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# Assessment of intrinsic vulnerability to contamination for Gaza coastal aquifer, Palestine

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**Abstract**

Gaza coastal aquifer (GCA) is the major source of fresh water for the 1.5 million residents of Gaza Strip, Palestine. The aquifer is under deteriorating quality conditions mainly due to the excessive application of fertilizers. The intrinsic vulnerability of GCA to contamination was assessed using the well-known DRASTIC method. Detailed analysis of the intrinsic vulnerability map of GCA was carried out and did consider different relationships between the vulnerability indices and the on-ground nitrogen loadings and land use classes. In addition, correlation between vulnerability values and the nitrate concentrations in GCA was studied. Based on the vulnerability analysis, it was found that 10% and 13% of Gaza Strip area is under low and high vulnerability of groundwater contamination, respectively, while more than 77% of the area of Gaza Strip can be designated as an area of moderate vulnerability of groundwater contamination. It was found that the density of groundwater sampling wells for nitrate concentration is high for the moderate and high vulnerability zones. The highest first quartile, median, mean, and third quartile of nitrate concentrations are reported in the high vulnerability zones. Results of sensitivity analysis show a high sensitivity of the high vulnerability index to the depth to water table.


*Keywords:* Groundwater; Vulnerability; Agriculture; Fertilizers; Management; Coastal aquifers; Palestine

## 1. Introduction

Groundwater is the most important water resource on earth (Villeneuve et al., 1990). The quality of groundwater is generally under a considerable potential of contamination especially in agriculture-dominated areas with intense activities that involve the use of fertilizers and pesticides (Giambelluca et al., 1996; Soutter and Musy, 1998; Lake et al., 2003; Thapinta and Hudak, 2003; Chae et al., 2004). The issue of protection of groundwater against pollution is of crucial significance (Zektser et al., 2004). The concept of groundwater vulnerability is a cornerstone in the evaluation of the risk of groundwater contamination and in the development of management options to preserve the quality of groundwater (Fobe and Goossens, 1990; Worrall et al., 2002; Worrall and Besien, 2004).

Groundwater vulnerability maps provide useful information to protect groundwater resources and to evaluate the potential for water quality improvement with changes in agricultural practices and land use applications (Burkart and Feher, 1996; Rupert, 2001; Connell and Daele, 2003; Babiker et al., 2005). In addition, such maps can be used for regional planning and development of groundwater resources since they provide a preliminary indication of possible contamination risks of groundwater (Fobe and Goossens, 1990; Worrall et al., 2002).

Groundwater vulnerability mapping is based on the idea that specific land areas are more vulnerable to groundwater contamination than others (Gogu and Dassargues, 2000). Hence, groundwater vulnerability assessment delineates areas that are more susceptible to contamination due to the hydrogeologic factors and anthropogenic sources and shows areas of greatest potential for groundwater contamination. In general, this connotes the estimation of the potential for contaminants to migrate from the land surface through the unsaturated zone until reaching the areas of interest (Connell and Daele, 2003). As such, the concept of groundwater vulnerability is important for a rational management of groundwater resources and

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subsequent land use planning (Rupert, 2001; Connell and Daele, 2003; Babiker et al., 2005).

The importance of groundwater vulnerability assessment to contamination arises from the fact that groundwater monitoring is time consuming and too costly to adequately define the geographic extent of contamination at a regional scale. Thus, examination and identification of the spatial distribution of the various vulnerable areas to contamination is quite important. The vulnerability maps are useful tools for allocating limited monitoring resources to areas where they are most needed (Burkart et al., 1999; Thapinta and Hudak, 2003).

There are two major vulnerability assessment types, intrinsic and specific. Intrinsic vulnerability deals with pollution possibilities without considering a particular pollutant. Specific vulnerability means that vulnerability refers to a specific contaminant of interest (Mádl-Szönyi and Füle, 1998). Many techniques exist to compute the vulnerability of groundwater resources to contamination. However, simple techniques are preferable over more sophisticated ones especially when considering that the output of the vulnerability assessment will be utilized to set up preliminary management options to minimize groundwater contamination. The DRASTIC method developed by Aller et al. (1985) is one of the most widely used methods to assess intrinsic groundwater vulnerability to contamination (Banton and Villeneuve, 1989; Evans and Mayers, 1990; Navulur, 1996; Rupert, 2001; Al-Adamat et al., 2003; Babiker et al., 2005). The DRASTIC method integrates simple qualitative indices that bring together key factors believed to influence the solute transport processes (Connell and Daele, 2003). In the US, the DRASTIC method was developed as a means of creating an index to rank sites in terms of their vulnerability to contamination.

The use of groundwater vulnerability assessment in planning, policy analysis, and decision making varies and reflects different aspects including (but not limited to): (i) advising decision makers of the need for adopting specific management options to mitigate the quality of groundwater resources; (ii) elucidating the implications and consequences of their decisions; (iii) providing direction for allotting water resources; (iv) enlightening decisions about land use practices and activities; and (v) educating the general public about the potential for groundwater contamination throughout public awareness campaigns (National Academy of Sciences, 1993).

The outcome of groundwater vulnerability assessment is of great importance especially in cases where the groundwater is the sole source of fresh water. This is the very situation in Gaza Strip, Palestine. Gaza coastal aquifer (GCA) is almost the only source for drinking water to over 1.4 million residents of Gaza Strip and is utilized extensively to satisfy agricultural, domestic, and industrial water demands. Most municipalities in Gaza Strip use groundwater without any treatment except for disinfection. Contamination of the groundwater of the GCA is a major continuing problem not only due to the existence of different point and non-point contaminating sources but also due to the high vulnerability of the aquifer to pollution. Human activities such as the unmanaged handling and dumping of solid wastes, the improper disposal of wastewater, and the concentrated agricultural practices have contributed to the current deteriorating quality of GCA. The efforts put-forth to boost up the agricultural production and the associated revenue had led to the excessive application of fertilizers, pesticides, herbicides, and soil fumigants. This in turn did elevate the contamination occurrences in GCA. In addition, the infiltration of untreated leaking wastewater and the overloaded malfunctioning treatment plants and the corresponding effluent contribute to the on-going contamination of GCA. Due to the above-mentioned malpractices, high occurrences of nitrates, pesticides, and chlorides are being encountered in GCA (UNEP, 2003).

The continually increasing demand for potable water and the on-going degradation of the groundwater quality in GCA motivated the restoration and preservation of the aquifer. To address the water quality related issues and problems, the Palestinian Water Authority (PWA) in collaboration with the Palestinian Environmental Quality Authority (EQA) has developed the first National Water Plan and the National Environmental Action Plan in part to better manage and preserve the water resources including groundwater by promoting protective policies. Such policies demand that the agricultural and industrial development to be in full compliance with the available water resources based on sustainable development and that pollution control measures ought to be introduced and ensured through enforcement if needed.

As such, restoration efforts have intensified the need for developing protection alternative measures and management options such that the high contamination occurrences in the aquifer are reduced. This implies for instance that nitrate concentrations at the critical receptors are below the maximum contaminant level (MCL) of 10 mg/L $NO_3$-N as set up by the US Environmental Protection Agency (US EPA, 2002). Such protection alternatives include the restriction on the use of fertilizers and the proper treatment and disposal of wastewater.

The first step in proposing and developing efficient management options is through the spatial assessment and evaluation of groundwater vulnerability to contamination. This assessment points out the areas of high priority that can be easily contaminated. At such areas, agricultural activities and wastewater disposal can be controlled, minimized, or even banned. This is obvious since groundwater contamination is most likely to occur in areas having high vulnerability to contamination such as areas characterized by shallow groundwater table and sandy soils with high infiltration rates as the case for GCA. Therefore, a quantitative evaluation of a regional vulnerability map is needed and ought to be developed for GCA to facilitate the demarcation of the high susceptibility areas to contamination. Once such high priority areas are outlined, a preliminary economic analysis can be conducted to evaluate the cost incurred from introducing the proposed protection alternative measures that aim at restoring the groundwater quality through the efficient management of the on-ground pollution sources.

Several impediments limit the use of vulnerability-based analysis and subsequent decision making. Key limitations include the inability to process and manage the large volumes of data required for carrying out such analysis and the difficulty in accounting for the spatial heterogeneities associated with the systems of natural resources (Tim et al., 1996). A geographic information system (GIS) offers the tools to manage, manipulate, process, analyze, map, and spatially organize the data to facilitate the vulnerability analysis. In addition, GIS is a sound approach to evaluate the outcomes of various management alternatives (Wylie et al., 1995; Tim et al., 1996; Burkart and Feher, 1996; Nolan et al., 1997; Refsgaard et al., 1999; Lasserre et al., 1999; Shaffer et al., 2001; Hall et al., 2001; Almasri and Kaluarachchi, 2003; Thapinta and Hudak, 2003; Lake et al., 2003; Al-Adamat et al., 2003; Almasri and Kaluarachchi, 2004; Jordan and Smith, 2005).

This paper utilizes the DRASTIC method and GIS for developing a groundwater intrinsic vulnerability map for GCA in order to be utilized in the demarcation of the areas of high susceptibility to contamination and to aid in the development of the management options to preserve/restore GCA. Detailed analysis of the intrinsic vulnerability map of GCA was carried out. The dissimilar relationships between the vulnerability indices with different explanatory parameters such as the on-ground nitrogen loadings and land use classes were investigated. In addition, correlation between vulnerability values and the nitrate concentrations in GCA was studied.

## 2. Groundwater vulnerability assessment methods

The concept of aquifer vulnerability to contamination has dissimilar meanings and definitions. In its broadest perspective, groundwater vulnerability indicates whether the on-ground activities will result in contaminating the underlying aquifer or not. According to The National Academy of Sciences (1993), groundwater vulnerability to contamination is *The tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer.* As can be inferred from the above definition, groundwater vulnerability is not an absolute or measurable property, but an indication of the relative possibility with which contamination of groundwater resources will occur. This understanding implies a very basic vulnerability concept that all groundwater is vulnerable.

Often a key product of a vulnerability assessment is a map, delineating areas of different vulnerability extents. Presentation of vulnerability results may include the demarcation of regions with different vulnerability levels so that resource allocation decisions can be made. Such maps are very easily understood through the use of the graphical means for conveying information to decision makers. Such graphical means include mainly GIS (Tim et al., 1996). In addition, a vulnerability assessment could be used to determine areas where specific practices and activities should be restricted or prohibited and/or explicit management alternatives ought to be put into action.

Plentiful approaches have been proposed and utilized for assessing groundwater vulnerability. These approaches range from complicated models of the physical, chemical, and biological processes occurring in both the vadose zone and groundwater regime, to models that weight crucial factors deemded to have an effect on vulnerability through either expert judgment or statistical methods. The potential for contaminants to leach and reach groundwater depends on many factors, such as the structure of the soils and geologic material in the unsaturated zone, the depth to the water table, the recharge rate, and environmental factors.

The composition of the unsaturated zone can greatly influence chemical and biological transformations and reactions. For the depth to the water table, longer flow paths from land surface to the water table can diminish the potential for contamination by pollutants that sorb or decay along the flowpath. The recharge rate is critical because it dictates and influences the extent and rate of transport of contaminants through the unsaturated zone (Alemaw et al., 2004). Finally, environmental factors, such as temperature and water content, can significantly influence the loss of contaminants by microbial transformations.

Generally, complex and detailed methods require more complex and detailed knowledge of the system being assessed. Simpler methods incorporate more approximations and are less precise, but require less detailed information about the system being assessed. Although complex methods may describe transport mechanisms more precisely, the data required are often unavailable and must be approximated from limited existing information. In the following, a brief description of the three main methods used in vulnerability assessment is presented.

### 2.1. Overlay and index methods

Overlay and index methods depend principally on qualitative or semi-quantitative compilations, assemblage, explanation, and interpretations of mapped data. Overlay and index methods are driven largely by data availability and expert judgment rather than with processes and kinetics controlling groundwater contamination. An overlay-type groundwater vulnerability map is prepared by superposing a series of maps viewing the distributions of attributes considered important in characterizing the potential for groundwater contamination. In general, the product is a single map depicting areas of differing vulnerability, designated by a score, pattern, or color. On the contrary to simple overlay methods, index methods assign a numerical value to each attribute based on its magnitude or qualitative ranking. Each attribute, in turn, is assigned a relative importance or weight compared to the other attributes. The weighted-attribute ratings are summed to obtain an overall numerical score for groundwater vulnerability. These numerical scores are used to congregate similar areas into classes or categories of vulnerability, low, medium, and high; that are then displayed on the intrinsic vulnerability map. The most widely-used indexing method is the DRASTIC method (Aller et al., 1985). The DRASTIC method is universally applicable and incorporates parameters that should be available to some degree virtually everywhere. Elucidation of DRASTIC method is furnished in Section 3.

### 2.2. Process-based simulation models

Process-based simulation models incorporate many of the physical, chemical, and microbial processes that dictate the fate and transport of contaminants in the unsaturated and saturated zones. These models are distinctive from all other methods because they predict contaminant transport in both space and time. Generally, process-based models have been developed and applied primarily by research scientists rather than by regulators. These models vary in the level of complexity and data requirements. They may employ the advective–dispersive solute transport approach along with different chemical reaction models that can describe the dynamics a pollutant may undergo. An example of such models include SUTRA (Voss, 1984), PRZM (Carsel et al., 1985), LEACHP (Wagenet and Histon, 1987), and GLEAMS (Leonard et al., 1987). Several authors have combined GIS with process-based models. For instance, Pierce et al. (1991), Shaffer et al. (1995) and Ersahin and Karaman (2001) used the NLEAP model (Shaffer et al., 1991) to predict the spatial distribution of nitrate leaching. de Paz and Ramos (2002) linked GIS with the GLEAMS model to facilitate the assessment of nitrate leaching at a regional scale and thus the identification of the nitrate pollution risk areas.

### 2.3. Statistical techniques for vulnerability assessment

Statistical methods can be used to evaluate, determine, assess, and quantify the association between measures of vulnerability and various explanatory parameters that are deemed to be highly related to vulnerability. Statistical methods rely on the concept of uncertainty which is described in terms of probability distributions for the variables of interest. Statistical methods relate the probability of a contaminant concentration to exceed a threshold concentration to a set of possible influencing variables (Nolan et al., 2002; Twarakavi and Kaluarachchi, 2005). Statistical approaches are flexible since they can deal with qualitative, quantitative, or mixed data sets. Examples of statistical methods include simple and multiple regression analysis for single and multivariate variables and analysis of variance. A possible application of statistical techniques in groundwater vulnerability assessments includes the estimation of the likelihood that a pollutant will contaminate the underlying aquifer.

## 3. The DRASTIC method

The DRASTIC method was developed by the US EPA to be a standardized system for evaluating groundwater vulnerability to pollution (Aller et al., 1985). The primary purpose of DRASTIC is to provide assistance in resource allocation and prioritization of many types of groundwater-related activities and to provide a practical educational tool. DRASTIC can be used to set priorities for areas where groundwater monitoring activities can be carried out. For example, a denser monitoring system might be installed in areas where aquifer vulnerability is higher and land use suggests a potential source of pollution. DRASTIC is named for the seven factors considered in the method: depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone media, and hydraulic conductivity of the aquifer (Aller et al., 1985). Each of the abovementioned hydrogeologic factors is assigned a rating from *one* to *ten* based on a range of values. The ratings are then multiplied by a relative weight ranging from *one* to *five* as summarized in Table 1. The most significant factors have a weight of *five* while the least significant have a weight of *one*. The equation for determining the DRASTIC index is (Aller et al., 1985)

$$D_wD_r + R_wR_r + A_wA_r + S_wS_r + T_wT_r + I_wI_r + C_wC_r, \tag{1}$$

where $D$, $R$, $A$, $S$, $T$, $I$, $C$ represent the seven hydrogeologic factors, $r$ designates the rating, and $w$ the weight. The resulting DRASTIC index represents a relative measure of groundwater vulnerability. The higher the DRASTIC index, the greater the vulnerability of the aquifer to contamination. A site with a low DRASTIC index is not free from groundwater contamination, but it is less susceptible to contamination compared with the sites with high DRASTIC indices. The DRASTIC index can be converted into qualitative risk categories of low, moderate, high, and very high corresponding to the intervals 1–100, 101–140, 141–200, and greater 200; respectively.

## 4. Description of the study area

This section is intended to provide a concise overview of Gaza Strip and GCA. Gaza Strip is a narrow, low-lying stretch of sand dunes bordering the Mediterranean Sea as shown in Fig. 1. It forms the foreshore that slopes gently up to an elevation of 105 m. The total area of Gaza Strip is 365 km$^2$ with an approximate population of 1.4 million and a coastline of 40 km. Gaza Strip has a characteristically semi-arid climate (Metcalf and Eddy, 2000). Annual average rainfall ranges between 400 mm in the north to about 200 mm in the south near Rafah. Apparently, there is

Table 1
Assigned weights for DRASTIC hydrogeologic factors (Aller et al., 1985; Babiker et al., 2005)

| Hydrogeologic factor | Description | Weight |
|---|---|---|
| Depth to water | Represents the depth of material from the ground surface to the water table through which a contaminant travels before reaching the aquifer. The shallower the water depth, the more vulnerable the aquifer is to pollution | 5 |
| Net recharge | Represents the total quantity of water that reaches the water table. Recharge is the principal vehicle for leaching and transporting contaminants. The more the recharge is, the more vulnerable the aquifer is | 4 |
| Aquifer media | Represents the media that serves as an aquifer. The larger the grain size is and the more fractures or openings within the aquifer are, the higher the permeability, and thus vulnerability, of the aquifer | 3 |
| Soil media | It is the upper weathered zone of the earth. In general, the less the clay shrinks and swells and the smaller the grain size of the soil, the less likely contaminants will reach the water table and the less vulnerable the aquifer is | 2 |
| Topography | It refers to the slope of the land surface. Topography indicates whether a pollutant will run off or remain long enough to infiltrate. Where slopes are high, there is high runoff, and the high vulnerable the aquifer is | 1 |
| Impact of vadose zone media | It is the unsaturated zone above the water table. The texture of the vadose zone determines the time of travel of the contaminant through it | 5 |
| Hydraulic conductivity | It refers to the rate at which water flows horizontally through an aquifer. The higher the conductivity is, the more vulnerable the aquifer | 3 |

a general north-south pattern of rainfall. There is a five-month period in winter (November–March) with a rainfall surplus. During the rest of the year, evaporation greatly exceeds the rainfall. The annual average relative humidity is about 72%. The average mean daily temperature in Gaza City ranges from 26 °C in summer to 12 °C in winter.

The width of GCA varies from 3–10 km in the north to about 20 km in the south. The depth to groundwater in GCA ranges from 60 m in the east to 8 m or less near the shore. The coastal aquifer is composed of sands, calcareous sandstone, and pebbles. Semi-permeable and impermeable layers are sandwiched in between, dividing the aquifer system into sub-aquifers especially in the western part. Further inland, the sub-aquifers effectively merge to form one system. All along the coast, there are areas of seawater intrusion due to over-pumping of the freshwater aquifer. The topography of Gaza Strip is characterized by elongated ridges and depressions, dry streambeds and shifting sand dunes.

Heavy agricultural activities take place in Gaza Strip including citrus and greenhouses. A land use map of Gaza Strip is shown in Fig. 1 and is based on the regional plan developed by the Palestinian Ministry of Planning and International Cooperation in 1998 for the West Bank and Gaza Strip. Agricultural land occupies about 65% of the land surface and is the dominant economic sector in Gaza Strip. The heavy agricultural activities in Gaza Strip have led to elevated nitrate concentrations in GCA beyond the MCL of 10 mg/L $NO_3$-N as depicted in Fig. 2. Fig. 3 shows the spatial distribution of the annual average nitrate concentration for GCA for the years from 2000 to 2004. The average percentage of MCL exceedance for the sampled wells for the years from 2000 to 2004 is approximately 84%.

GCA consists of the Pleistocene age Kurkar Group and recent (Holocene age) sand dunes. The Kurkar Group consists of marine sandstone, reddish silty sandstone, silts, clays, unconsolidated sands, and conglomerates. Regionally, the Kurkar Group is distributed in a belt parallel to the coastline. Fig. 4 presents a generalized geological cross-section of the coastal aquifer (Baalousha, 2003). Within Gaza Strip, the thickness of the Kurkar Group increases from east to west and ranges from about 70 m near the Gaza border to approximately 200 m near the coast. Marine clays are present along the coast at various depths within the formation. They pinch out about 5 km from present coastline and appear to become more important towards the base of the Kurkar Group. The dune sands and loess soils which overlie the Kurkar Formation consist of mostly fine, well-sorted sands of eolian origin.

## 5. Development of the intrinsic vulnerability map for GCA

### 5.1. Discretization of the study area

Eq. (1) is the basis for computing the DRASTIC index for a specific area and hence the basis for carrying out the vulnerability assessment. Since the aim is to produce an intrinsic vulnerability map for GCA, as a result, the map represents spatial indicators that vary from place to place across the study area based on the spatial distribution of the parameters present in Eq. (1). In other words, spatiality of data input and output is inherent and inescapable. In order to account for this spatiality, the study area, often referred to as the model domain, is divided into smaller areas, called cells, such that each area carries a one representative value that is assumed constant. Once the discretization of Gaza Strip is carried out, all the input parameters are processed in concordant with this discretization. If the input parameters are referred to as layers

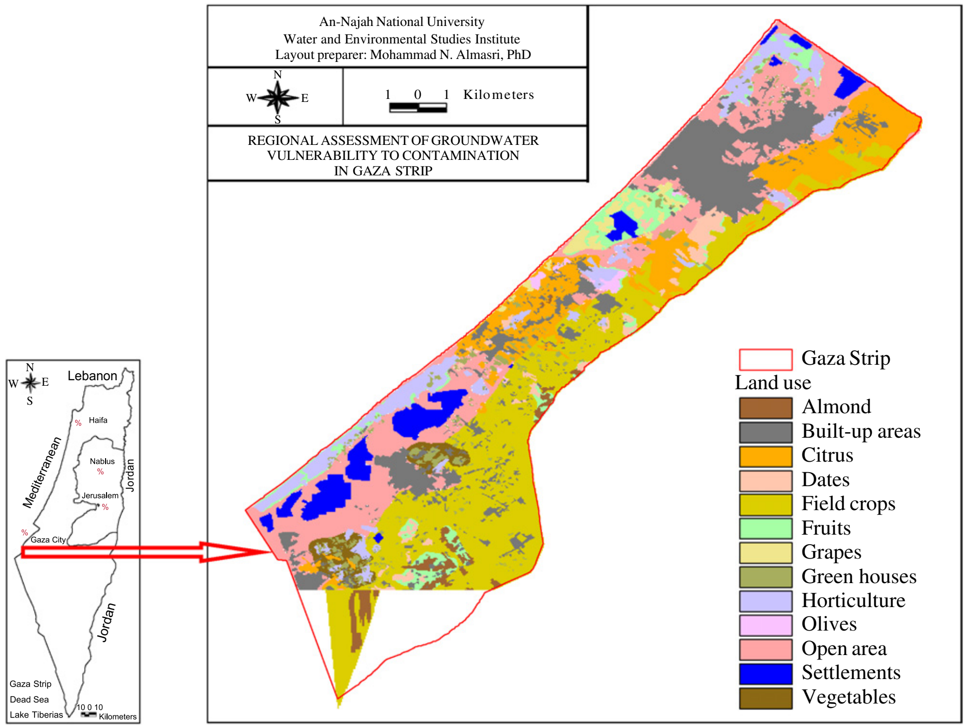


Fig. 1. Land use distribution of Gaza Strip (adapted from the database of the PWA).

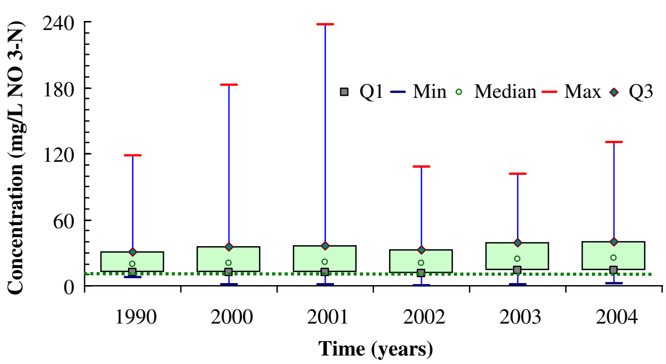


Fig. 2. Boxplots of monthly nitrate concentration in the aquifer for the years from 2000 to 2004. The dotted line denotes the MCL.

(a common nomenclature used in GIS), then the internal discretization should be identical compared to the other layers. This is essential to permit the sequential processing of the different parameters as described by Eq. (1). A finite-difference grid was used to discretize Gaza Strip with uniform squared cell sizes of $50 \times 50\,m^2$. This resolution was thoroughly considered after a close examination of the different properties pertaining to the DRASTIC method implementation. That is, no parameter such as groundwater recharge and so varies within the designated cell size. For each cell of the finite-difference grid, Eq. (1) is implemented and a unique DRASTIC index is obtained. Therefore, the ultimate output will be a grid comprised of cells where each cell carries a DRASTIC index and the transpired grid is a grid of DRASTIC indices or more specifically the intrinsic vulnerability map.

### 5.2. Preparation of the DRASTIC parameters

Preparation of the DRASTIC input parameters entails processing the available data to produce the grids that can be later assigned the ratings. The spatial distribution of the depth to groundwater was computed using the grid calculator of GIS by subtracting the water table elevation from the ground surface elevation distribution. The water table elevation grid was obtained from a groundwater flow model that was developed by the author for GCA using MODFLOW (Harbaugh and McDonald, 1996) while the ground surface elevation grid was interpolated from a GIS point shapefile of ground surface elevation using GIS capabilities and converting the shapefile to a grid. The distribution of groundwater recharge of GCA was computed based on rainfall, irrigation return flow, wastewater leakage (cesspits and wastewater network), and leakage from water supply network. Rainfall distribution was computed using data from 15 rainfall/meteorological stations using the Thiessen method as supported by GIS. Based on Metcalf and Eddy (2000), the infiltration fractions from rainfall were considered as 0.6 and 0.15 for sand and clay, respectively. For groundwater recharge from irrigation, the GIS tabular data manager capability was used to select irrigated agricultural areas. The average irrigation depths were computed from the actual pumping rates from the agricultural wells. It was assumed, based on Metcalf and Eddy (2000), that a fraction of 0.25 from irrigation recharges GCA. The remaining groundwater recharge components were considered based on Metcalf and Eddy (2000). As for the percentage slope of ground

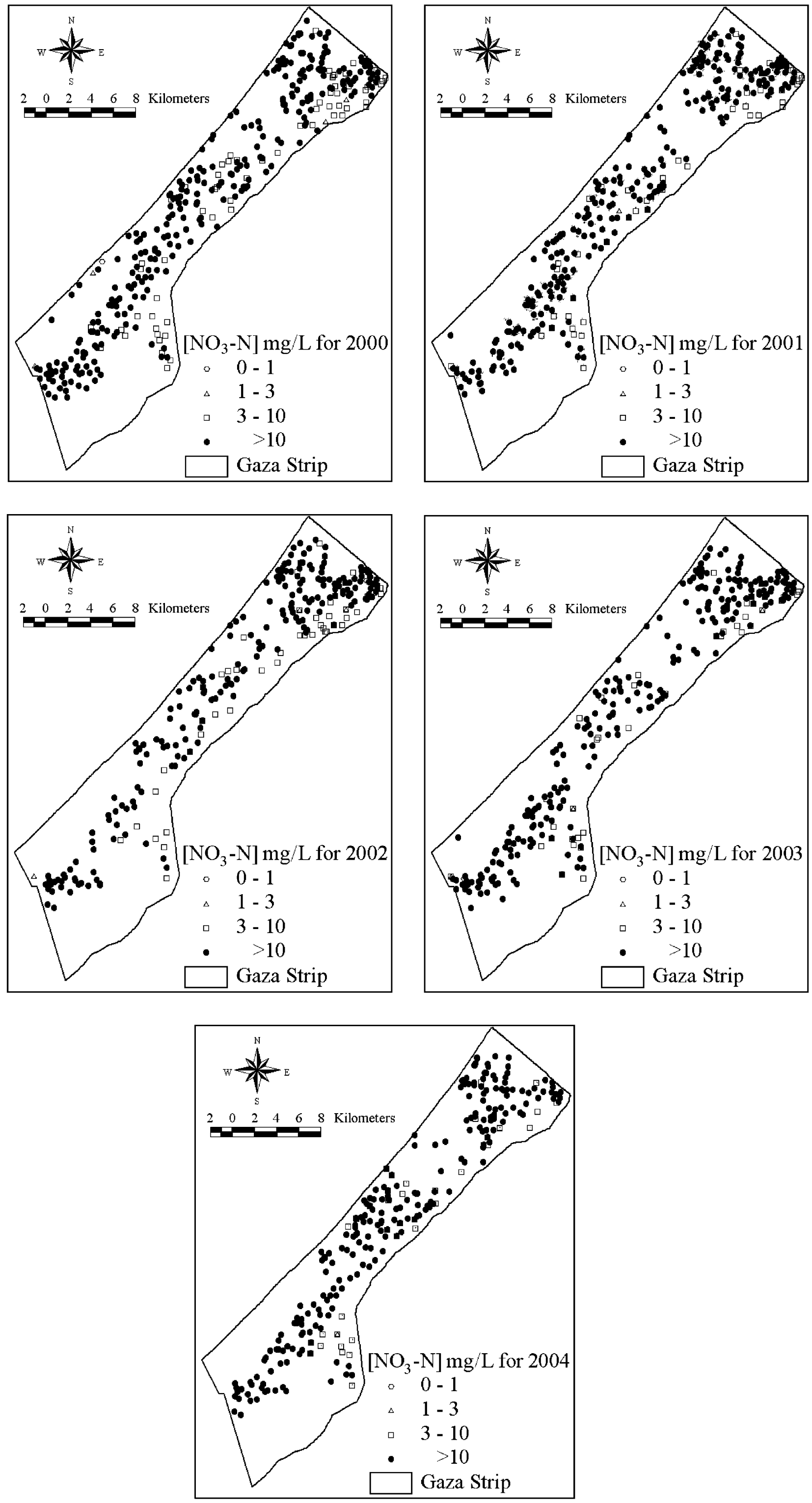


Fig. 3. The spatial distribution of average annual nitrate concentration for GCA for the years from 2000 to 2004.

surface, it was computed using GIS Spatial Analyst based on the ground surface elevation. The spatial distributions of the aquifer hydraulic conductivity and the soil, vadose zone, and aquifer media were obtained for GCA and processed appropriately. After obtaining all the seven input parameters needed to implement Eq. (1), categorization of these parameters was carried out and the corresponding rates were assigned accordingly. Fig. 5 depicts the maps of the rates of depth to water table and net recharge for the study area.

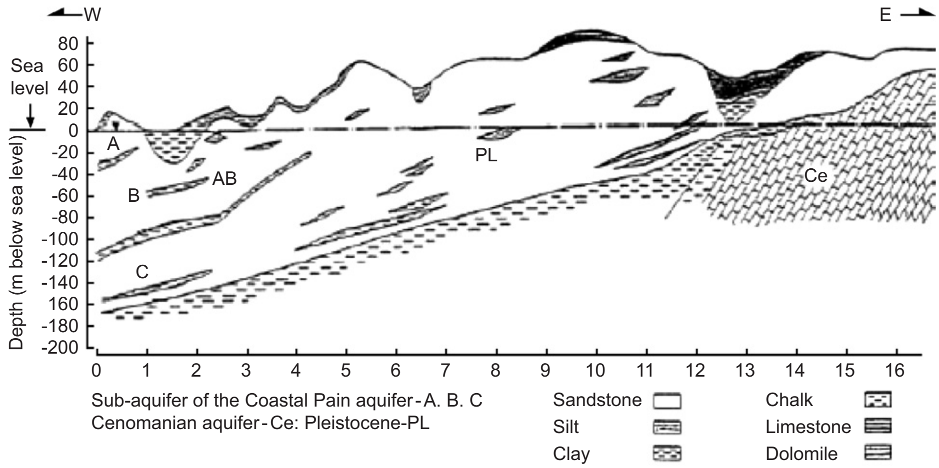


Fig. 4. Generalized geological cross-section of the coastal aquifer (Baalousha, 2003).

### 5.3. *The map of vulnerability to contamination for GCA*

Fig. 6 depicts the intrinsic vulnerability map for GCA. As can be seen from Fig. 6, the DRASTIC values for GCA fall between 80 and 180. Apparently, the vulnerability areas are concentrated in the southern eastern parts of Gaza Strip. High vulnerability zones are located across the shoreline and in the center of Gaza Strip. For better assessment, the DRASTIC values were converted into qualitative indices (see Fig. 7) based on the classifications furnished earlier. To better assess the very extent of the different vulnerability zones within Gaza Strip, Figs. 8 and 9 were developed to elucidate the variability of the DRASTIC index according to the occupied area. It can be concluded, based on Figs. 8 and 9 that 10% and 13% of Gaza Strip is under low and high vulnerability of groundwater to contamination, respectively. More than 77% of the area of Gaza Strip can be designated as an area of moderate vulnerability of groundwater to contamination. One can also tell from Fig. 8 that the high frequency of vulnerability zones occurs within the moderate qualitative indexed area. A close look at Fig. 8 shows that a considerable area in Gaza Strip that is under moderate vulnerability is close to the high vulnerability zone. Considering the uncertainty in the parameters used in developing the DRASTIC indices, a gray area is expected between moderate and high vulnerability zones. This uncertainty may in reality affect the distribution of the vulnerability qualitative indices of Fig. 9.

## 6. Model output evaluation and validation

### 6.1. *Groundwater vulnerability and the nitrate sampling wells*

As mentioned earlier in this paper, one of the major uses of vulnerability assessments is the optimal determination of the spatial distribution of the groundwater monitoring wells such that the areas of high vulnerability indices are well covered. This resource allocation is essential for an efficient capturing of nitrate dynamics especially in the areas characterized by high vulnerability to contamination. Fig. 7 shows the spatial distribution of the wells that were sampled for nitrate concentration for the period from 2000 to 2004. Apparently, the wells cover fairly well GCA. However, for a better assessment of the well distribution beyond eye inspection, the number of wells for the total area of each vulnerability zone was computed and summarized in Table 2. The density of groundwater sampling wells for nitrate concentration is high for the moderate and high vulnerability zones for Gaza Strip, which allows an effective assessment of nitrate pollution in these areas.

### 6.2. *Groundwater vulnerability and nitrate contamination*

In order to examine the relationship between groundwater vulnerability zones and nitrate contamination of groundwater, GIS was utilized to spatially join the map of the vulnerability zones and the map of the point nitrate concentrations in Gaza Strip. The intrinsic vulnerability map which is a polygon map is spatially joined with the nitrate concentration map which is a point map. The outcome of this joining is a table that indicates the nitrate concentration values and the corresponding vulnerability zone index. Fig. 10 shows the boxplots of the distribution of the nitrate concentrations for the three DRASTIC qualitative indices. As can be concluded from this figure, the highest first quartile, median, mean, and third quartile nitrate concentrations are for the high vulnerability zones. However, the highest value of the maximum nitrate concentration is encountered in the moderate vulnerability zones. Apparently, there is no conclusive relationship between nitrate concentration in GCA and the vulnerability indices. One possible reason for this is that the

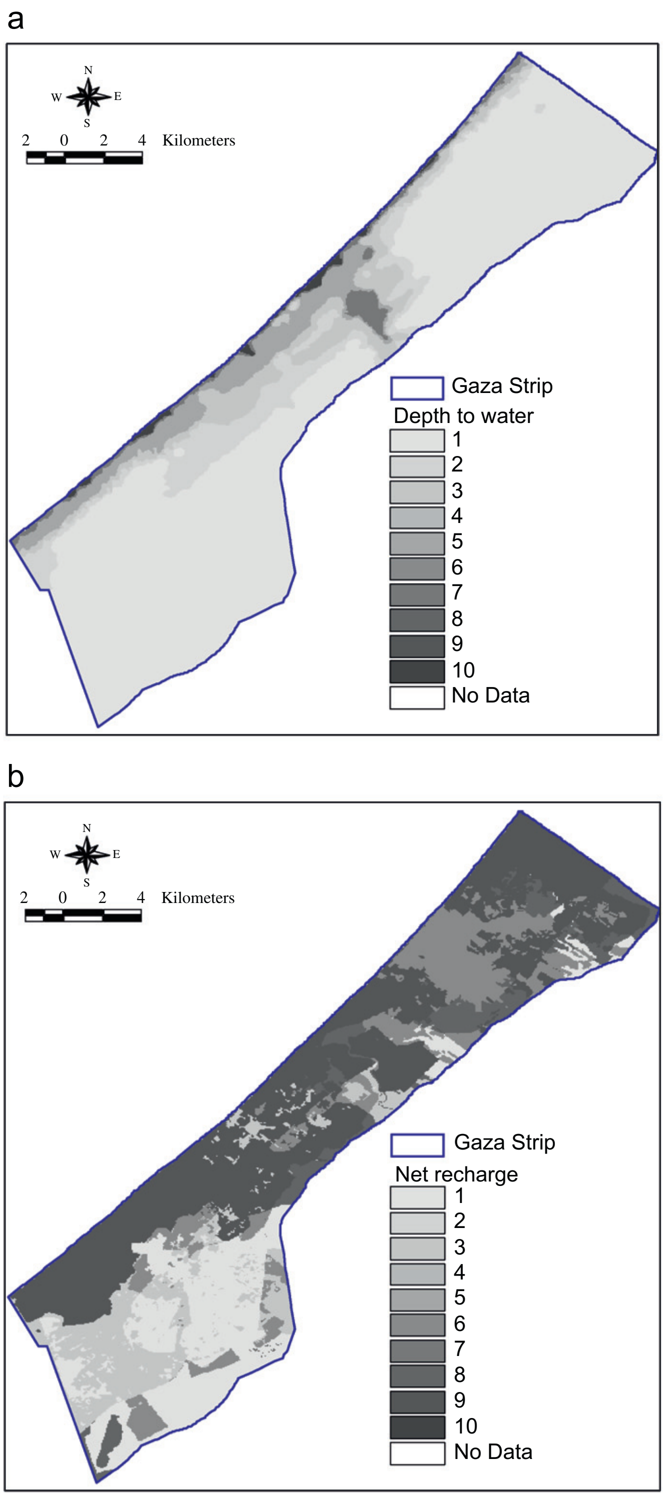


Fig. 5. The rated maps of (a) depth to water and (b) net recharge. The rating score 1 implies a minimum impact on vulnerability while the score 10 indicates the maximum impact.

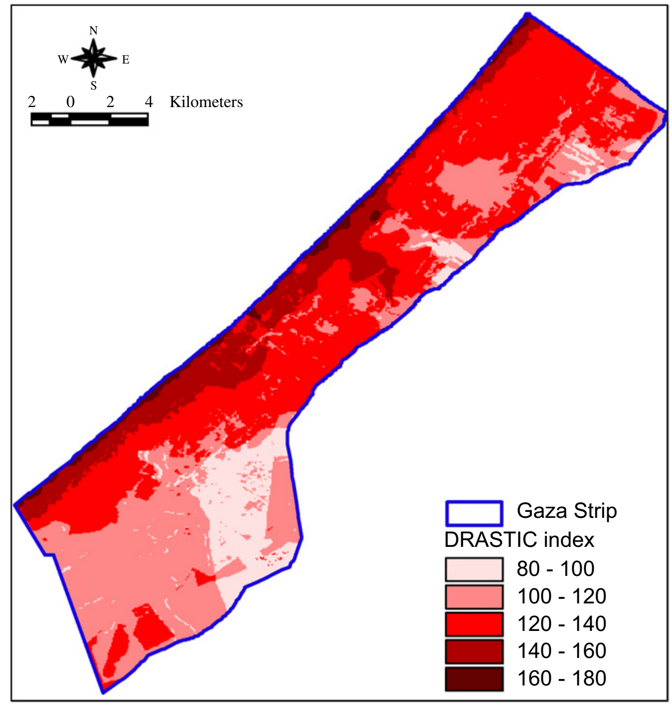


Fig. 6. The map of intrinsic vulnerability to contamination for Gaza coastal aquifer.

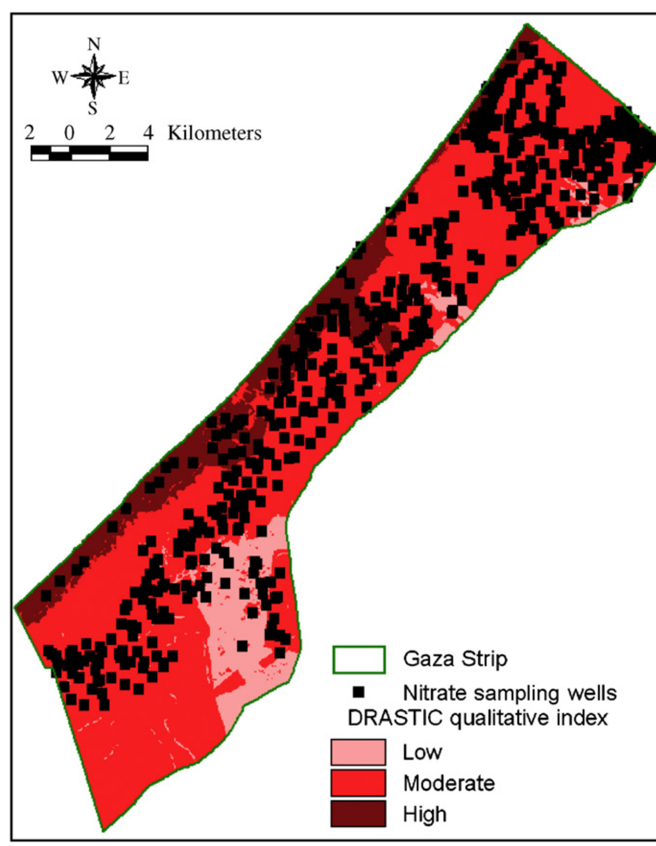


Fig. 7. The map of the DRASTIC qualitative indices for Gaza coastal aquifer along with the spatial distribution of the groundwater sampling wells that were sampled for nitrate concentration since the year 2000.

DRASTIC method accounts for the vertical movement of the contaminants until reaching the water table without the exclusive accounting for the possible fate and transport of nitrate in the aquifer system. However, the fact that the

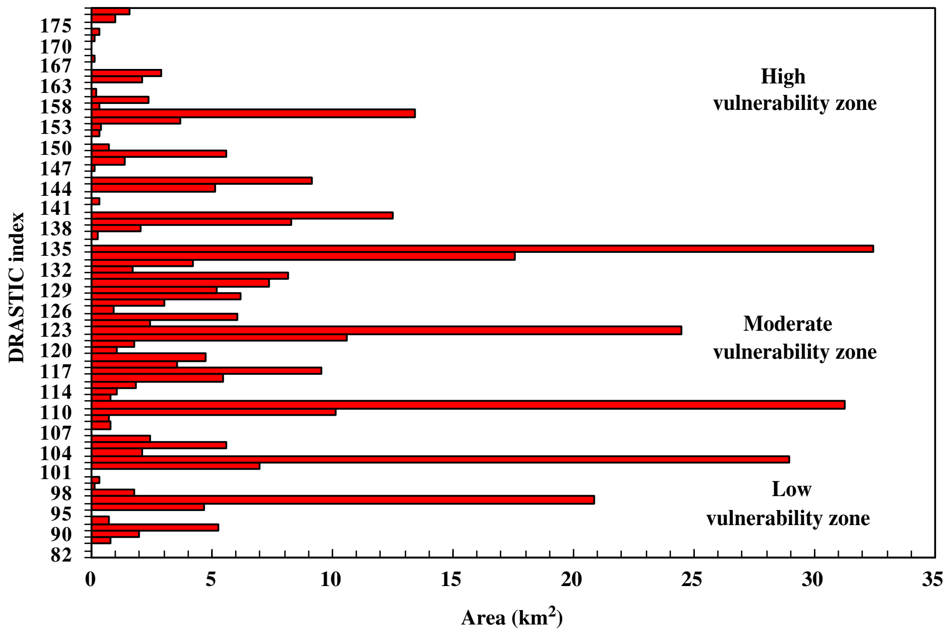


Fig. 8. The variability of DRASTIC index values with the corresponding areas for Gaza Strip.

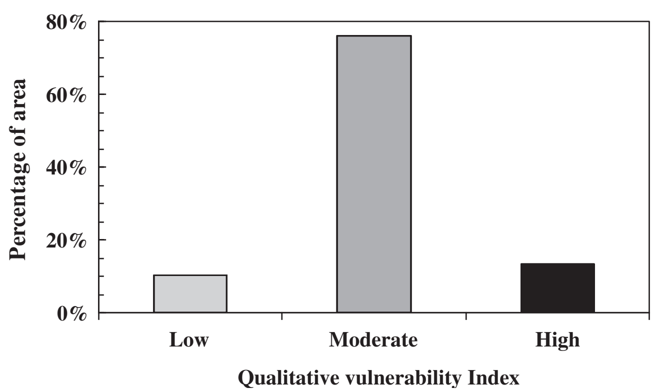


Fig. 9. The overall percentage of area occupied by each qualitative DRASTIC vulnerability index.

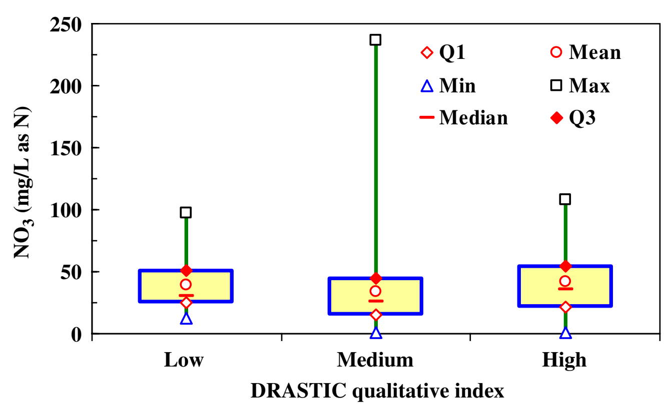


Fig. 10. Boxplots of the distribution of nitrate concentration in the GCA under the different vulnerability zone qualitative indices.

DRASTIC method does not consider the loads is likely to be a major factor in this regard. Other reasons could be the well depth and the weights assigned to the factors.

### *6.3. Groundwater vulnerability and agriculture-based land use practices*

This section investigates the relationship between on-ground nitrogen loading and the different vulnerability zones of GCA. The distribution of on-ground nitrogen loading for GCA was computed from the non-point sources pertaining to the agricultural practices. Two sources were considered including the application of nitrogen-based fertilizers and the irrigation with water contaminated by nitrate. The land use map of Gaza Strip (see Fig. 1) was utilized in the allocation of nitrogen sources and thus in computing the distribution of on-ground nitrogen loading. An old land use map was used since a newer one is unavailable. However, this is not that relevant since there is a lag time between when water first infiltrates the ground and when it arrives at the well screen depending on the well depth. Annual fertilizer application rates that correspond to the land use classes depicted in Fig. 1 were obtained from the Palestinian Ministry of

Table 2
The number of wells sampled for nitrate concentration and the density of wells for the different vulnerability zones in GCA

| Vulnerability zone | Number of sampled wells | Density of wells per unit area |
|---|---|---|
| Low | 29 | 0.77 |
| Moderate | 459 | 1.67 |
| High | 70 | 1.45 |

Agriculture and allocated accordingly using GIS grid calculator. The on-ground nitrogen loading from irrigation was computed by multiplying the annual irrigation volume with the nitrate concentration distribution for the year 2004. This distribution was obtained by creating the Thiessen polygons from the monitored nitrate concentrations. The total on-ground nitrogen loading was then computed. To do so, ArcView GIS was utilized to spatially join the attributes of the total on-ground nitrogen-loading map and the groundwater intrinsic vulnerability map. Thereafter, the relationship between the total on-ground nitrogen loading and groundwater vulnerability indices was plotted as depicted in Fig. 11. Apparently, the highest median on-ground nitrogen loading correlates well with the areas characterized as of low vulnerability. However, the high vulnerability areas encounter high median and maximum on-ground nitrogen loadings.

To further investigate the relationship between land use practices and the vulnerability zones, the land use map for Gaza Strip (see Fig. 1) was spatially joined with the groundwater intrinsic vulnerability map and Fig. 12 was developed. In order to provide an informative overview in this regard, the land use categories were lumped into four general types. these are irrigated agriculture, unirrigated agriculture, urban residential, and open area. As can be seen from the figure, it is almost difficult to get a conclusive relationship between land use classes and vulnerability indices. However, it is clear that the ‘‘irrigated agriculture’’ and ‘‘open area’’ land use categories witness the highest maximum, third quartile, and median vulnerability indices. The same almost applies for the ‘‘urban residential’’ land use category. Except for the maximum vulnerability indices, all the vulnerability statistics for the four land use categories are within the moderate and low vulnerability zones.

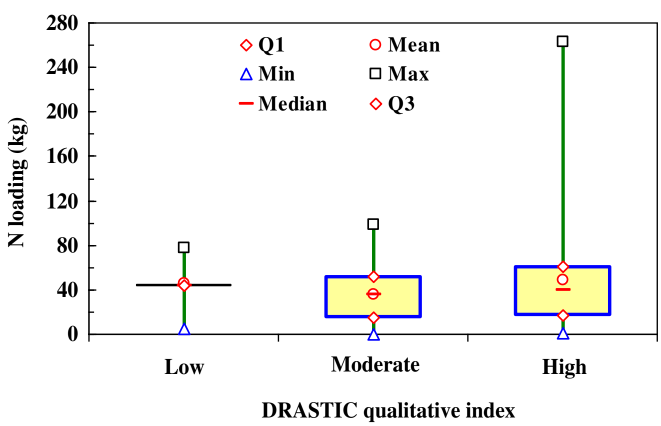


Fig. 11. Boxplots of the distribution of on-ground nitrogen loadings as classified for the different vulnerability zones for GCA.

## 7. Sensitivity analysis of the model

### 7.1. Parameter removal sensitivity analysis

The DRASTIC method relies on seven parameters to evaluate the intrinsic vulnerability of groundwater to contamination. Sensitivity analysis can help in determining the most important and influential parameters on the groundwater intrinsic vulnerability map of GCA.

Two tests of sensitivity analyses were carried out; the map removal and the single-parameter sensitivity analyses (Babiker et al., 2005). The map removal sensitivity analysis determines the sensitivity of the intrinsic vulnerability map towards removing one or more parameter from the vulnerability analysis and is computed using the following equation (Babiker et al., 2005):

$$S = \frac{|(V/N) - (V'/n)|}{V} \times 100, \quad (2)$$

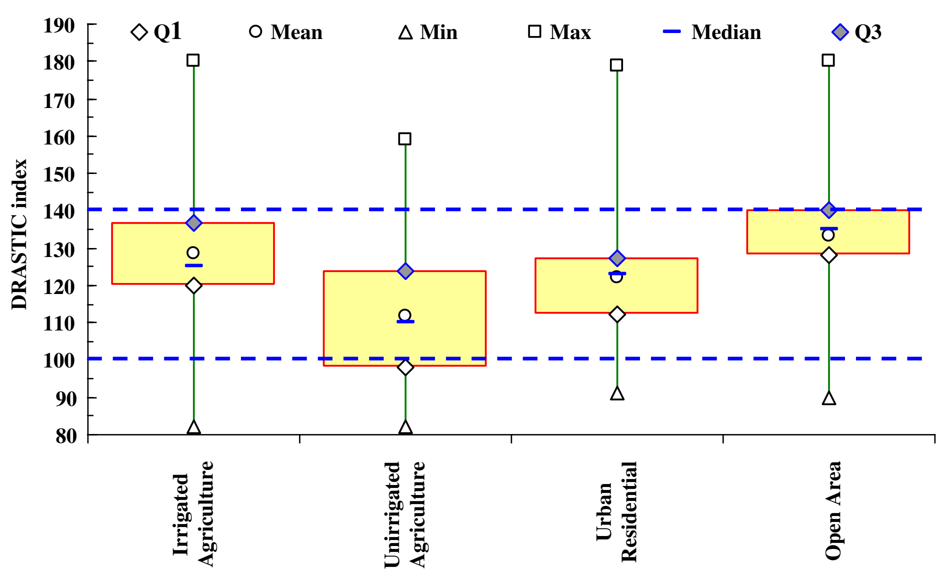


Fig. 12. Boxplots of the distribution of DRASTIC index values for the different land use classes for Gaza Strip.

Table 3
Statistics of the map removal sensitivity analysis for the removal of one parameter at a time

| Parameter removed | Variation index (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | *D* | *R* | *A* | *S* | *T* | *I* | *C* |
| Mean | 1.40 | 1.56 | 0.30 | 0.54 | 1.07 | 1.77 | 0.30 |
| Minimum | 0.11 | 0.07 | 0 | 0 | 0.47 | 0.49 | 0 |
| Maximum | 2.40 | 2.88 | 1.28 | 1.73 | 2.25 | 3.72 | 1.28 |
| SD[a] | 0.47 | 0.57 | 0.22 | 0.46 | 0.26 | 0.60 | 0.22 |
| Median | 1.59 | 1.69 | 0.24 | 0.35 | 1.09 | 1.68 | 0.24 |
| Q1 | 1.19 | 1.04 | 0.14 | 0.16 | 0.88 | 1.32 | 0.14 |
| Q3 | 1.70 | 2.06 | 0.45 | 0.74 | 1.23 | 2.16 | 0.45 |

[a]SD: standard deviation.

Table 4
Statistics of the map removal sensitivity analysis for the removal of multiple parameters

| Parameter used | Variation index (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Mean | Minimum | Maximum | SD | Median | Q1 | Q3 |
| *D*, *R*, *S*, *T*, and *I* | 2.60 | 1.07 | 4.94 | 0.72 | 2.50 | 2.06 | 3.07 |
| *D*, *R*, *S*, and *I* | 3.91 | 1.64 | 6.43 | 0.93 | 3.77 | 3.22 | 4.53 |
| *D*, *R*, *T*, and *I* | 4.62 | 2.19 | 7.40 | 1.04 | 4.34 | 3.87 | 5.73 |
| *R*, *S*, and *I* | 5.02 | 3.09 | 8.59 | 0.86 | 4.93 | 4.29 | 5.75 |
| *D*, *R*, and *I* | 5.93 | 2.91 | 8.97 | 1.21 | 5.52 | 4.98 | 7.16 |
| *R* and *I* | 7.05 | 4.64 | 10.41 | 1.06 | 6.90 | 6.14 | 7.98 |
| *R* and *S* | 9.17 | 7.09 | 13.25 | 1.32 | 8.82 | 8.08 | 9.98 |
| *R* | 11.20 | 9.02 | 14.29 | 1.50 | 10.65 | 9.84 | 12.48 |

where $S$ is the sensitivity measure expressed in terms of variation index; $V$ and $V'$ are the unperturbed and the perturbed vulnerability indices respectively; and $N$ and $n$ are the number of data layers used to compute $V$ and $V'$. The actual vulnerability index obtained using all seven parameters was considered as an unperturbed vulnerability index while the vulnerability computed using a lower number of data layers was considered as a perturbed one.

The results of the map removal sensitivity analysis computed by removing one or more data parameters at a time are presented in Tables 3 and 4. The statistical analysis of the variation index (the sensitivity measure) was applied for all the cells within the model domain where the total number of indices analyzed exceeds 144,000. To handle this huge amount of data, a FORTRAN code was developed and used to compute the statistical measures pertaining to the sensitivity analysis.

Table 3 summarizes the variation of the vulnerability index as a result of removing only one parameter at a time. As can be inferred from Table 3 and when considering the median and the maximum values of the variation index, the vulnerability index seems to be most sensitive to groundwater recharge and vadose zone media. In addition, depth to water table seems to pose a high influence on the vulnerability index. One apparent possible reason for this high sensitivity in these three parameters can be attributed to the high theoretical weight assigned to these parameters as well as the ratings. In addition, the results summarized in Table 3 show that the aquifer media and hydraulic conductivity have the lowest impact on the vulnerability index. In Table 4, the statistical measures of the sensitivity analysis of the DRASTIC index for the removal of multiple parameters at once are summarized. In carrying out this multiple parameter sensitivity analysis, two or more parameter layers were taken off, the vulnerability index was computed, and the corresponding statistical measures of the variation index were calculated. As can be noticed from the table and with increasing the number of the removed parameters, the variation index does increase. The increase in the variation index with the exclusion of the parameters can be possibly attributed to the weights assigned to each parameter and the corresponding ratings.

### 7.2. Single parameter sensitivity analysis

The single parameter sensitivity analysis compares the effective weights with the theoretical weights of the parameters used in the DRASTIC index computation (see Table 1). The effective weight is computed for each cell in the model domain using the following formula (Babiker et al., 2005):

$$W = \frac{P_r P_w}{V} \times 100, \quad (3)$$

where $W$ is the effective weight of each parameter, $P_r$ and $P_w$ are the rating value and weight of each parameter, and $V$ is the overall vulnerability index.

The effective weight is a function of the value of the single parameter with regard to the other six parameters as well as the weight assigned to it by the DRASTIC model. The effective weights of the DRASTIC parameters exhibited some deviation from their theoretical weights as summarized in Table 5. The vadose zone media tends to be the most effective parameter in the vulnerability assessment (mean effective weight is 21.5%) while the net groundwater recharge comes in the second place in this regard with a mean effective weight of 16.45%.

### 7.3. Sensitivity analysis due to parameter uncertainty

The last type of sensitivity analyses performed herein is the sensitivity of DRASTIC index due to the uncertainty in specific parameters used in the development of this index. In order to carry out this sensitivity analysis, two parameters were selected. These parameters are the depth to water table and the groundwater recharge. These parameters exhibit high uncertainty and the evaluation of the sensitivity of the DRASTIC index to them would reveal information regarding the importance of the accurateness in the designation of these parameters. To assess the sensitivity of the DRASTIC index to each selected parameter, reasonable perturbation percentages were made to each parameter and the change in the area corresponding to the index of high vulnerability was computed after each perturbation. A range of perturbation percentages of −20% to +20% was used. Fig. 13 depicts the sensitivity for depth to water table and groundwater recharge. As can be concluded from the figure, depth to water table shows a higher impact on the area of high vulnerability. Nevertheless, groundwater recharge does show a symmetrical impact on the area of the high vulnerability when being increased and decreased.

## 8. Development of management options

As has already been established earlier in this paper, GCA encounters contamination problems in terms of high nitrate and chloride pollution. Many sources attribute to

Table 5
Statistics of the effective weight sensitivity analysis for the removal of one parameter at a time

| | Theoretical weight (%) | Effective weight (%) | | | | |
|---|---|---|---|---|---|---|
| | | Mean | Minimum | Maximum | SD | Median |
| *D* | 21.74 | 6.07 | 0.00 | 27.27 | 4.86 | 3.82 |
| *R* | 17.39 | 16.45 | 0.00 | 32.99 | 8.73 | 19.39 |
| *A* | 13.04 | 12.90 | 10.91 | 18.56 | 2.25 | 13.74 |
| *S* | 8.70 | 10.83 | 3.64 | 18.56 | 4.17 | 10.91 |
| *T* | 4.35 | 6.79 | 0.61 | 10.31 | 1.55 | 6.87 |
| *I* | 21.74 | 21.50 | 18.18 | 30.93 | 3.75 | 22.90 |
| *C* | 13.04 | 12.90 | 10.91 | 18.56 | 2.25 | 13.74 |

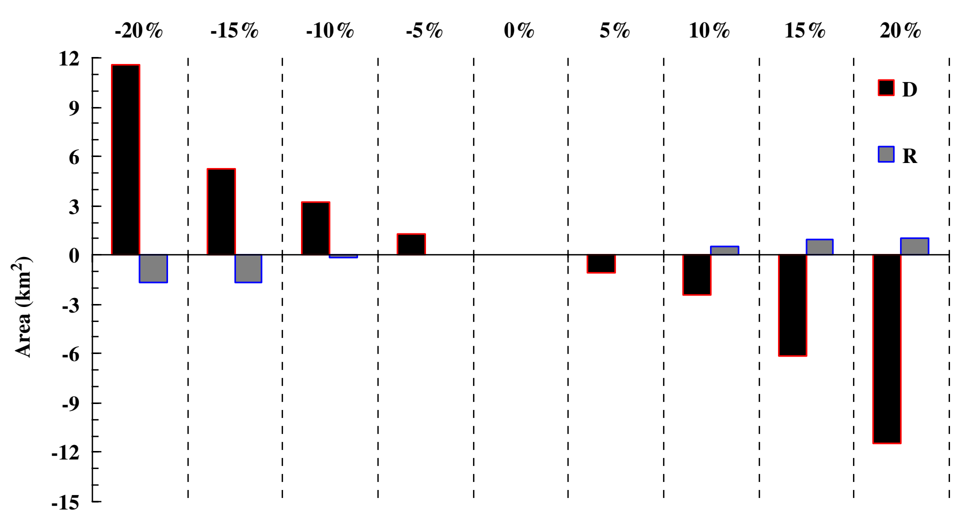


Fig. 13. Sensitivity of the area of high vulnerability of GCA to contamination due to different perturbation percentages in the depth to water table and groundwater recharge.

the on-going contamination problems among which are the existing heavy agricultural activities that are taking place in Gaza Strip and the intrinsic geologic and hydrologic characteristics that favor the high vulnerability of GCA to contamination.

The analysis performed on the intrinsic vulnerability map shows that high on-ground nitrogen loadings are applied in areas of high vulnerability. One possible management option is to reduce the on-ground nitrogen loading. Analysis was conducted to find out the percentage of the areas of different vulnerability indices that receive different loading amounts. Results are depicted in Fig. 14 and show an inverse relationship between on-ground nitrogen loading and the application area.

To show the spatial distribution of the areas that can be targeted for different on-ground nitrogen loading amounts, Fig. 15 was developed using GIS spatial analyst. In developing Fig. 15, the on-ground nitrogen loading grid and the grid of the vulnerability qualitative indices were spatially joined to sort out the different vulnerability areas with the corresponding on-ground nitrogen loadings. This figure helps decision makers and water resources mangers in designating areas that can benefit from contamination prevention programs. For instance, Fig. 15 delineates the high vulnerability areas that receive different on-ground nitrogen loadings ($L$ values in Fig. 15). If it was recommended that the allowable on-ground nitrogen loading not to exceed $L$ value, then the areas that receive an amount beyond this loading corresponds to Fig. 15 and can be accordingly targeted.

Many management options can be designed to address the on-going pollution problem of GCA. The following is a recommended list of possible and potential management options that can be introduced in the designated areas (see Fig. 15). It is important to consider an economic analysis for each option before implementation.

(1) Managing the amount, type, and timing of nitrogen application is the most practical and acceptable approach to minimize groundwater contamination resulting from fertilizer use. Since fertilizer application on agricultural areas has been recognized as a main source of nitrate contamination of GCA, reduction in nitrogen fertilizer application rates is an efficient option (Mercado, 1976; Yadav and Wall, 1994, 1998). However, irrational reductions in fertilizer applications may entail a dropdown in crop yield, which in turn bring about serious economic ramifications;
(2) Setting up realistic crop yield goals and crediting nitrogen from sources other than commercial fertilizers should be considered (Waskom, 1994);
(3) Fertilizer applications should be applied during the period of maximum crop uptake. Fall applications of nitrogen fertilizers increase the potential for nitrate leaching specially in areas of high groundwater recharge magnitudes. Also, split applications of nitrogen-based fertilizers ought to be taken into account;
(4) The use of nitrification inhibitors: The nitrogen becomes nitrate through mineralization and nitrification. Nitrification is the key transformation that produces nitrate in the soil. A common management alternative to reduce the mass of nitrate in the soil is the use of inhibitors to hold back nitrification (Addiscott et al., 1992). Walters and Malzer (1990) evaluated the effect of nitrification inhibitors on nitrate leaching and showed their efficacy especially with proper nitrogen application rates. The effect of nitrification inhibitors is simulated by reducing the magnitude of the nitrification rate coefficient (Shaffer et al., 1991); and
(5) Land use change: One of the common management alternatives in order to reduce groundwater pollution from on-ground activities is to make changes in the land use cover (Latinopoulos, 2000). Such changes involve developing land uses that are more prone to produce nitrate leaching to groundwater with less likely on-ground nitrogen loadings.

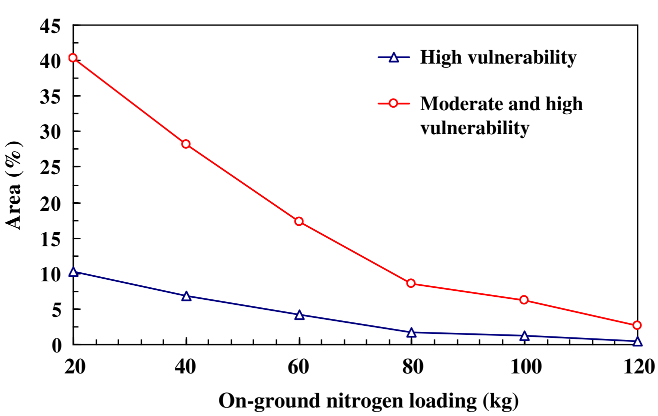


Fig. 14. The percentage of area that corresponds to the different on-ground nitrogen loading for different vulnerability indices.

## 9. Summary and conclusions

GCA is the major source of fresh water for the 1.4 million residents of Gaza Strip. The aquifer is under deteriorating quality conditions due to the excessive application of fertilizers. As part of the efforts to restore the aquifer's water quality, it was decided to introduce protection alternative measures. Vulnerability assessment to contamination of groundwater resources is an important step in developing and designing protection alternative measures to protect these resources.

The well-known DRASTIC method was used to compute the vulnerability of GCA to contamination by using the GIS spatial capabilities to prepare, arrange, process, and manage the data pertaining to the implementation of this method. The final output from DRASTIC is a map that shows the spatial distribution of the intrinsic vulnerability values and the corresponding qualitative indices for GCA. The intrinsic vulnerability map of GCA

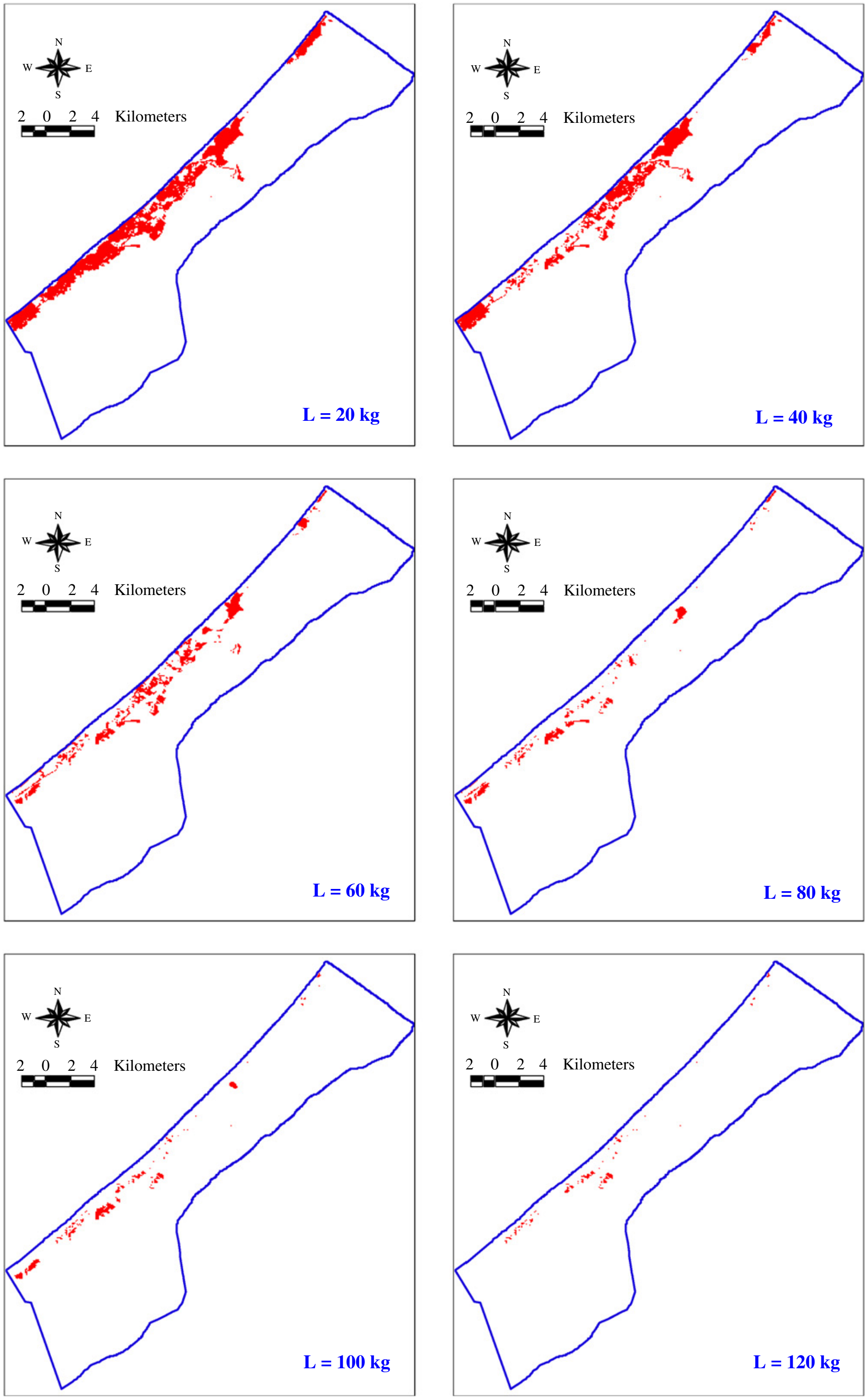


Fig. 15. The spatial distribution of the high vulnerability areas that correspond to the different on-ground nitrogen loading levels ($L$).

provides a preliminary indication to the areas of high priority in terms of intervention of protection alternative measures. In addition, it aids in directing the monitoring efforts for water sampling and observations of GCA. Detailed analysis of the intrinsic vulnerability map of GCA was carried out and considered the dissimilar relationships between the different vulnerability indices with other explanatory parameters such as the on-ground nitrogen loadings and land use classes. In addition, correlation with nitrate concentrations in GCA was investigated.

Based on the research outcome, it can be concluded that 10% and 13% of Gaza Strip area is under low and high vulnerability of groundwater contamination, respectively. More than 77% of the area of Gaza Strip can be designated as an area of moderate vulnerability of groundwater contamination. The density of groundwater sampling wells for nitrate concentration is high for the moderate and high vulnerability zones for Gaza Strip. The highest first quartile, median, mean, and third quartile of nitrate concentrations are reported in the high vulnerability zones. However, maximum nitrate concentration is encountered in the moderate vulnerability zones. There is no conclusive relationship between nitrate concentration in GCA and the vulnerability indices. One possible reason for this is that the vulnerability method accounts for the vertical movement of the contaminants until reaching the water table without accounting for the possible fate and transport of nitrate in the aquifer system. However, the fact that the DRASTIC method does not consider the loads is likely to be a major factor in this regard. One final conclusion is that it is important to keep in mind that the DRASTIC method, like any other method, has limitations. Models are simplifications of real systems and actual conditions can differ markedly from predictions. As such, follow-up studies ought to be carried out where the DRASTIC method could be calibrated for GCA by adjusting the weights of the factors that are most sensitive such as recharge, depth to water table and the impact of the vadose zone.

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