmers' interviews, for each farm the average plant uptake was calculated using Equation 6 (After Al-Adamat, 2002).

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

Where APU: Average plant uptake, A_n: Area of crop n (ha), and PU_n: Plant uptake for crop n (as in Table 8) (kg ha^{-1}).

Equation 6 was applied to the farm map (Figure 3) after updating its attribute file with crop type, crop area and plant uptake for each crop (Table 7). The results of this operation are shown in Tables 8 and 9.

Table 8. Average plant uptake of NO_3 (kg ha^{-1}) in the tree farms

Farm Code	Average plant uptake of NO_3 (kg ha^{-1})
NUR4	101
NUR5	126
RK1	68
SM2	429
SUQ1	116
SUQ2	179

2.2. Nitrate decay (denitrification and volatilization) in inorganic fertilisers

Denitrification and volatilization were assumed to be the only decay processes in inorganic fertilisers in the agricultural lands. Table 10 illustrates the estimated denitrification rates from the applied fertilisers as estimated in a review published by Rolston (1981). Based on this table, it was assumed that the denitrification rate in the study area was *ca.* 20%, which is approximately the average value from these estimates. This percentage was subtracted from the applied inorganic fertilisers within the GIS. The volatilization rate was also estimated from FAO (2001) statistics as shown in Table 11. This table shows the volatilization rate for three types of fertilisers used in the study area. Also, these values were subtracted within GIS for the farms that use such fertilisers.

Table 9. Average plant uptake of NO_3 (kg ha^{-1}) in the vegetable farms

Farm Code	Average plant uptake of NO_3 (kg ha^{-1})	Farm Code	Average plant uptake of NO_3 (kg ha^{-1})
EARF1	584.52	NUR2	468.56
EASH2	456.5	NUR3	498.2
EMFR	331.4	NUR4	456.5
NASH1-EASH1	482.3	NUR5	555.26
NMA1	518.29	RK2	661.76
NMA1-NMA3	546.67	SAF1	605.55
NMA2	513.4	SAF2	750.42
NMA4-NSA1	821.35	SAF3	376.31
NMK1	552.3	SAF4	352.25
NN1	446.9	SAF5	667.34
NRH1	452.24	SM1	551.36
NUR1	599.82	SN1	1320

Table 10. 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 11. Estimated volatilization losses (based on FAO, 2001).

Fertilizer Name	Estimated volatilization losses (%)
UREA ($(NH2)_2CO$)	10
MAP (Mono Ammonium Phosphate)	15
NH_4NO_3 (Ammonium Nitrate)	2

3. Estimated nitrate leaching from the agricultural lands

The estimated nitrate leaching from the agricultural lands was based on having two scenarios as shown in Table 12. 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 vegetable and tree farms as shown in Tables 13 and 14.

Table 12. The Estimated nitrate leaching scenarios from agricultural lands

Assumptions	Scenarios	
	SA1	SA2
Water usage	Optimum	Excessive
Denitrification rate (inorganic fertilisers only)	20%	20%
Volatilization losses	Table 11	
Nitrate in organic manure	33% of nitrogen in organic manures was transformed into nitrate (NO_3)	
Nitrate in rainfall (kg ha^{-1})	6	
Nitrate in soil before cultivation (kg ha^{-1})	5.61	

Table 13. Estimated nitrate leaching from the vegetable farms (kg ha^{-1}) (◈ S5 soil sample location; ⊙ S1 soil sample location)

Farm Code	Scenarios		Farm Code	Scenarios	
	SA1 (kg ha^{-1})	SA2 (kg ha^{-1})		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

Table 14. Estimated nitrate leaching from the tree farms (kg ha^{-1})

Farm code	Scenarios		Farm code	Scenarios	
	SA1 (kg ha^{-1})	SA2 (kg ha^{-1})		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

4. Nitrate leaching from Cesspools

Based on a field survey, Waddingham (1994) estimated the actual per capita water demand for the study area of *ca.* 115 L d^{-1}. It was assumed that the average family size in the study area is *ca.* 6 which gives a daily water consumption of *ca.* 690 L $family^{-1}$. It was assumed that only *ca.* 10% of that water would reach the cesspool on a daily basis. This means that the water input to the cesspool is *ca.* 4 m^3 $month^{-1}$. Based on Figure 6, it was estimated that the cesspool size is *ca.* 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 since the ventilation hole (Figure 6) is too small (*ca.* 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 (Equation 7) (After Al-Adamat, 2002).

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

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 number of 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 month is groundwater recharge (together with its nitrate).

Three scenarios were evaluated in this research project using Equation 7. A low risk scenario, where the house owner was assumed to empty the cesspool every three months. In the second scenario, it was assumed that the house owner emptied the cesspool every six months, while in the third scenario, the house owner emptied the cesspool only once every year.

The total nitrogen in sewage before treatment is *ca.* 40 mg l^{-1} of which 15 mg l^{-1} is organic N and the remaining 25 mg l^{-1} is ammonia (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 (O) 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 and Bannayan (1993) the nitrate concentration at the inlet of the ATP was *ca.* 11.2 mg l^{-1}. The maximum concentration recorded in this plant during the treatment process was *ca.* 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 *ca.* 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 *ca.* 18 mg l^{-1}.

In order to apply Equation 7, the village map (Figure 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 15. The total estimated amount of leached nitrate in the study area supplied from cesspools was estimated to lie between *ca.* 796 and 1989 kg $year^{-1}$ (*ca.* 0.3 to 0.7 kg $household^{-1}$ $year^{-1}$).

Table 15 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 high estimated nitrate leaching to groundwater. The distribution of these villages over a large area (Figure 2) increases the risk of having both chemical and biological groundwater contamination problems.

Model Validation

In this research, the model was validated for the agricultural lands only. In order to validate the model, the NO3 concentrations (mg 1^{-1}) found in the soil-water extracts from the two cultivated fields in 2000 (S1 and S5) were used to estimate the amount of nitrate lost (leached through the soil).Equation 5 was used to calculate the amount of NO3 (kg) in the soil profile. The average NO3 concentrations in the soil profile for each site were assumed to be the average concentrations from the three different sampling depths. The average NO3 concentrations at S1 and S5 were 7 mg 1^{-1} and 10.9 mg l^{-1} respectively. S1 was located inside NUR2 farm while S5 was located in NMA1&NMA3 farm. The outcome from this operation showed that the total amount of nitrate in the soil at S1 (depth 0-100 cm) was 320 kg ha-1 and 359.7kg ha^{-1} at S5 after cultivating the land for one season. When comparing these values to the estimated nitrate leaching from these farms, it was found that at S1, for the two scenarios, nitrate leaching estimates were similar to what was found in the soil (*ca*. 92% for SA1 and *ca*. 107% for SA2), while at S5, the nitrate leaching estimates were much higher than what was found in the soil (*ca* 190% for SA1 and *ca*. 205% for SA2). At S1, the estimated nitrate leaching was ca. 83% of the total nitrate input, while at S5 it was ca. 56% of the total nitrate input.

Table 15. The estimated leached nitrate (kg $year^{-1}$) in each village based on three scenarios; SC1: cesspool is emptied every three 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
Ath-Thalaj	4.3	8.6	10.8	Max.	96.2	192.4	240.5
Dayr Al-Kahf	49.2	98.5	123.1	Mean	22.3	44.6	55.7
				SD.	25.0	50.0	62.5

Suggested Management Scenarios

In this research paper, it was found that inorganic fertilisers pose more threat in the study area. Cesspools also have been identified as potential sites for chemical and biological contamination. Nutrient loading from both contaminant sources (agriculture and cesspools) were estimated in the study area. In order to suggest locally acceptable management options, several scenarios have been examined to overcome the nitrate leaching problem in the study area.

1. "Do nothing" scenario

This scenario is based on taking no management action in order to control nitrate leaching in the study area. This scenario was examined earlier in this paper, where it appeared that nitrate leaching in the study area could cause groundwater contamination. Doing nothing about this situation will mean more nitrate will leach to groundwater from both cesspools and irrigated agriculture. There is also a risk that biological contamination could occur in the study area from the cesspools.

2. "What if scenarios"

Fertiliser management

In this paper, nitrate leaching was estimated for all farms. It was found that in each farm, farmers had used more fertilisers than required for plant uptake. If farmers know:

1. The available nitrate in irrigation water (groundwater) (optimum usage). Schepers *et al*., (1983) argued that nitrate in the groundwater is a potential source of nitrogen for plant growth when used for irrigation.
2. Available nitrate in the soil before cultivation,
3. The nitrate content in organic manure,
4. Plant uptake rates.

Such knowledge could be used to calculate how much inorganic fertiliser is needed to compensate the difference adding *ca.* 30% extra fertiliser as a "safe margin". This safe margin was assumed to compensate any losses that might occur due to denitrification and volatilisation processes. This percentage could be modified if the denitrification rate in the area is quantified in the future. This scenario was conducted in a GIS environment where all nitrate data used in estimating the nitrate leaching from agricultural land (inputs and losses) were used again except the amount of nitrate from inorganic fertilisers. The amount of nitrate in inorganic fertiliser was based on the above assumption. Based on this scenario, the estimated nitrate leaching would drop dramatically. The decrease in the estimated nitrate leaching was up to 99% in some farms (Table 16). This scenario is viable and could be implemented by providing farmers with extension services and basic water and soil tests.

3. Cesspool management

There are three possible management scenarios for controlling nitrate leaching from the cesspools. The first scenario is to empty the cesspool on a regular basis as discussed earlier in this paper. It was found that if the house owner emptied the cesspool every two months, nitrate leaching could be minimised. Local government councils could participate by providing such services to the local people as they currently provide the service of collecting garbage for an annual fee (council tax). Currently the cost of taking the sewage from the cesspools in the area could cost up to 30 JD (*ca.* US$45) in the western part of the study area. For remote villages, this cost could be much higher.

The second management scenario is to have a better design for cesspools. Leaving the bottom of the cesspool without a proper lining overlaying fractured basalt is not an option in any suggested design. Government intervention through the local councils could guarantee that new designs eliminate or minimise nitrate leaching from the cesspool. This scenario could be implemented easily, where local councils in the area could insist on such designs before issuing a building licence. Local people could use the available material in the area such as basalt rocks with cement to line the bottom of the cesspool, similar to what they usually do for the cesspool walls.

The third management scenario is to have a sewerage system to serve the major towns in the area which, as shown before in this paper, are the major contributors of the nitrate originating from cesspools. Villages like Um Al-Quttain and Al-Mukayfita have the potential to have a local sewage treatment plant. The distribution of villages in the area could assist in making this scenario viable. There are two clusters of villages in the study area; (1) on the main road to Baghdad, (2) parallel to the Syrian borders. Any sewage treatment plant in the area could also serve other villages to the west of the study area having the same problem with cesspools. Such sewage treatment plants must be assessed environmentally in order to take into consideration all measures that it does not itself cause groundwater quality deterioration.

Table 16. Managing the amount of inorganic fertilisers used in the vegetable farms

Farm Code	Currently estimated NO_3 leaching (kg ha^{-1})	Expected leaching after management (kg ha^{-1})	Difference (kg ha^{-1})	Reduction (%)
EARF1	121	100	21	17
EASH2	277	52	225	81
EMFR	351	40	311	89
NASH1+EASH 1	295	85	210	71
NMA1	356	94	262	74
NMA1+NMA3	384	86	298	78
NMA2	743	80	663	89
NMK1	685	128	557	81
NN1	765	75	690	90
NRH1	895	56	839	94
NSA1+NMA4	1202	160	1042	87
NUR1	1483	122	1361	92
NUR2	1453	88	1365	94
NUR3	2126	103	2023	95
NUR4	1362	8	1354	99
NUR5	2046	88	1958	96
RK2	1926	120	1806	94
SAF1	1735	133	1602	92
SAF2	2973	164	2809	94
SAF3	3116	16	3100	99
SAF4	2608	47	2561	98
SAF5	2729	123	2606	95
SM1	3309	76	3233	98
SN1	4598	338	4260	93

Summary and Conclusion

In this research paper, a GIS-based model was developed to estimate nitrate leaching from the agricultural lands that took into considerations all possible sources of nitrate input and losses from cultivated fields. The nitrate inputs included (a) rainfall, (b) soil store, (c) irrigation water, (d) organic manure and (e) inorganic fertilisers. The losses were assumed to be (a) plant uptake, (b) denitrification and volatilisation and (c) leaching. In the case of cesspools, it was suggested that the only losses of nitrate occurred through either leaching or denitrification.

In the agricultural lands, the estimated amount of leached nitrate from several sources was evaluated. This included rainfall, which contributed to the farmed area *ca.* 5 kg ha^{-1}, and irrigation water with values ranging between *ca.* 39 to 165.6 kg ha^{-1} if farmers used optimum irrigation water, and between *ca.* 64 and 275 kg ha^{-1} if farmers used excessive amounts of irrigation water. These sources of nitrate also included what existed in the soil before cultivation. This source had contributed to the input of *ca.* 5.6 kg ha^{-1} in the agricultural area. Organic manure and inorganic fertilisers 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 and volatilisation decays and plant uptake. The outcome of this model has shown that the estimated nitrate leaching from the agricultural lands range between 121 and 4598 kg ha^{-1} if farmers used optimum irrigation water and between 158 and 4659 kg ha^{-1} if farmers used excessive 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 yr^{-1}.

It was also found that nitrate leaching from agricultural lands was much higher than that predicted from the cesspools.

Several management scenarios were discussed in this research, including having better fertiliser management, which could reduce the estimated nitrate leaching by more than 90%. This would only possible, however, if farmers know the available plant nutrients in water, soil and organic manure and used such knowledge to estimate the required amount of inorganic fertilisers. Nitrate leaching from cesspools could also be reduced or eliminated by having the water extracted on a regular basis, or by having a better design or a local sewerage system.

In conclusion, it seems that both agricultural lands and cesspool pose a threat to future groundwater quality in the study area. Although, in the study area, 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.

Finally, although the groundwater is relatively deep, care should be taken when having 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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نمذجة ترشح النترات إلي المياه الجوفية في حوض الأزرق/ الأردن باستخدام نظم المعلومـــات الجغرافيـــة

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مركز بحوث وتطوير البادية الأردنية – الأردن

يعتبر الأردن أحد البلدان التي ستواجه مشكلة مياه مطلقة في المستقبل ومن الممكن أن لا يستطيع أن يوفر احتياجاته من المياه عام 2025. تعتبر المياه الجوفية أحد أهم مصادر المياه للكثير من مناطق الأردن، وأحياناً المصدر الوحيد في بعض المناطق. إن معظم الخزانات الجوفية في الأردن تم استغلالها بطاقة أكبر من الحدود الآمنة للـــضخ، حيث أنه يتم ضخ ما يزيد على 479 مليون متر مكعب سنوياً من هذه الخزانات في حين أن الحد الآمـــن للـــضخ يبلغ 418.5 مليون متر مكعب سنوياً فقط ومع هذا فأن المياه الجوفية في الأردن عرضة للتلوث من مصادر كثيرة زراعية وصناعية وسكانية والتي أدت وتؤدي إلي تدهور جودة هذه المياه. هناك ثلاثة أنواع رئيسية من الملوثات التي تؤثر في المياه الجوفية وهي (1) الاستخدام الزائد للأسمدة ومبيدات الأعشاب والحشرات في الزراعـــة (2) الحفـــر الامتصاصية في القرى والمخيمات والتي تستخدم لأغراض الصرف الصحي و (3) الزيوت والرصـــاص والـــصدأ الناتج من السيارات.

في هذه الدراسة تم استخدام تقنيات نظم المعلومات الجغرافية لدراسة موارد الميـــاه الجوفيـــة في المنطقـــة البازلتية من حوض الأزرق حيث تم عمل نموذج رياضي ضمن نظم المعلومات الجغرافية لتقدير كميات النيتـــرات التي من الممكن أن تصل إلي المياه الجوفية من استخدام الأسمدة وكذلك من الحفر الامتصاصية الموجـــودة ضـــمن منطقة الدراسة.وقد تم عمل سيناريوهات لحل مثل هذه المشاكل باستخدام تقنيات نظم المعلومات الجغرافية.