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Trends and occurrences of nitrate in the groundwater of the West Bank, Palestine

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A B S T R A C T

Groundwater is the major source of water to the Palestinians. Efficient management of this resource requires a good understanding of its status. This understanding necessitates a characterization of the quality of the utilizable volumes. This paper focuses on the assessment of nitrate concentrations in the aquifers of the West Bank, Palestine. A preliminary statistical analysis is carried out for the spatial and temporal distributions of the nitrate concentrations. GIS is utilized to facilitate the analysis and to efficiently account for the spatiality of nitrate concentrations. The analysis was carried out at different spatial levels and key parameters including soil type, watersheds, depth, population, and rainfall. It is observed that elevated nitrate concentrations in the groundwater greatly coincide with increasing rainfall, particularly in the last few years. Results confirm that the annual mean nitrate concentration in the Western groundwater basin has an increasing trend over the period from 1982 to 2004 indicating its vulnerability to contamination. This result can be attributed to the agricultural activities along with the high groundwater recharge. However, leaking septic and sewer systems are considerably causing nitrate contamination of groundwater in populated areas. Overall, the recommendations call for an immediate intervention to manage the quality problems in the West Bank aquifers.

Introduction

Nitrogen (N) is an essential input for the sustainability of agriculture (Delgado, 2002; Lake et al., 2003; Schröder, Schofield, Cabral, & Hofman, 2004). However, nitrate contamination of groundwater is a worldwide problem (Birkinshaw & Ewen, 2000; Saãdi & Maslouhi, 2003). Nitrate is soluble and negatively charged and thus has a high mobility and potential for loss from the unsaturated zone by leaching (Chowdary, Rao, & Sarma, 2005; DeSimone & Howes, 1998). Elevated nitrate concentrations in drinking water can cause *methemoglobinemia* in infants and stomach cancer in adults (Addiscott, Whitmore, & Powlson, 1992; Hall, Shaffer, Waskom, & Delgado, 2001; Lee, Dahab, & Bogardi, 1991; Wolfe & Patz, 2002). As such, the US Environmental Protection Agency (US EPA) has established a maximum contaminant level (MCL) of 10 mg/l NO_3-N (50 mg/l NO_3) (US EPA, 2000).

Groundwater pollution due to point and nonpoint sources is caused mainly by agricultural practices (noticeable is the use of inorganic fertilizers, pesticides, and herbicides), localized industrial activities (organic pollutants and heavy metals), and inadequate or improper disposal of wastewater and solid waste (including hazardous materials) (Almasri & Kaluarachchi,

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2004; Delgado & Shaffer, 2002; Dunn, Vinten, Lilly, DeGroote, & McGechan, 2005; Hall et al., 2001; Shrestha & Ladha, 2002; UNEP, 2003). Nitrate is the most common pollutant found in shallow aquifers due to both point and nonpoint sources (Postma, Boesen, Kristiansen, & Larsen, 1991).

With nonpoint sources, groundwater quality may be depleted over time due to the cumulative effects of several years of practice (Addiscott et al., 1992; Schilling & Wolter, 2001). Nonpoint sources of nitrogen from agricultural activities include fertilizers, manure application, and leguminous crops (Hubbard & Sheridan, 1994). The extensive use of fertilizers is considered a main nonpoint source of the nitrate that leaches to groundwater (Chowdary et al., 2005; Hubbard & Sheridan, 1994; Postma et al., 1991). In addition to agricultural practices, nonpoint sources of nitrogen involve precipitation, irrigation with groundwater containing nitrogen, and dry deposition. Point sources of nitrogen are shown to contribute to nitrate pollution of groundwater (Almasri & Kaluarachchi, 2004). The major point sources include septic tanks and dairy lagoons. Many studies have shown high concentrations of nitrate in areas with septic tanks (Amade, 1999; Cantor & Knox, 1984; Keeney, 1986; MacQuarrie, Sudicky, & Robertson, 2001).

In the West Bank, Palestine, nitrate contamination of groundwater is caused by infiltration of fertilizers and raw sewage (UNEP, 2003). Marei and Haddad (1998) found that nitrate levels in up to one-third of the sampled wells in the Jordan Valley in the West Bank were above the MCL.

The objectives of this work are to identify and document the regional long-term trends of nitrate concentrations in the groundwater of the West Bank; to explore the probable sources of elevated nitrate concentrations; and to analyze the temporal and spatial variability in nitrate concentrations at different spatial levels and for key parameters including district, groundwater basin, soil type, watersheds, depth, population, and rainfall. The assessment is carried out using ArcGIS. Overall, the analysis furnished herein is intended to improve our understanding to the nitrate contamination extent of groundwater in the West Bank.

Description of the study area

The area under consideration is the West Bank, Palestine (see Fig. 1). Administratively, the West Bank is divided into eleven districts: Bethlehem, Hebron, Jenin, Jericho, Jerusalem, Nablus, Qalqilya, Ramallah and Al-Bireh, Salfit, Tubas, and Tulkarm (see Fig. 1). The districts are sub-divided into 89 municipalities. In addition, there are local councils that manage all infrastructure and basic services in the towns and villages. Approximately 1.6 million Palestinians live in the West Bank (PCBS, 1997b). Around 65% of the population lives in urban areas (UNFPA, 2001). Annual population growth ranges from 3 to 4.1% in the period from 1997 to 2006 (PCBS, 2008).

The total area of the West Bank is approximately 5800 km^2. It has a length of 130 km from north to south and a width between 40 and 65 km (Abdul-Jaber, Rabbo, Scarpa, Qannam, & Younger, 1999). The West Bank is mostly composed of limestone hills that are between 700 and 900 m in high. The lowest elevation of the study area is the Dead Sea at 400 m below sea level while the highest is the Tall Asur at 1022 m above sea level (UNEP, 2003). Fertile soils are found in the plains. Soil cover is generally thin. The West Bank formations are comprised of limestone, dolomite, chalk, marl, chert, shale, and clays (PWA, 2001).

The climate in the West Bank can be characterized as hot and dry during the summer and cool and wet in winter (UNEP, 2003). The climate becomes more arid to the east and south. Evaporation is high in summer when there is always a water deficit. The average annual rainfall in the central highlands is 700 mm and becomes less than 100 mm near the Dead Sea. However, great variations in rainfall amounts and distribution exist.

The principal water resources available to Palestinians include groundwater, springs, and harvested rainwater (UNEP, 2003). Both groundwater and surface water drain either westwards to the Mediterranean or eastwards to the Jordan River and Dead Sea. The lower Jordan River flows southwards at the eastern edge of the West Bank from Lake Tiberias to the Dead Sea (Abdul-Jaber et al., 1999). The West Bank lies over the Mountain aquifer. The Mountain aquifer is divided into the eastern aquifer, the northeastern aquifer, and the western aquifer. The eastern aquifer and part of the northeastern aquifer flow east towards the Jordan River. The western aquifer and part of the northeastern aquifer flow westerly towards the Mediterranean Sea (Abed & Wishahi, 1999; PWA, 2001; Scarpa, 1994).

Methods and data analysis

Data collection

The annual nitrate concentration data used in this study were obtained entirely from the Palestinian Water Authority (PWA). All available data were assembled into a single composite database to facilitate the analysis. The total number of the wells in the West Bank is 623 yet the total number of wells in the available database is 479. However, there are only 430 wells with 4372 measurements of nitrate concentration in the database covering the period from 1981 to 2004. The database includes well ID, well coordinates, concentration, measurement year, locality, district, aquifer, basin, well use, soil type, sub-watershed, watershed, average long-term annual pumping rate, and sampling depth.

The data was made available in a format that is accessible via GIS. The use of GIS tools, techniques, and capabilities enabled data processing, visualization, computation, analysis, and map preparation. Many problems were encountered in the original database. Some parameters were not accurately specified and listed like the district and basin. A GIS polygon shapefile for the districts of the West Bank was spatially joined to the original database. The same was carried out for the GIS polygon shapefiles of the groundwater basins and watersheds of the West Bank. In addition, the database shows many missing parameters for the different wells.

It was noticed that the frequency of sampling for nitrate concentration varies noticeably from well to well. Analysis showed that the frequencies of readings of nitrate concentration for each well vary between 1 and 22 as depicted in Fig. 2 with an average value that exceeds 10 readings. The following analysis furnished in the following subsections addresses the nitrate occurrences in the groundwater of the West Bank at different scales and for different explanatory parameters including the entire West Bank, districts, basins, watersheds, soil types, aquifers, depth, population, and rainfall.

Nitrate distribution across the West Bank

Since the objective of the analysis is to study the overall trend of nitrate concentration in the groundwater of the West Bank, no attempt was made to remove wells of short time series that do not represent the complete period from 1981 to 2004.

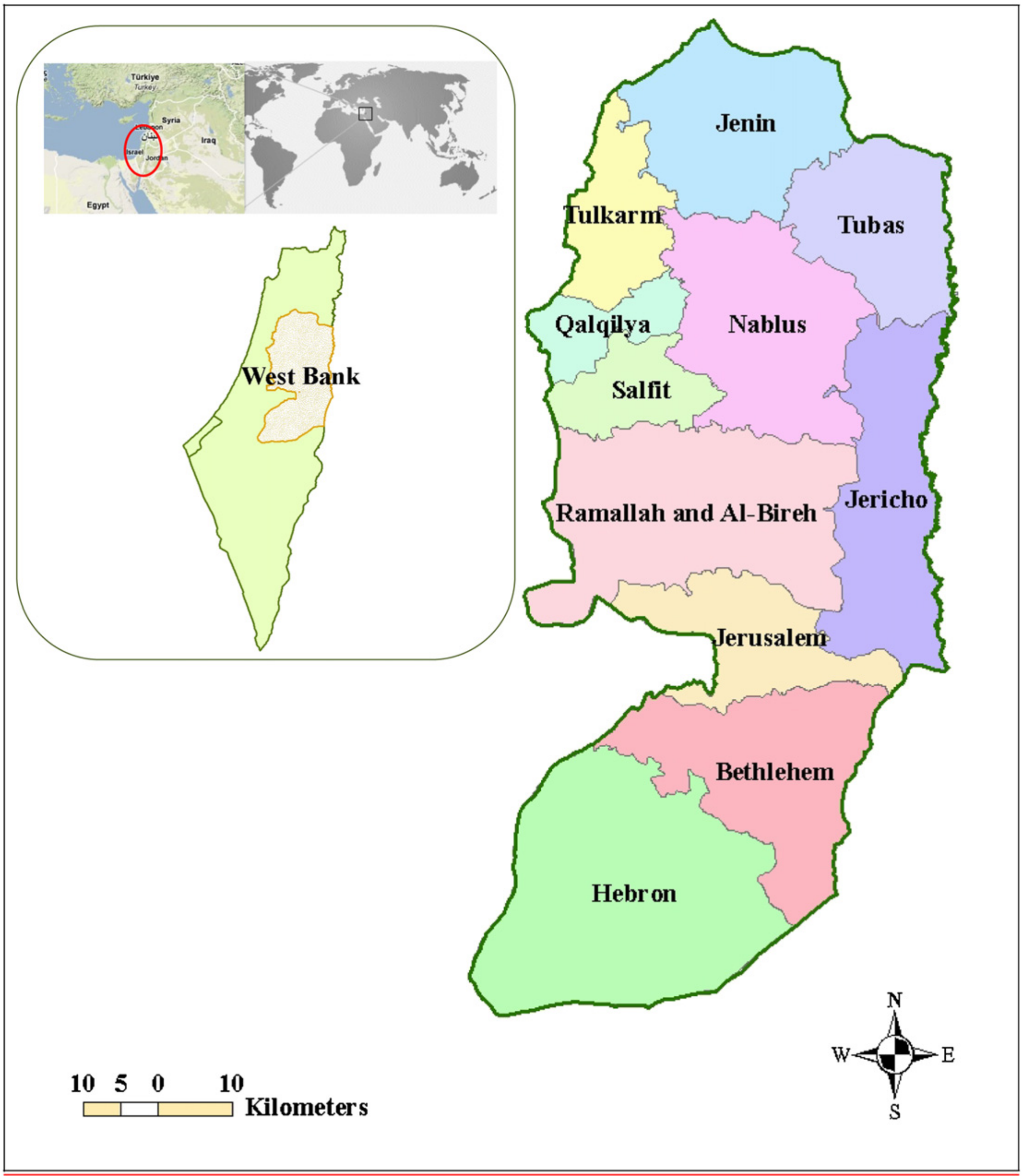

Fig. 1. The districts of the West Bank, Palestine.

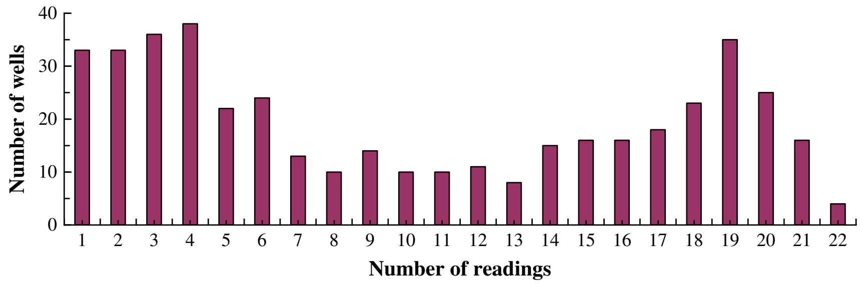

Fig. 2. Frequency distribution of nitrate concentration readings for the period from 1981 to 2004 and the corresponding number of wells.

This approach is common in many studies especially studies conducted for regional-scale assessment for the development of best management practices (Almasri & Kaluarachchi, 2004; Nolan & Stoner, 1995; Parliman, 2002).

Fig. 3 illustrates the frequency of the annual nitrate concentration readings for the period from 1981 to 2004. This figure was prepared using the "summarizing tables" capability of GIS. The average number of annual readings is approximately 182, which means that about 42% out of the 430 wells were sampled for nitrate. It is obvious from Fig. 3 that the maximum number of samples is 328 in 1999, while the minimum number of samples is 3 in 1990. Annual nitrate concentration statistics from 1981 to 2004 are shown in Fig. 4. The distribution of nitrate concentrations in 1981 and 1990 was as expected and as shown in Fig. 3. This expectation is because of the low number of readings in these two years. The results also show that the median is always below the MCL, indicating that at least 50% of the nitrate concentrations are below the MCL from 1981 to 2004. It is noticeable that the average is always higher than the median and closer to the MCL. As can be concluded from Fig. 4, the 75% percentile (3rd quartile) is generally closer to the MCL which was in turn exceeded in five years.

The annual median nitrate concentration exhibits an overall increasing trend to some extent (P-value = 0.09 with 95% confidence interval). The median concentration approached its maximum value in 1982 then decreased to its minimum value in 1990. The same trends were noticed for the mean concentrations, yet, the maximum value exceeded the MCL. The annual maximum concentrations are always above the MCL. A value of 285 mg/l is observed in 2004.

Fig. 5 shows the spatial distribution of nitrate concentration across the West Bank for the year 2004. This distribution was developed using the inverse distance weighting interpolation method (IDW) as supported by GIS. To assess the possible anthropogenic effects on groundwater quality, nitrate concentrations were classified into four groups based on the work of Cox and Kahle (1999) and Madison and Brunett (1985). The four concentration ranges were approximated as shown in the legend of Fig. 5 and these are: 0–5 mg/l to indicate the most likely background concentration; 5–15 mg/l to indicate a possible human influence; 15–50 mg/l to indicate pollution due to human influence; and greater than 50 mg/l to indicate that the MCL was exceeded as a result of excessive human activities.

It can be deduced from Fig. 5 that the highest nitrate concentrations are mainly encountered in the north specifically in Jenin and Tubas districts as well as in the south in Hebron district. In addition, some areas in Tulkarm and Qalqilya districts come across such high concentrations. These nitrate concentrations exceed the MCL of 50 mg/l. These observations could be possibly attributed to the agricultural activities that are associated with the elevated on-ground nitrogen loadings due to the use of nitrogen-based fertilizers. However, further analysis to the fertilizer's application in the study area ought to be conducted to confirm the foregone conclusion.

To better comprehend and assess the distribution of nitrate concentrations in the groundwater of the West Bank, the on-ground nitrogen loadings ought to be computed. This in fact will enable the spatial correlation between the on-ground nitrogen loadings and the corresponding nitrate concentrations in groundwater. In order to compute the nitrogen loadings, the land use distribution in the West Bank should be available in a processable format, which is not the case herein. The land use map enables the spatial allocation of the nitrogen loadings according to the land use type. Ultimately, the nitrogen sources in the study area may include (but not limited to) manure, inorganic fertilizers, atmospheric deposition, irrigation with

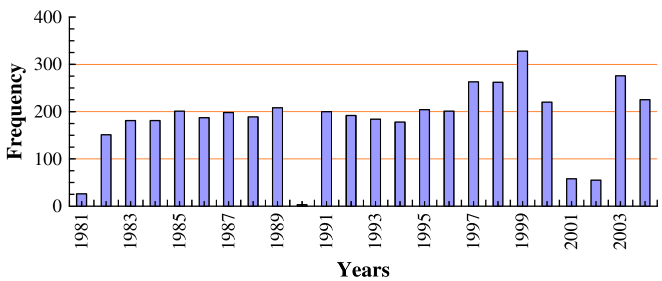

Fig. 3. Frequency of annual nitrate concentration readings for the period from 1981 to 2004 for the entire West Bank.

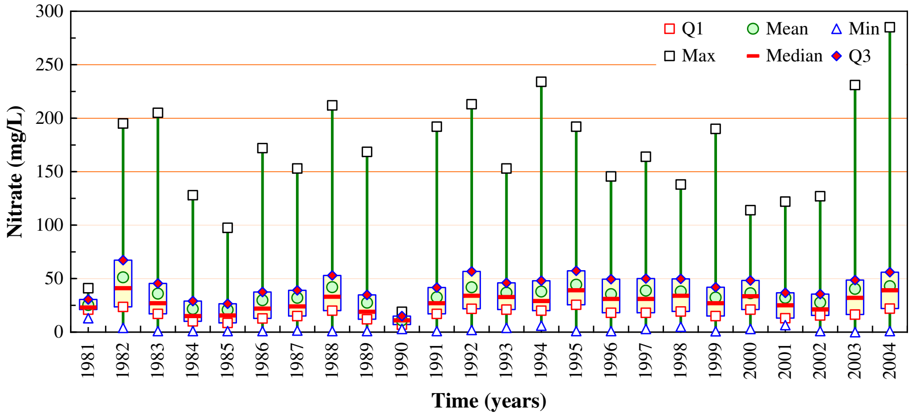

Fig. 4. Annual nitrate concentration statistics in the entire West Bank in the period from 1981 to 2004.

nitrogen-contaminated groundwater, cesspits, and nitrogen fixed by legumes, and this conclusion is supported by the foregoing work of Abdul-Jaber et al. (1999), Abed and Wishahi (1999), Wishahi and Awartani (1999), and UNEP (2003).

Nitrate distribution across the West Bank districts

As indicated earlier, to analyze nitrate concentration at the district level, the GIS shapefile of the outlines of the West Bank districts was used to spatially join the nitrate sampling wells (and hence the concentrations) to the district polygons (outlines).

The ranges of nitrate concentrations in the West Bank districts were analyzed (Fig. 6). The ranges represent the differences between the maximum and the minimum nitrate concentrations during the period from 1981 to 2004. A value of 284 mg/l is the maximum range in the West Bank, which was observed in *Jenin* district where a whole lot of agriculture-dominated areas are located within. *Tubas* district, which is adjacent to Jenin district, has the second rank with a range of 226 mg/l. Both districts have similar land use practices. *Tulkarm* district has the third rank of about 182 mg/l. *Jerusalem* and *Salfit* districts were ignored due to the little available data reported in them. In general, all the districts except *Ramallah and Al-Bireh*, have nitrate concentrations that severely exceed the MCL. These results reflect the intensive agricultural activities as well as the

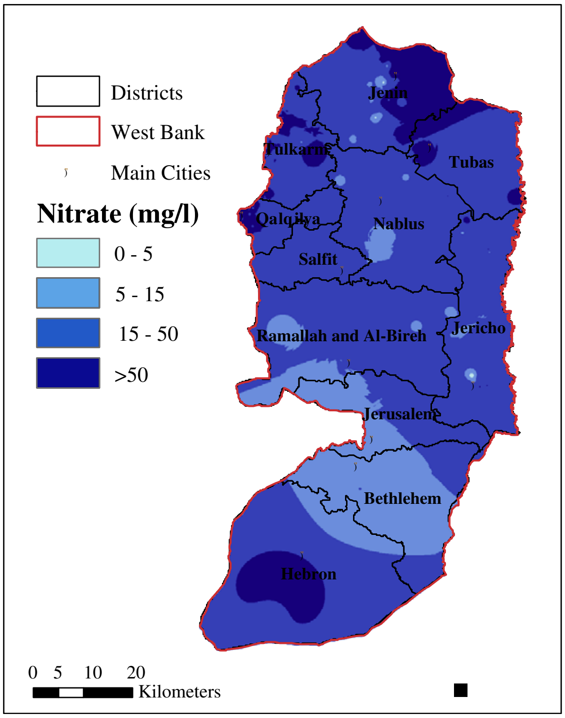

Fig. 5. The distribution of nitrate concentration across the West Bank for the year 2004 as interpolated using the IDW method.

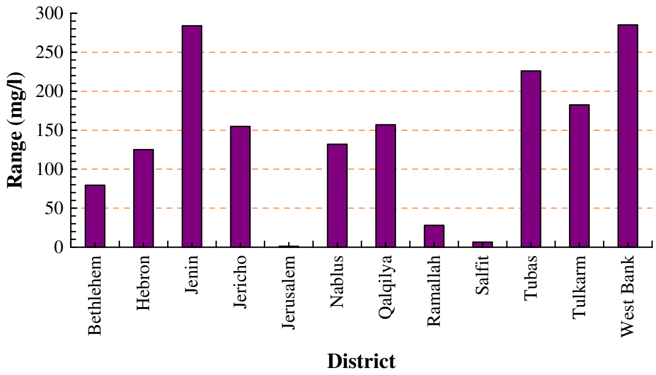

Fig. 6. Ranges of nitrate concentrations in the West Bank districts for the period from 1981 to 2004.

existence of other possible sources including the cesspits and the disposal of untreated wastewater. It is important to keep in mind that the sources might be at a remote distance from the sampling wells due to the possible fate and transport processes that may act on the nitrate once in the groundwater. This may imply that the sources could be in a district while nitrate may appear in an adjacent district.

Nitrate distribution in the West Bank groundwater basins

The Mountain Aquifer system underlying the West Bank is by far the most important source of water. The aquifer system is highly permeable due to its geological nature (UNEP, 2003). The limited soil cover over the water recharge zones makes the aquifer highly susceptible to pollution since there is no natural barrier to contaminants that travel down rapidly to the water table (UNEP, 2003). Groundwater in the Mountain Aquifer system flows in three main directions, according to which three main groundwater basins had been identified, namely the *Western*, *Northeastern*, and *Eastern* Aquifer Basins (Abed & Wishahi, 1999; UNEP, 2003).

Nitrate concentration data for the West Bank groundwater basins were analyzed to obtain the trends of nitrate concentrations in groundwater per each basin. The GIS shapefile of the West Bank groundwater basins was used to spatially join the well locations to the basin outline. The results of the analysis show mean values of 29.8, 35.4, and 45.0 mg/l for the *Eastern*, *Northeastern*, and *Western* basins, respectively, for the period from 1981 to 2004. Since the three basins are the main source of drinking water and do recharge many springs, the mean annual nitrate concentrations from 1981 to 2004 were computed and depicted in Fig. 7 for the three groundwater basins.

These time series depicted in Fig. 7 provide a qualitative understanding of the general trend of annual mean nitrate concentrations in the three basins. For instance, Fig. 7a confirms that the nitrate concentration in the *Eastern* basin has a decreasing trend until 1990 after which the oscillations in concentrations diminish with time. Fig. 7b shows that the nitrate concentration in the *Northeastern* basin has an upward behavior with an increasing trend in the last few years. In the *Western* basin, the nitrate concentration behaves in a different manner. Fig. 7c confirms that the nitrate concentration in the *Western* basin has an increasing trend over the entire period from 1982 to 2004. For instance, the mean annual nitrate concentration in the *Western* basin increased drastically after 1984 and the highest value occurred in 1995. Out of the 1301 samples from the *Western* basin, a total of 423 samples (33%) exceeded the MCL. It is worth mentioning that the sampled wells are owned and operated by the Palestinians and thus are shallow and can easily detect elevated nitrate concentrations. Therefore, every care should be taken into account when examining the time series of Fig. 7.

Using the spatial analysis capability of GIS, the occurrence of these 423 samples was analyzed and it was found that 200 samples are located within Qalqilya district, 199 samples are located within Tulkarm district, and 24 samples are located in Hebron district. From the analysis shown above, it can be concluded that the most vulnerable groundwater basin to contamination is the *Western* basin. This result can be attributed to the agricultural activities along with the high groundwater recharge.

Nitrate distribution across the West Bank aquifers

Each of the three basins mentioned above covers a large area with a wide range of different features of climate, water use, topography, geology, and hydrogeology (PWA, 2001). Each basin can be divided into seven aquifer systems based on the geologic formations. These aquifers are: *Alluvium*, *Alluvium and Eocene*, *Eocene*, *Lower Cenomanian*, *Cenomanian*, *Neogene*, and *Upper Cenomanian*. The *Cenomanian* aquifers have four samples and thus they were not considered in the analysis. The statistics of annual nitrate concentrations of the different aquifer systems from 1981 to 2004 were computed and are depicted in Fig. 8.

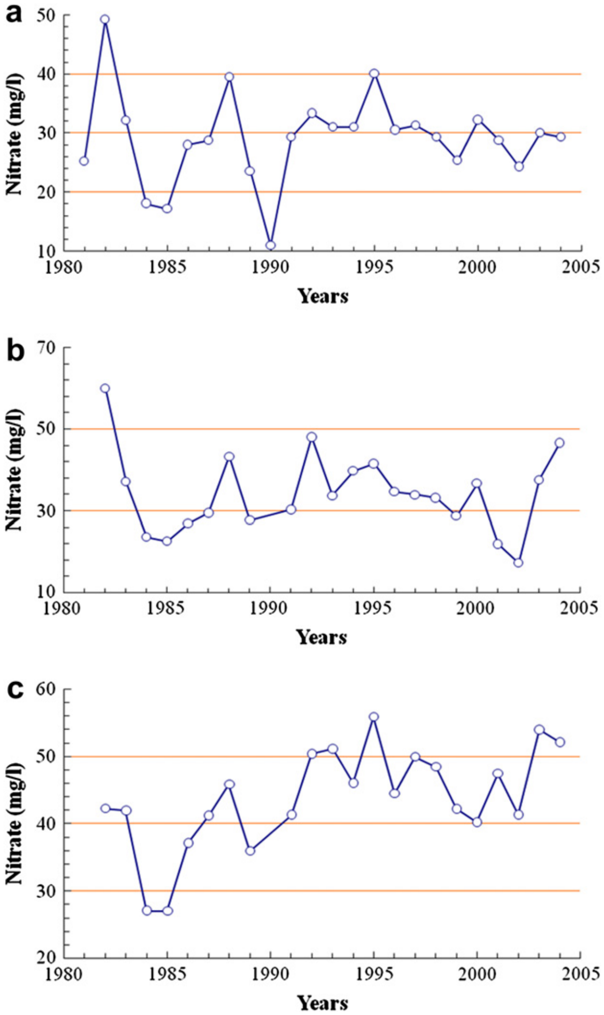

Fig. 7. Time series of annual mean nitrate concentration in the (a) Eastern, (b) Northeastern and (c) Western basins for the period from 1981 to 2004.

Almost all the maximum nitrate concentrations are above the MCL of 50 mg/l for the aquifer systems. A value of 285 mg/l was observed in the groundwater of the *Eocene* aquifer. The 75th percentile is above the MCL in the *Upper Cenomanian* aquifer only, therefore, further analysis should take place for this aquifer since it contains about 34% of the samples. The 75th percentile is close to the MCL in the *Eocene* aquifer. The *Alluvium* aquifer is ranked as the third in terms of the elevated nitrate concentration. In terms of the frequency of nitrate sampling, these three aquifer systems are the most representative because they have almost 90% of the nitrate samples.

In these aquifer systems, the majority of the land surface is occupied by agriculture-dominated areas and highly-condensed populated localities. The remaining 460 nitrate samples out of the 4372 are distributed across the middle part of the West Bank. Despite the fact that the mean nitrate concentrations are always higher than the median concentrations, nevertheless both are lower than the MCL for all the aquifers throughout the period from 1981 to 2004. It is noted that all the aquifer systems, except the *Lower Cenomanian*, have mean and median nitrate concentrations close to the MCL, typically in the range of 15–50 mg/l. Nitrate concentration in this range is the result of anthropogenic (man-made) effects. The highest mean and median nitrate concentrations are encountered in the *Upper Cenomanian* aquifer.

Nitrate distribution according to the soil type

A polygon GIS shapefile of the spatial distribution of the soil types for the entire West Bank was utilized in the analysis described in this section. The spatial distribution of nitrate concentration in groundwater was spatially joined with the corresponding distribution of soil type classes. Table 1 summarizes the mean, median, and maximum nitrate concentrations in the groundwater for the different soil classes for the period from 1981 to 2004. The results indicate that the groundwater under the *Brown-red degrading sandy* soils have a high mean nitrate concentration that exceeds the MCL followed by *Vertisols* soils and *Renzina soils of valleys*. The same ranking is approximately applicable for the median nitrate concentrations. These

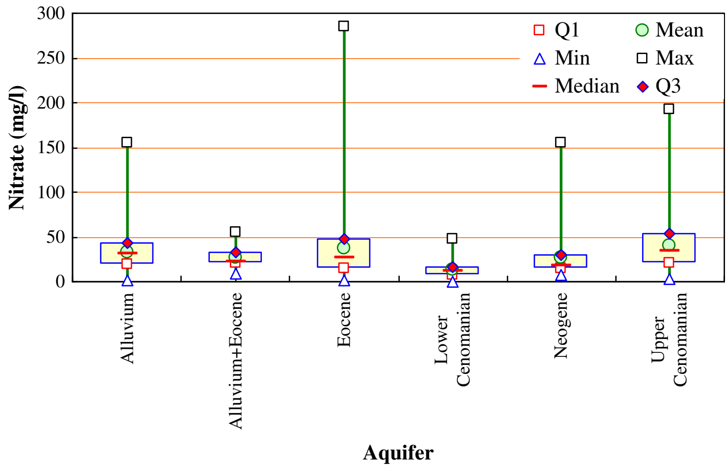

Fig. 8. Statistics of annual nitrate concentration for the aquifer systems for the period from 1981 to 2004.

results do not imply the highest vulnerability to nitrate contamination for the *Brown-red degrading sandy* soils. This is because a small number of wells are located within this soil type class signifying a possible bias in the results.

Except for *Desert stony land* and *Rendzina soils of valleys* soil type classes, all the maximum nitrate concentrations are higher than the MCL. The overall maximum nitrate concentration is found in the groundwater under the *Colluvial-Alluvial* soils with a value of 285 mg/l.

Nitrate distribution according to the watersheds

The West Bank overlays three watersheds; *Dead Sea*, *Jordan River*, and *Mediterranean Sea*. Each of them contains several sub-watersheds. A polygon GIS shapefile of the spatial distribution of the watersheds for the West Bank was utilized in the analysis described in this section. The spatial distribution of nitrate concentrations was spatially joined to the corresponding watersheds. Thereafter, the mean nitrate concentrations were calculated.

Using GIS in summarizing results, the annual maximum and mean nitrate concentrations for each watershed from 1981 to 2004 are summarized in Table 2. The mean in the *Mediterranean* watershed exhibits a general increasing trend and exceeds the MCL in 2004. The opposite takes place in the *Dead Sea* watershed. The mean in the *Jordan River* watershed is almost constant especially in the period after 1990.

The mean nitrate concentrations in the *Jordan River* watershed were always the lowest except in the last five years. The maximum nitrate concentrations in the *Mediterranean Sea* watershed are always above the MCL in the range of 97.5–285 mg/l with an overall peak in 2004. The *Mediterranean Sea* watershed almost has the highest reported maximum nitrate concentrations. Results show that the maximum nitrate concentration exhibits a general increasing trend from the year 2000. The mean nitrate concentration exceeds the MCL in two years; 1982 and 2004.

The mean concentration is somehow close to the MCL in the remaining years in the range of 15–50 mg/l. Nitrate concentrations in this range are the result of anthropogenic effects. The median nitrate concentration also exhibits a general increasing trend from 1984 except for the year 2002 due to missing data. The median nitrate concentrations are always in the range of 15–50 mg/l which is potentially indicating pollution due to human influence. The maximum reported nitrate concentration is from the same watershed.

The maximum nitrate concentrations in the *Jordan River* watershed (except for the years 1981 and 1990) are always above the MCL and range from 61 to 231 mg/l with the peak in 2003. The results show that the annual maximum exhibits a general

Table 1
Mean, median, and maximum nitrate concentrations (mg/l) for the different soil type classes for the period from 1981 to 2004.

Soil types	Number of samples	Mean	Median	Maximum
Alluvial	1265	35.1	27.0	192.5
Brown-red degrading sandy	11	104.3	93.5	164.0
Brown alluvials (Vertisols)	189	46.6	43.0	153.0
Brown desert skeletal	153	25.0	22.0	70.0
Colluvial-alluvial	958	40.7	31.0	285.0
Desert alluvial	1050	32.7	30.3	155.5
Desert stony land	8	11.4	12.0	15.0
Mediterranean brown forest	172	23.0	16.0	130.0
Rendzina (mountains)	45	34.2	17.0	97.0
Rendzina (valleys)	3	46.1	45.0	49.0
Terra Rossa	518	36.3	25.0	231.0

Table 2
Annual maximum and mean nitrate concentrations (mg/l) according to the watershed from 1981 to 2004.

Maximum

Year	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
Dead Sea		127.5	104	73	82	156	101	124.5	87		94	91
Jordan River	41	111.5	136.5	70	78.5	61.5	109.5	141.5	83.5	19	104.5	97.5
Mediterranean		195	205	128	97.5	172	153	212	168.5		192	213

Year	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Dead Sea	77	72	97	73	64	67	80.5	85	61	34.3	79.9	54
Jordan River	106	77	154.5	93.5	150.5	92	107	114	90	73.5	231	143
Mediterranean	153	234	192	145.5	164	138	190	110	122	127	192.5	285

Mean

Year	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
Dead Sea		61.7	43	27.8	26.9	49.5	38.1	50.7	33.2		38.5	37.5
Jordan River	25.3	39.1	25.9	14.1	12.9	18.5	24.2	34.6	19	11	24.6	30.4
Mediterranean		52.6	39.3	25.2	24.6	31.5	35.1	44.4	31.6		36.1	49.1

Year	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Dead Sea	34.6	44	42.9	36.9	32.5	34.8	33.3	39.3	22.3	16.7	26.2	29.3
Jordan River	28.5	25.1	38.4	26.6	30.8	26.8	21.8	28.9	36.9	26.4	32.7	29.8
Mediterranean	42.3	42.8	47.9	39.4	44.2	43	37.1	39	34.8	32.5	48.1	50.4

increasing trend from about 1991. None of the mean nitrate concentrations exceed the MCL. Except for the years 1984, 1985, and 1990; the mean concentration is in the range of 15–50 mg/l. The maximum nitrate concentrations in the *Dead Sea* watershed (with the exception of the year 2002) are always above the MCL and range from 54 to 155 mg/l with the peak in 1986. The results show that the maximum exhibits a general decreasing trend from the year 1982. The mean nitrate concentration also exceeds the MCL in 1982 and 1988. The mean concentration is always in the range of 15–50 mg/l.

Many of the wells in the abovementioned watersheds show high nitrate concentrations over time. More than 28% and 22% of the samples in the *Mediterranean Sea* and *Dead Sea* watersheds have nitrate concentrations above the MCL, respectively. This percentage drops to almost 9% for the *Jordan River* watershed. None of the watersheds had maximum nitrate concentrations below the MCL during the period from 1981 to 2004. Three observed maximum values with a limited number of data; in 1981, 1999, and 2002, show up because of the low maximum nitrate concentrations. There were fluctuations in the maximum nitrate concentrations in the individual watersheds, but in general, there are increasing trends in the *Mediterranean Sea* and *Jordan River* watersheds associated with a decreasing trend in the *Dead Sea* watershed. The *Mediterranean Sea* watershed has the highest maximum nitrate concentrations during the study period.

Vertical nitrate distribution in groundwater

In general, the nitrate concentration in groundwater decreases with increasing sampling depth (Close, Rosen, & Smith, 2001; Freeze & Cherry, 1979; Hallberg, 1989; Hallberg & Keeney, 1993; Tesoriero & Voss, 1997). The frequencies of nitrate sampling based on the depth of the sampling well were significantly varying. Therefore, the nitrate samples were classified based on several depth intervals. Upon inspecting the database, it was noticed that almost half of the nitrate samples fall within the depth interval of 50–100 m. Needless to mention that the depth interval from 0 to 50 is of interest since it represents the nitrate concentration immediately after leaching.

For all the nitrate samples, the nitrate concentrations were associated with the corresponding depth of the sampling wells to investigate the relationship between these two parameters. Fig. 9 depicts this scattered relationship for the West Bank for the years from 1981 to 2004. Many observations can be drawn out from Fig. 9. First, the results compare well with the general trend of nitrate concentration variability with the sampling depth as reported in many studies (Hanson, 2002; Nolan & Stoner, 1995; Parliman, 2002). It is shown that high nitrate concentrations are within the upper 100 m of groundwater in the West Bank. After this depth, nitrate concentrations decrease with depth. Although the nitrate concentrations could have been generally influenced by groundwater recharge, land cover, and soil type, yet, no explicit justifications and conclusions can be made with respect to the vertical nitrate profile in groundwater. Nevertheless, this phenomenon can be attributed mainly due to three main factors; denitrification in groundwater, vertical groundwater movement and the associated nitrate transport, and mixing (Almasri & Kaluarachchi, 2004).

The statistics of the nitrate concentrations based on the depth of the sampling well for the entire West Bank for the period from 1981 to 2004 are shown in Fig. 10. This figure provides a better visualization of the variability of nitrate concentration with depth. Fig. 10 shows that all maximum nitrate concentrations exceed the MCL. The maximum nitrate concentration is encountered at the depth interval of 75–100 m. The figure also shows that the 3rd quartile exceeds the MCL at the following depth intervals of 25–50, 50–75, 100–125, and 175–200 m. The 3rd quartile in the surface wells is below the MCL. Moreover, the highest mean and median nitrate concentrations were within the depth interval of 175–200 m. This observation may be justified by the high groundwater recharge rate or heavy on-ground nitrogen loadings. This observation is in concordant with

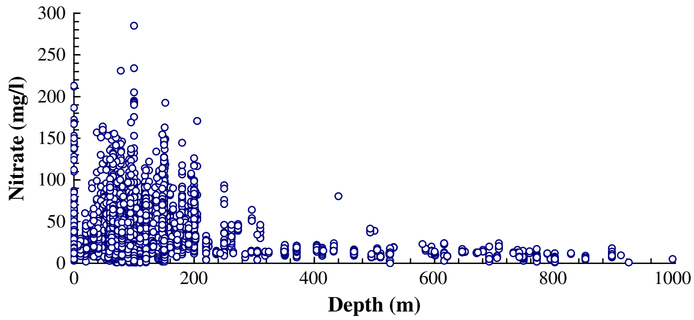

Fig. 9. Variability of nitrate concentration with sampling depth for the West Bank for the period from 1981 to 2004.

the fact that 83% of the samples are located in Qalqilya and Tulkarm districts where agricultural activities are intensive. In addition, pumping rates of these wells are relatively high which enhance the vertical downward transport of nitrate.

Nitrate and population

Urbanization is a pervasive phenomenon around the world and therefore water demands are increasingly growing and intuitively ought to be of adequate water quality (Showers, Genna, Mcdade, Bolich, & Fountain, 2008). Contamination of groundwater in urban areas could possibly result from different sources (see Abu Maila, El-Nahal, & Al-Agha, 2004; Drake & Bouder, 2005; Nolan, Ruddy, Hitt, & Helsel, 1997). Identifying these sources is inevitably a vague and challenging problem. Many studies authenticate that leaking septic tanks and sewer systems in addition to the foregone land use are considerably causing nitrate contamination of groundwater in urban areas (Bohlke, 2002; Showers et al., 2008; Silva et al., 2002). In the West Bank, almost 45% of the households are connected to public sewage networks while the remainder households are connected to cesspits (PCBS, 2007). This obviously confirms the importance of studying the population as a potential polluting parameter and its relevant correlation to nitrate occurrence in the groundwater of the West Bank.

The population size of each locality (community) in the West Bank is given by the PCBS (1997a). The average nitrate concentrations for 82 localities were determined by averaging the mean nitrate concentrations for all the wells that exist within the locality outline. The relationship between the average nitrate concentration and the population size is depicted in Fig. 11.

Although there is an increasing trend in the linear trend line, however, this is not exclusively evidence that there is an explicit relationship between population size and nitrate concentration as the R^2 value is too low. The regression analysis was carried using the least square method. This made it possible to perceive how the nitrate occurrence (dependent variable) is influenced by the number of population (independent variable). Table 3 summarizes the results of this linear regression. As the *P*-value is less than 0.05, we are 95% confident that the population parameter is statistically significant and affecting the nitrate occurrences in the West Bank groundwater resources.

Nitrate distribution with groundwater recharge

Nitrate occurrences in groundwater correspond to the groundwater recharge (Almasri & Kaluarachchi, 2004; Green, Fisher, & Bekins, 2008; Iqbal & Krothe, 1995). Many studies from the literature have shown that nitrate concentration in the

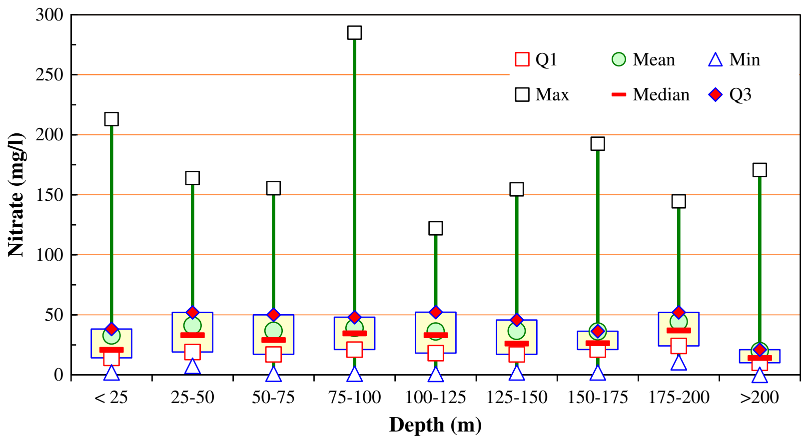

Fig. 10. Statistics of nitrate concentrations based on depth of the sampling well for the entire West Bank for the period from 1981 to 2004.

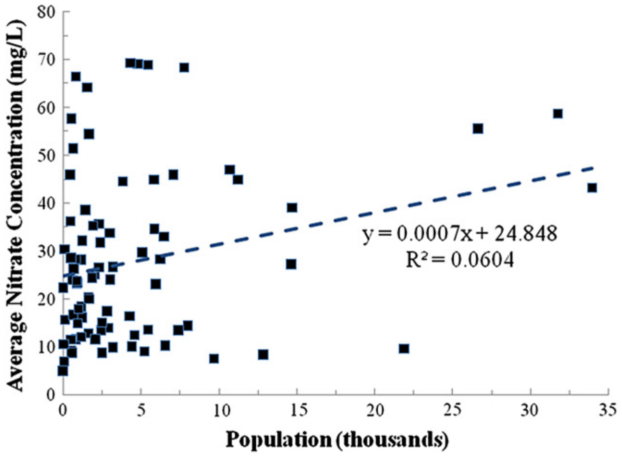

Fig. 11. Average nitrate concentration for 82 localities in the West Bank.

groundwater of shallow aquifers increases with recharge (Hanson, 2002; Saffigna & Keeney, 1977; Spalding et al., 2001). Groundwater recharge is a function of many parameters including but not limited to soil type, antecedent soil water content, land cover, and rainfall (Anuraga, Ruiz, Mohan Kumar, Sekhar, & Leijnse, 2006; Ladekarl, Rasmussena, Christensena, Jensenc, & Hansen, 2005; Sophocleous, 2004). Estimation of groundwater recharge from rainfall is deemed fairly difficult since it depends on these uncertain parameters (Baalousha, 2005) as well as the interactions among all these parameters. Therefore, multiple mathematical models are used for estimating the groundwater recharge from rainfall (see for instance Baalousha, 2005; Hemstreet, 1996; Schroeder, McEnroe, Peyton, & Sjostrom, 1989; Wu, Zhang, & Yang, 1996). In addition to these mathematical models, there are several linear relationships that relate groundwater recharge to rainfall (see for instance Datta, Desai, & Gupta, 1980; Koo & Kim, 2008; Sharda, Kurothe, Sena, Pande, & Tiwari, 2006; Simmers, 1987; Wu & Zhang, 1994).

As such, we have used rainfall as a substitute for recharge for simplicity of analysis. Mapping the relationship between nitrate concentration and the rainfall provides a preliminary understanding of these factors. This relationship can also help in designating the areas of high risk of nitrate contamination in groundwater and thus providing a priority for future management actions.

The available data include annual measurements of nitrate for wells, monthly measurements of water level at these wells, and daily rainfall data for specific rainfall stations. To better conduct a meaningful analysis of nitrate concentrations and corresponding rainfall, the seasonal variability should be addressed, and hence, more frequent measurements of nitrate are essentially required. However, nitrate is measured only once a year and thus the annual rainfall data are used in this analysis in lieu of daily data. Two wells are selected to study the nitrate distribution with rainfall and water level, namely well 14-17/005 in Qalqilya district and well 15-20/004 in Tulkarm district as depicted in Figs. 12 and 13, respectively. As lands in these districts are particularly fertile, agriculture occupies most of the land in these two districts at a rate greater than twice that in the West Bank which is at most 25% of the total land (UNDP, 2003).

In Figs. 12 and 13, nitrate concentrations evidently correspond to the annual rainfall and consequently to the water level. It is obvious that nitrate concentration dramatically increases when both rainfall and water table increase as apparent in the last few years. This observation may be justified by the high groundwater recharge rate (as evident by the high rainfall) and the heavy on-ground nitrogen loadings (due to intense agricultural activities). In addition, the actual annual abstractions for well 14-17/005 and well 15-20/004 are fairly high. As pumping rates of these wells are relatively high, this would modestly enhance the vertical downward transport of nitrate.

Summary and conclusions

Elevated nitrate concentrations in the groundwater of the West Bank are of increasing concern. Almost all the annual maximum nitrate concentrations in the entire West Bank are above the MCL over the period from 1982 to 2004. The results show that the annual median nitrate concentrations are always below the MCL, indicating that at least 50% of the nitrate concentrations are below the MCL. It is noticeable that the mean is always higher than the median and closer to the MCL. In general, all the districts except *Ramallah and Al-Bireh*, have nitrate concentrations that severely exceed the MCL. The areas

Table 3
Results of regression analysis of the nitrate-population data.

	Coefficients	Standard error	*t* Stat	*P*-value	Lower 95%	Upper 95%
Intercept	24.8476	2.3094	10.7594	0.0000	20.2518	29.4435
X Variable 1	0.0007	0.0003	2.2679	0.0260	0.0001	0.0012

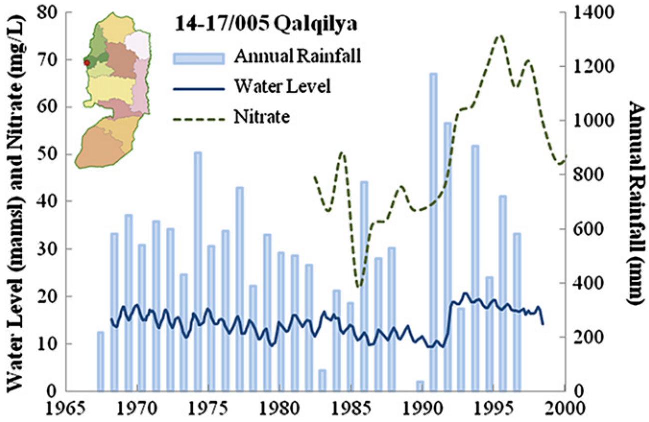

Fig. 12. Annual rainfall, water level, and nitrate concentration for well 14-17/005.

with the most elevated nitrate concentrations are areas characterized by heavy agricultural activities. Such activities are intense in *Jenin*, *Tubas*, *Tulkarm*, and *Qalqilya* districts. Agricultural practices involving inorganic fertilizer applications could be identified as one of the main sources and contributors to nitrate contamination of groundwater in the West Bank. However, further analysis to the fertilizer's application in the study area ought to be conducted to confirm the foregone conclusion.

The analysis confirms that the annual mean nitrate concentration in the *Western* groundwater basin has an increasing trend. Out of the 1301 samples from the *Western* basin, a total of 423 samples or 33% (mostly in *Qalqilya* and *Tulkarm* districts) exceed the MCL. From the analysis, it can be concluded that the most vulnerable groundwater basin to contamination is the *Western* basin. This result can be attributed to the agricultural activities along with the high groundwater recharge. It is noted that all the aquifer systems, except the *Lower Cenomanian*, have mean and median nitrate concentrations close to the MCL, typically in the range of 15–50 mg/l. Nitrate concentration in this range is the result of anthropogenic effects. The highest mean and median nitrate concentrations are encountered in the *Upper Cenomanian* aquifer.

For the soil types, almost all the maximum nitrate concentrations are higher than the MCL. The overall maximum nitrate concentration is found in the groundwater under the *Colluvial-Alluvial* soils with a value of 285 mg/l. The annual mean nitrate concentration in the *Mediterranean* watershed exhibits a general increasing trend and exceeds the MCL in 2004 as an indication that it is the most vulnerable watershed to nitrate contamination. During analysis, it is found that high nitrate concentrations are within the upper 100 m of groundwater in the West Bank. After this depth, nitrate concentrations decrease with depth.

Regression analysis proves that the population parameter is statistically significant and affecting the nitrate occurrences in the West Bank groundwater resources. This authenticates that leaking cesspits and sewer systems are considerably causing nitrate contamination of groundwater predominantly in urban areas. Nitrate concentrations are evidently corresponding to the annual rainfall and consequently to the water level. It is obvious that nitrate concentration dramatically increases when both rainfall and water table increase as apparent in the last few years. This observation may be justified by the high groundwater recharge rate (as evident by the high rainfall) and due to the heavy on-ground nitrogen loadings (due to intense agricultural activities).

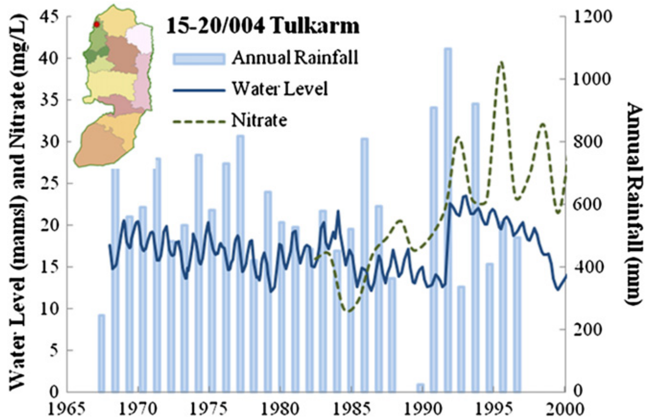

Fig. 13. Annual rainfall, water level, and nitrate concentration for well 15-20/004.

In light of the analysis carried out in this paper, the nitrogen sources in the study area may include (but not limited to) manure, inorganic fertilizers, atmospheric deposition, irrigation with nitrogen-contaminated groundwater, nitrogen fixed by legumes, and leaking cesspits and sewer systems. Eventually, more frequent sampling will provide better understanding of nitrate occurrences and distribution temporally and spatially, identify accurately the nitrate contamination sources, and ultimately aid in the selection of the best management options. Overall, this will inevitably develop the planning and management of groundwater resources in the West Bank under the current and future challenges.

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