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Ionic and isotopic ratios for identification of salinity sources and missing data in the Gaza aquifer

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Abstract

Groundwater is the only source of fresh water in the Gaza Strip. However, it is severely polluted and requires immediate effort to improve its quality and increase its usable quantity. Intensive exploitation of groundwater in the Gaza Strip over the past 40 years has disturbed the natural equilibrium between fresh and saline water, and has resulted in increased salinity in most areas. Salinization in the coastal aquifer may be caused by a single process or a combination of different processes, including seawater intrusion, upconing of brines from the deeper parts of the aquifer, flow of saline water from the adjacent Eocene aquifer, return flow from irrigation water, and leakage of wastewater. Each of these sources is characterized by a distinguishable chemistry and well known isotopic ratios. In this paper Na/Cl, SO_4/Cl, Br/Cl, Ca/(HCO_3+SO_4), and Mg/Ca ionic ratios were used to distinguish different salinization sources. $\delta^{11}B$ and $^{87}Sr/^{86}Sr$ isotopic composition were also included in the model to study their importance in this monitoring task. The task of monitoring and the associated decision making process are characterized by a high degree of uncertainty with respect to input data and accuracy of models. For this reason, probabilistic expert systems, and more specifically, Bayesian belief networks (BBNs) are used to identify salinization origins. The BBN model incorporates the theoretical background of salinity sources, area-specific monitoring data that are characteristically incomplete in their coverage, expert judgment, and common sense reasoning to produce a geographic distribution for the most probable sources of salinization. The model is also designed to show areas where additional data on chemical and isotopic parameters are needed.

Keywords: Salinization; Ionic ratios; Isotopes; Bayesian networks; Monitoring

1. Hydro-geological setting

The coastal aquifer lies along the southeastern edge of the Mediterranean Sea and extends from the foothills of Mt. Carmel southward to Gaza and northern Sinai. It is composed of Pliocene–Pleistocene age calcareous sandstone, unconsolidated sands,

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and layers of clays (Vengosh and Rosenthal, 1994; Vengosh et al., 1999; Mercado, 1985). In the Gaza Strip, the aquifer extends about 15–20 km inland, where it overlies Eocene age chalks and limestone or the Miocene–Pliocene age Saqiye Group. The Saqiye Group is a 400- to 1000-m thick sequence of marls, marine shales, and claystones. Approximately 10- to 15-km inland from the coast, the Saqiye Group pinches out, and the coastal aquifer rests directly on Eocene chalks and clastic sediments of Neogene age (see M&E, 2000; Vengosh and Rosenthal, 1994; Vengosh et al., 1994; Mercado, 1985). Fig. 2 presents a generalized geological cross-section of the coastal aquifer.

Near the coast in the Gaza Strip, clay layers subdivide the coastal aquifer into four separate sub-aquifers (Fig. 2). They extend inland about 2- to 5-km, depending on location and depth. Further east, the marine clays pinch out and the coastal aquifer can be regarded as one hydro-geological unit. Sub-aquifer A is unconfined, whereas sub-aquifers B1, B2, and C become increasingly confined towards the sea.

2. Available data

The modeling and analysis reported here are based upon the results of a recent (2000) water quality survey of 101 municipal and agricultural wells. Those wells were sampled and tested for calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^{+}), potassium (K^{+}), bromine (Br^{-}), chloride (Cl^{-}), nitrate (NO_3^{-}), bicarbonate (HCO_3^{-}), and sulphate (SO_4^{-}). Fig. 1 shows the locations of the sampled wells. The analysis

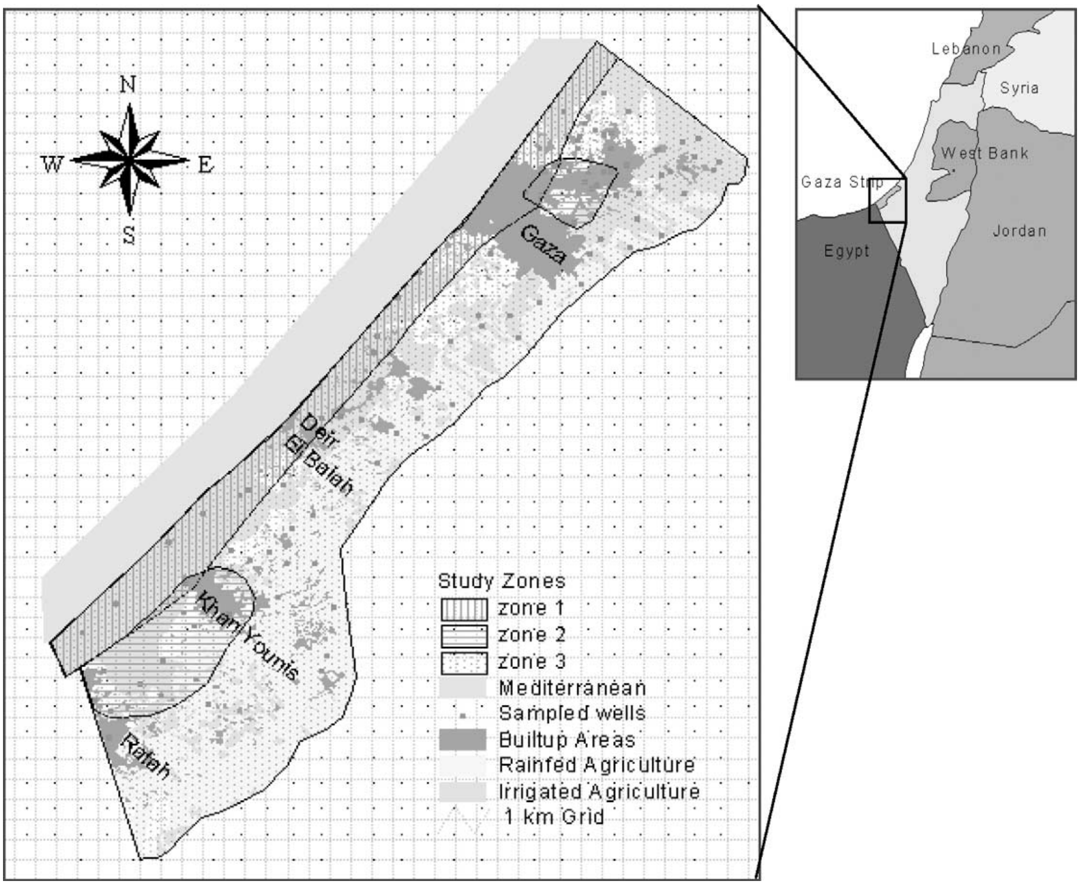

Fig. 1. Location map showing land use and sampled wells.

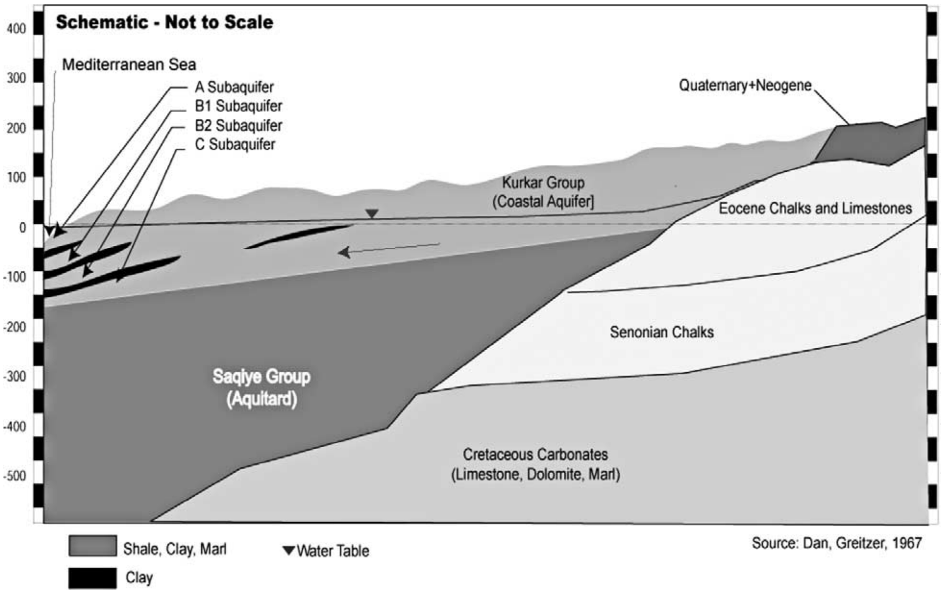

Fig. 2. Generalized geological cross section of the coastal aquifer (M&E, 2000).

reported here is also limited to the area within the boarders of the Gaza Strip. For the purpose of this study, areas within the coastal aquifer and outside the Gaza Strip are considered boundaries with no information (Fig. 2).

3. Bayesian belief networks

Bayesian belief networks (BBNs) provide a very efficient language for building models that have domains with inherent uncertainty. A BBN consists of a set of variables (or 'nodes') and a set of directed edges (or 'links') that represent connections between variables. Each node is treated as a random variable that can have a continuous distribution or a discrete distribution with a finite set of mutually exclusive states (see Jensen, 1996; Pearl, 2000). Directed graphs in BBNs present the sets of variables that are related to each other in providing knowledge about the state of the system (Pearl, 2000). BBNs are particularly useful for communicating risk and uncertainty, and for providing a framework for analyzing cause-and-effect relationships in complicated systems.

The basic concept in the Bayesian treatment of uncertainties is conditional probability. To each variable A, with parents $B_1, \ldots, B_n$, there is attached a conditional probability. Whenever a statement of the probability of an event is given, then it is given conditioned by other known factors as follows (Castillo et al., 1997):

$$p(a_i/b_1\ldots b_n) = \frac{p(a_i, b_1, \ldots, b_n)}{p(b_1, \ldots, b_n)} = \frac{p(a_i) * p(b_1, \ldots, b_n/a_i)}{p(b_1, \ldots, b_n)} \quad (1)$$

where

$p(a_i)$ is called the marginal, prior, or initial probability that variable $A = a_i$

$p(a_i/b_{1\ldots}b_n)$ is the posterior or conditional probability that $A = a_i$ given that $B_1 = b_1, \ldots, B_n = b_n$.

$p(b_{1,\ldots,}b_n/a_i)$ is referred to as the likelihood that parent $B_1 = b_1$ causes $A = a_i$

.

The uncertainties in the parent nodes, represented by marginal probability distributions, produce uncertainties in the child nodes that are based on conditional probabilities and physical cause-and-effect relationships. Fig. 3a shows a simple BBN example. Seawater intrusion, Eocene rocks, and deep

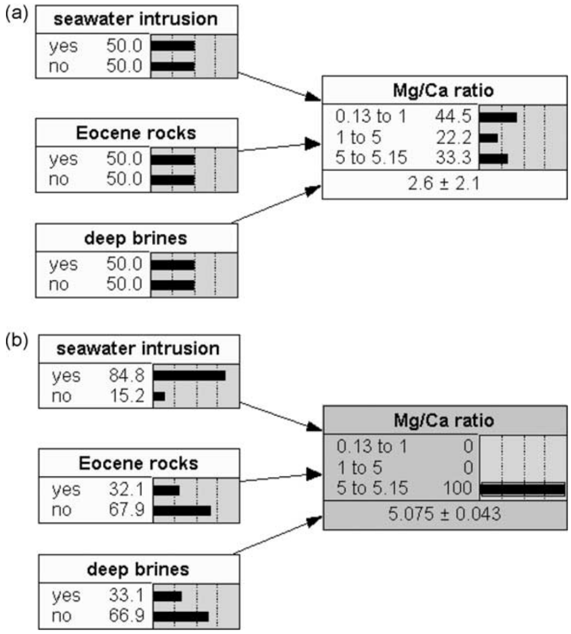

Fig. 3. (a) BBN example; (b) Backward propagation in BBN.

brines represent three probable salinity sources and are the parent nodes for the Mg/Ca ionic molar ratio node. In each node, the left-hand side column represents a finite set of states that describe the variable, and the right-hand side column shows the probability attached to each state. The probability that the Mg/Ca molar ratio will fall within a particular range of values is quantified on the basis of knowledge of the probabilities of the related parent variables.

Bayes rule, as expressed by Eq. (1), can be used to discover the changes in state probabilities of parent variables based on known evidence of the value of a child node or information about the probability distribution of the states of the child node. This is called “backward propagation”. Fig. 3b shows a backward propagation example. New information or evidence about the value of the Mg/Ca ionic molar ratio changes the state probabilities in the salinity sources nodes. In other words, knowing that the Mg/Ca molar ratio lies between 5 and 5.15 changes the belief/probability that seawater intrusion is the main source of salinity from 50 to 85%.

In this work, Netica software (version 1.27) from Norsys Corp is used to represent the BBN structure and perform the needed Bayesian calculations. The Netica application is a comprehensive tool for working with BBNs and influence diagrams. It can build, learn, modify, transform, and store networks, as well as answer queries or find optimal solutions using its powerful inference engine (Norsys Software Corporation, 1997).

4. Model structure

The BBN model is composed of a set of parent nodes that represent the potential sources of salinity in the Gaza coastal aquifer, mentioned previously. Each of the parent nodes is described by two mutually exclusive states, namely “YES” and “NO”. “YES” represents the existence of a particular salinization source, and “NO” represents the absence of that source. Each of the parent nodes is connected to four or more child nodes, which represent the ionic or isotopic ratios that are likely to be altered by this particular source. Each of the child nodes is described by a number of mutually exclusive states, each of which can be related to a specific source of salinization. For example, a low Br/Cl ionic ratio (0.0005) indicates the existence of wastewater pollution (Vengosh et al., 1999). A Br/Cl ratio of 0.0015 characterizes seawater intrusion and waters from the Eocene formation and saline plumes (Vengosh et al., 1999, 2002). A high Br/Cl ionic ratio (0.02) indicates water from agricultural return flows (Vengosh et al., 2002). Details of these connections and the cause-and-effect relationships are explained in the Section 5. New information or evidence in the child nodes propagates backward and changes the state probabilities in the parent nodes. Fig. 4 shows a graphical representation of the Gaza Strip BBN model.

The parent nodes, which represent salinization sources are treated as independent nodes. The existence of one source is independent of the existence of other sources. For example, the existence of seawater intrusion, which is generally caused by fresh water deficit, is not linked to the occurrence of anthropogenic sources, which are caused by overland activities. However, the two sources can be detected in one location. Also the existence of deep brines, which are trapped deep water that has undergone different geochemical processes for hundreds of years,

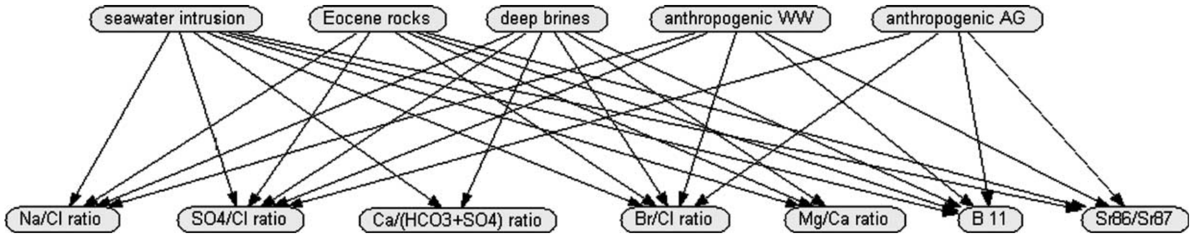

Fig. 4. Gaza Strip water quality monitoring model.

is independent of Eocene water that continuously flows from the east to the shallow part of the aquifer. Each source is characterized by a distinguishable chemistry. Eocene water is usually enriched with sodium, while deep brine water is sodium-depleted and enriched with calcium (see more details in Section 5.2).

The occurrence of new evidence in the child node changes the status of parent nodes that are linked to it from independent to conditionally-dependent. In other words, if the posterior state is changed in one parent node, the posterior state in the other parent will change to satisfy the new condition/evidence set in the child node.

5. Relationships and background information

5.1. Marginal probabilities in the parent nodes

The types of data that can be used to populate a BBN may include historical records of observed information, expert judgement, surveyed opinions, information from journal articles, and data available from reports related to the study area. In order to avoid bias in the results, the following resources were utilized to populate the marginal probabilities in the parent nodes:

5.1.1. Previous/existing hydrologic model simulations and land use map

The probable extent of the seawater intrusion wedge and the water table level were simulated by Metcalf and Eddy (M&E) in association with Camp Dresser and McKee (CDM) through the Coastal Aquifer Management Program (CAMP), funded by the US Agency for International Development (M&E, 2000). Based on the results of the hydrologic model simulations and the existing land use map, the study area was divided into three overlaping zones (Fig. 1). Zone 1 comprises the data points (wells) within two kilometers of the sea shore. Seawater intrusion is highly expected in this zone. Zone 2 is located farther inland and comprises the areas with negative water table levels relative to mean sea level (MSL). In these areas deep brines are expected to contribute to groundwater salinity. Zone 3 includes the entire area of the Gaza Strip, where heavily urban and agricultural activities occur. If groundwater flow/movement is considered, the impact from urban and agricultural activities cannot be geographically distinguished. In this zone, any pollution source can be expected.

5.1.2. Water quality analysis

The data from 101 wells were analyzed for potential sources of salinization using chemical indicators that are different from the ionic and isotopic ratios that are used in the model. Elevated chloride and total dissolved solids (TDS) concentrations are good indicators for seawater intrusion in the wells located near the seashore. Deep brines may have high calcium (Ca^{+2}) content caused by base-exchange reactions with clay minerals and dissolution of carbonate minerals (Vengosh and Rosenthal, 1994). Also, waters that have moved through limestone and chalks have a high Ca^{+2} content. 78% of the wells in Zone 1 have elevated chloride concentrations relative to drinking water standards. Fifty-six percent of them have high TDS concentrations (greater than 600 ppm). Seventy-five percent of the wells in Zone 2 have high Ca^{+2} content relative to drinking water standards (75 ppm). In Zone 3, which is the whole Gaza Strip, 75% of the wells have high Ca^{+2} content, 91% of the wells have high (greater than 45 ppm) nitrate (NO_3^-) content, and 56% of them have high sulphate (SO_4^{+2}) content relative to drinking water standards.

5.1.3. Expert judgement

Expert judgements were used to specify the prior/marginal probabilities was based on the following: (1) the author's experience in the study area; (2) additional consultation of groundwater experts; (3) interpretation of the above information; (4) information about land use practices, geology of the study area, and groundwater regional flow directions.

Table 1 shows the assigned prior/marginal probabilities in the parent nodes based on the above information. In areas where information is not sufficient, 0.5 probability was used to describe the existance or non-existance of any particular salinization source. Zone 3 is divided into two subzones to account for the soil type that overlays the aquifer and the water table depth. For example, the top soil in most of the eastern areas of the Gaza Strip is characterized by red silty-clayey sandstones and fluvial clays (M&E, 2000). The water table in these areas could reach 75 m. In the sand dunes near the seashore the water table is very shallow and land use practices are more likely to play a major role in salinization.

5.2. Conditional probabilities in the child nodes

Information from expert opinion and data from journal articles were used to define relationships among the variables in the network. The model uses a descriptive or qualitative type of cause-and-effect relationship to describe connections between parent and child nodes. The general rule is that for any child node, if only one source of salinization exists then a probability of 1.0 is given to the state in the child node which is related to this particular (parent) salinity source. For example, if seawater intrusion is expected to be the only source of salinization then the probability that the Mg/Ca ionic ratio will be greater than 5 is 1.0. A Mg/Ca ionic ratio greater than 5 is a direct indicator of seawater contamination (M&E, 2000).

If more than one source of salinization is involved, then the probabilities attached to each state in the child nodes are distributed evenly. Table 2 shows the chemical and isotopic composition of different potential salinization sources. The information in Table 2 was used in the network to define the relationships between the salinization sources and the chemical composition that represents the states in the child nodes. Details of these relationships and relevant background information are given in subsequent sections.

5.2.1. Seawater intrusion

Shallow seawater intrusion has been documented in several areas along the coast of the Gaza Strip. Interpretation of the results of a recent time domain electro magnetic (TDEM) survey indicates that seawater has migrated up to 2 km inland in the deeper

Table 1
Prior/marginal probability distribution in the parent nodes

Location	State	Seawater intrusion	Flow from Eocene rocks	Deep brines upconing	Wastewater seepages	Agriculture return flows
Zone 1	Yes	0.75	0.65	50	0.80	0.70
	No	0.25	0.35	50	0.20	0.30
Zone 2	Yes	50	0.65	0.73	0.80	0.70
	No	50	0.35	0.27	0.20	0.30
Zone 3[a] (shallow water table (10–30 m))	Yes	50	0.65	50	0.80	0.70
	No	50	0.35	50	0.20	0.30
Zone 3 (deep water table (30–70 m))	Yes	50	0.65	50	0.55	0.55
	No	50	0.35	50	0.45	0.45

[a] Zone 3 covers the whole study area so when different zones overlap the higher figures are used.

Table 2
The chemical and isotopic composition of potential salinization sources

	Seawater intrusion	Flow from Eocene rocks	Deep brines upconing	Wastewater seepages	Agriculture return flows
Na/Cl	0.86–1[a]	1–1.8[b] 1.23[d] ~0.86[d]	~<0.8[c] <0.86[a,e] 0.5–0.8[d]	1.1[d]	
SO_4/Cl	0.05[a,d]	0.05–0.12[d]	~0.05[c,d]	0.09[d]	≫ 0.05[f]
Br/Cl	0.0015[a,d]	0.0014–0.0015[d]	0.0014–0.0016[c,d]	0.0005[d]	0.02[f]
B/Cl	0.0008	0.0018[d] 0.0087[d]	0.002[c] 0.0015–0.0018[d]	0.002–0.005[d]	0.005[f]
K/Cl	0.019		<0.019[d]		
Ca/(HCO_3+SO_4)	0.35–<1[a]		>1[c,e,a,d]		
Mg/Ca	>5[c] 5.2[e]	0.5–0.7[a]	>1[a] 2.5[e]		
δ^{18}O	−5%[d]		−2.95–4.73%[d]	High-4%[d]	
δ^{11}B	39-60‰[f,d]	38–48.5‰[d]	24.8–49.9‰[d]	0–10[d] 5.3–12.9‰[g]	19‰[f]
^{87}Sr/^{86}Sr	0.70923[d]	0.708102–0.708132[d]		0.708275–0.708532[d]	0.7082[f]
Cl	Up to 22,400[e]		Up to 60,000[e]		

[a] Vengosh and Rosenthal, 1994.
[b] Metcalf & Eddy Inc., 2000.
[c] Vengosh and Ben-Zvi, 1994.
[d] Vengosh et al.,1999.
[e] Mercado, 1985.
[f] Vengosh et al., 2002.
[g] Vengosh et al., 1994.

sub-aquifers in the Deir El Balah and Rafah areas and near Gaza City (M&E, 2000). Seawater and seawater diluted with freshwater have distinguished geochemical characteristics (M&E, 2000). Seawater has distinct ionic and isotopic ratios such as Na/Cl = 0.86, SO_4/Cl = 0.05, Br/Cl = 0.0015, Ca/(HCO_3 + SO_4) = 0.34, Mg/Ca = 5.2, δ^{11}B = 39‰, and ^{87}Sr/^{86}Sr = 0.70923 (Vengosh et al., 1999; Vengosh and Rosenthal, 1994). The Na/Cl molar ratio could reach unity due to the mixing of seawater and freshwater, which has a Na/Cl ratio greater than unity (Vengosh and Rosenthal, 1994). δ^{11}B in seawater would be modified to a higher value (up to 60‰) (Vengosh et al., 1999). In the coastal aquifer an Mg/Ca molar ratio greater than 5 is a direct indicator of seawater intrusion (M&E, 2000).

Based on this information, the seawater intrusion node in the model is designed to have seven child nodes (see Fig. 4) representing the different ionic and isotopic ratios mentioned above. Information about each indicator is used to update the prior probability of having seawater intrusion. In each sampling location, if all indicators hold true then we have 100% probability that seawater is the most dominant salinization source. If some of the indicators have different values than those mentioned above, other salinity sources might be involved.

5.2.2. Eocene rocks

Eocene rocks consist of chalks and limestone and are in hydraulic contact with the coastal aquifer 10 km east of the boarders of the Gaza Strip (M&E, 2000). The brackish groundwater that flows into the Gaza Strip portion of the coastal aquifer is chemically very similar to the Eocene water (Vengosh et al., 1999). It is chemically different from seawater and other salt bodies in the coastal aquifer in that it is enriched in sodium. This water is characterized by Na/Cl ionic ratio ranging between 1 and 1.8 (M&E, 2000). Water that flows through Eocene rocks has distinct ionic and isotopic ratios such as Na/Cl = 0.86 − 1.23, SO_4/Cl = 0.05 − 0.12, Br/Cl = 0.0014 − 0.0015, and $^{87}Sr/^{86}Sr = 0.70813$ (Vengosh et al., 1999). The Mg/Ca ionic ratio is normally in the range of 0.5–0.7 in waters that flow through chalks or limestone aquifers (Vengosh and Rosenthal, 1994). Low values of the Mg/Ca ratio and high values of the Na/Cl ratio relative to seawater may be caused by dissolution of $CaCO_3$. This raises the Ca^{+2} content that is further exchanged with Na^+ ions thus causing an increase in the Na/Cl ratio (Vengosh and Rosenthal, 1994).

Based on this information, the Eocene rocks parent node in the model is designed to have five child nodes (see Fig. 4), namely: Na/Cl, SO_4/Cl, Br/Cl, Mg/Ca and $^{87}Sr/^{86}Sr$ ionic and/or isotopic ratios. Information about each indicator/ratio is used to update the prior probability that Eocene rocks contribute to salinity in the coastal aquifer. In each sampling location, if all indicators hold true then we have 100 percent probability that water that has passed through the Eocene aquifer is the most dominant salinization source. If some of the indicators have different values than the values mentioned above, then other salinization sources might be involved or more dominant.

5.2.3. Deep brines

The presence of saline beds at the base of the coastal aquifer was first discovered in oil and gas exploration wells (M& E, 2000). Chloride concentrations of 50,000 to 65,000 parts per million (ppm) were depicted at a depth of about 120 m from MSL in some of the piezometers located in Deir El Balah, Khan Younis, and south of Gaza City (M&E, 2000). These concentrations are significantly higher than seawater chloride concentration and indicate the presence of brines. Heavy pumping activities in the upper layers accelerate brine water upconing and the formation of saline plumes beneath the pumping zones. Relative to seawater, the brackish groundwater of these saline plumes has relatively low Na/Cl ratios (0.5–0.8), low Mg/Ca ratios, high $Ca/(HCO_3+SO_4)$ ratios (greater than unity), marine SO_4/Cl ratios (0.05), marine Br/Cl ratios (0.0015), a $\delta^{11}B$ ratio between 24.8 and 49.9‰, and a $^{87}Sr/^{86}Sr$ ratio between 0.708275 and 0.708532 (Vengosh et al., 1999).

Modification of the geochemical characteristics of these saline waters is caused by water-rock interaction (Vengosh et al., 1999). Three mechanisms may be involved: (1) base-exchange reactions with clay minerals, which decrease Na^+ and increase Ca^{2+} and Mg^{2+} (Vengosh et al., 1999); Na^+ is exchanged for Ca^{2+} and Mg^{2+}, decreasing the Na/Cl ratio and increasing the $Ca/(HCO_3+SO_4)$ ratio (Vengosh et al., 1994); (2) adsorption onto clay minerals which affect B, K^+, and $\delta^{11}B$ concentrations; (3) carbonate dissolution-precipitation, which increases Ca^{2+} and decreases HCO_3 (Vengosh et al., 1999; Vengosh et al., 1994). Increasing the Ca^{2+} content by base-exchange reactions and dissolution of carbonate minerals results in a $Ca/(HCO_3+SO_4)$ ratio greater than unity, which is an indicator of Ca-chloride occurrence (Vengosh and Rosenthal, 1994). SO_4/Cl and Br/Cl ratios are not influenced by these processes and they are considered conservative tracers (Vengosh et al., 1999; Vengosh et al., 1994; Vengosh and Rosenthal, 1994). Enrichment of Ca^{2+} and Mg^{2+} and depletion of Na^+ may also suggest evaporation of original seawater followed by halite precipitation and dolomitization (Vengosh et al., 1999).

The same approaches used in the previous two sources of salinization are made here in the modeling procedure. The deep brines parent node in the model is designed to have six child nodes (see Fig. 4), namely: Na/Cl, $Ca/(HCO_3+SO_4)$, Mg/Ca, Br/Cl, SO_4/Cl, $\delta^{11}B$ ionic and isotopic ratios. In each sampling location, if all indicators hold true then we have 100% probability that deep brines are the most dominant salinization sources.

5.2.4. Wastewater seepage

Improper treatment and disposal of domestic wastewater could be one of the major sources of salinization in the Gaza coastal aquifer (M&E, 2000). The chemical signature of water polluted with urban wastewater or from the reuse of treated wastewater is very distinguishable. Sewage effluent has a relatively high Na/Cl ratio (greater than unity), a high SO_4/Cl ratio (0.09), a low Br/Cl ratio (0.0005), a low $\delta^{11}B$ (0–10‰) relative to seawater, and $^{87}Sr/^{86}Sr = 0.708275–0.708532$ (Vengosh et al., 1999). These ratios are attributed to applications of NaCl salts and boron-enriched detergent and are typical of domestic wastewater in Israel (Vengosh et al., 1999). $\delta^{11}B$ value ranges from 5.3 to 12.9% in sewage effluent due to the use of boron detergents (Vengosh et al., 1994).

Based on this information, the parent node for wastewater leakage is designed to have five child nodes (see Fig. 4), namely Na/Cl, SO_4/Cl, Br/Cl, $^{87}Sr/^{86}Sr$ ratios, and $\delta^{11}B$ ionic and isotopic ratios. Information on each indicator/ratio is used to update the prior probability that wastewater seepages contribute to salinity in the coastal aquifer. If we have a high Na/Cl ratio, a high SO_4/Cl ratio, a low Br/Cl ratio, and a low $\delta^{11}B$ ratio relative to seawater, then we are 100 percent confident that wastewater leakages are the major source of salinization at the sample location. If other sources are involved then the states in some of the child nodes, which represent the ionic ratios, will be altered.

5.2.5. Agricultural return flow

Intensive agricultural activities consume about two-thirds of the water resources in the Gaza Strip. It is estimated that 25-30 percent of this water returns to the aquifer and is expected to be one of the major salinization sources to the aquifer (M&E, 2000). Return flows from agriculture have a distinctive chemical composition relative to other salinization sources. This water is characterized by high SO_4/Cl ratios (much greater than 0.05), high B/Cl ratios (0.005), very high Br/Cl ratios (0.02) relative to seawater, low $\delta^{11}B$ ratios (19‰), and $^{87}Sr/^{86}Sr = 0.7082$ (Vengosh et al., 2002). A high B/Cl ratio is attributed to the enrichment of boron in gypsum fertilizers. A high SO_4/Cl ratio is attributed to the application of gypsum fertilizers (Vengosh et al., 2002). A high Br/Cl ratio may be related to the hydrolysis of methyl bromide in the soil, which releases inorganic Bromine to the shallow groundwater (Vengosh et al., 2002).

The agricultural return flows parent node in the model is designed to have four child nodes (see Fig. 4), namely SO_4/Cl, Br/Cl, $\delta^{11}B$, and $^{87}Sr/^{86}Sr$ ionic and isotopic ratios. If we have a high SO_4/Cl ratio, a very high Br/Cl ratio relative to seawater, a low $\delta^{11}B$, and $^{87}Sr/^{86}Sr=0.7082$, then we are 100 percent confident that agricultural return flows are the major source of salinization at the sample site. If other sources are involved then the states in some of the child nodes, which represent the ionic ratios, will be different.

6. Results and discussion

6.1. Likelihood results

The second column in Fig. 5 shows the probability distributions of available ionic ratios from 101 sampled wells. The network performed backward propagation (as explained in Section 3) for these distributions and the results that were produced are shown in the first column of Fig. 5. The ionic data from the sampled wells support the proposition that there is a 0.95 probability that leakage from wastewater is the most dominant source of salinization in the Gaza coastal aquifer. Other salinization sources are less significant, as the model indicates. The application of reclaimed wastewater in irrigation east of the Gaza Strip in Israel may support the idea that the underground lateral flow carries some of this water. A well-by-well analysis is presented in the Section 6.2.

6.2. Well-to-well results

The ionic data from each well were separately tested with the model. Backward propagation in

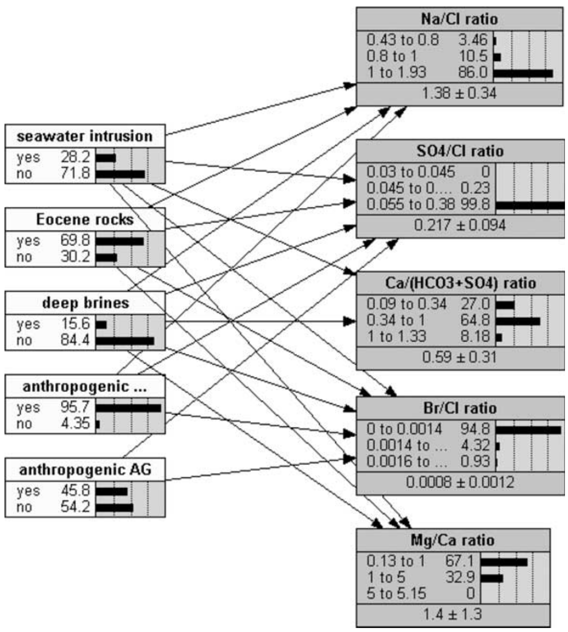

Fig. 5. The most likely pollutant.

Table 3
Summary of the BBN analysis of 101 wells

Location	Confidence level	Percentage of wells having this salinization source with the specified probabilities					
		Seawater intrusion	Eocene rocks	Deep brines upconing	Wastewater seepages	Agriculture return flows	Need more information
Zone 1 22 wells	>90%	59	9	32	86	9	9[a]
	>80%	59	14	41	91	14	5
Zone 2 27 wells	>90%	48	7	19	77	7	5
	>80%	56	15	48	85	15	11
Rest of the area	>90%	7	5	2	41	10	53
	>80%	38	10	25	44	20	22
Total 101 wells	>90%	26	10	13	57	15	36
	>80%	47	13	33	62	17	14

[a] The sum of the row probabilities may be more than 100% which indicates that in some of the wells two or more sources of salinization are dominant.

the BNN then produced the probability of existence of each source of salinization. Two different confidence levels were considered, namely, 90 and 80%. A 90% confidence level means that, in a particular well, we have a 0.9 probability or more that a particular source of salinization exists. Table 3 summarizes the results of this analysis.

Seawater intrusion is believed to be the most dominant source of salinization in Zone 1. With reference to the first row in Table 3, data from ionic ratios show that 59 percent of the wells have 0.9 or more probability that seawater intrusion is present. On the other hand, 86 percent of the same wells show that pollution from wastewater leakages is also present with the same high probability. Deep brines are also detected with high probability but in only 32% of the wells. The existing data in this zone does not support a high probability of salinization from other sources. In addition, in 9% of the wells more information is needed in order to improve the belief (to 0.9 probability or more) that a specific source of salinization exists. In the same way we can read the rest of the rows in Table 3 for other zones.

Available ionic data for the whole Gaza Strip shows that 26% of the wells have a probability of 0.9 or more that seawater intrusion is present, 57% of the wells support salinization from wastewater leakages, 15% indicate salinization from irrigation return flows, 13% indicate salinization from the deep brines origin, and 10% of the wells have the signature of the Eocene formation with the same high probability. In 36% of the wells, more information is needed in order to improve the belief (to 0.9 probability or more) that a specific source of salinization exists. These wells may represent more than half of the surface area of the Gaza Strip (Fig. 6f). Note that when the confidence level is reduced to 0.8, wells that need more information are reduced by half. In other words, reducing the uncertainty will result in more cost associated with data collection.

Fig. 6 shows a geographical distribution of each source of salinization separately. Fig. 6a shows the locations where seawater intrusion exists with probability 0.9 or greater. Figs. 6b–e show the locations, where other salinization sources exist with the same high probability. These maps were derived by applying area interpolation between data points that indicate a particular source of salinization and data points that need more information to decide. In some areas where the distance between wells is large, imaginary wells were added with no information to avoid false representation and unjustifiable extrapolation. The hatched areas in Fig. 6f represent areas with no data points or areas that need more information to improve the probability up to 0.9 that a particular source of salinization exists.

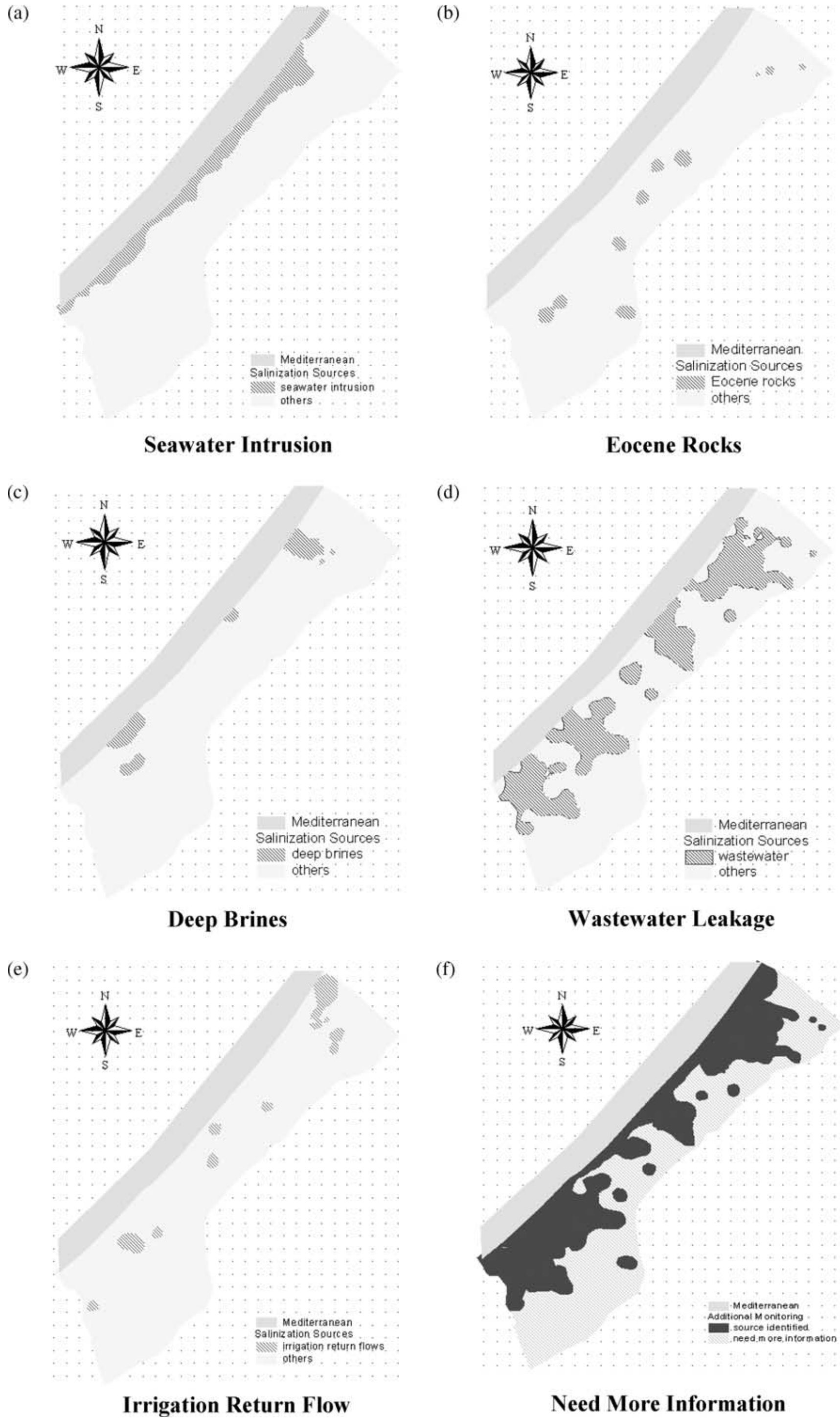

Fig. 6. Geographic distribution of salinization sources with probability 0.9 or greater. (a) Seawater intrusion; (b) Eocene rocks; (c) deep brines; (d) wastewater leakage; (e) irrigation return flow; (f) need more information.

6.3. Additional monitoring

The model results showed good agreement with the expectation in areas vulnerable to pollution from wastewater leakage. This source is found with a very high probability in areas north and south of Gaza, in the Deir El Balah area, the Khan Younis area, and the Rafah area. These areas are characterized by improper domestic wastewater treatment and disposal methods. In the coastal zone the model performed as expected in identifying the areas with seawater intrusion, although pollution from wastewater leakage also exists with a very high probability in the same locations. These two sources could jointly exist beside any other source. With the limited available information, only Br/Cl ratio can clearly distinguish wastewater from other sources. The high values of the other two indicators, namely Na/Cl and SO_4/Cl, relative to seawater can as well represent waters from Eocene rocks and irrigation return flows. Hence, to avoid over representation of areas polluted with wastewater, sampling for δ^{11}B and ^{87}Sr/^{86}Sr isotopic ratios is necessary to be more decisive. These isotopes have been used in other parts of the coastal aquifer (Vengosh et al., 1994; Vengosh et al., 1999).

Although there are intensive agricultural activities in the Gaza Strip, the model results do not say much about pollution from irrigation return flow. There may be two reasons for this: (1) most of the sampled wells are domestic wells and located mostly in urban areas, or (2) because of the limited availability of data, only two indicators were actually used to identify pollution from agricultural return flows, namely SO_4/Cl and Br/Cl ionic ratios. The value of the first ratio could as well represent wastewater leakages (see Table 2). The values of the Br/Cl ratio are available for only 60 wells. Hence, in order to have sufficient information to complete this monitoring task the following should be considered:

- Bromine concentration measurements are needed for the rest of the sampled wells.
- Include some of the wells located in irrigated agricultural areas and shallow groundwater table depths in the sampling and analysis.
- δ^{11}B and ^{87}Sr/^{86}Sr isotopic ratios have been used successfully to identify this source of pollution (Vengosh et al., 2002). It is worthwhile to test these isotopic ratios in areas suspected to have irrigation return flow pollution.

The model also identified some areas with deep brines, but only in some of the wells in Zone 2.This is logical because of two reasons: (1) most well screens are located at a shallow depth relative to the total depth of the bottom of the aquifer where those brines are found; and (2) movement of these saline waters is seasonal and very dependent on water table fluctuation and pumping rates. The data from deep piezometers near the seashore in the middle and the southern portions of the Gaza Strip showed chloride concentration up to 66,000 ppm, which indicates the presence of deep brines (M&E, 2000). Hence, in this regard, deep sampling is necessary to represent the deeper part of the aquifer.

The model showed a few wells that have the signature of water from the Eocene formation. Literature suggests that Eocene water is a major potential source of the brackish groundwater that flows into the Gaza Strip (Vengosh et al., 1999). Lack of information in the eastern areas of the Gaza Strip near the boarders with Israel could be the reason for this disagreement. Also, information about δ^{11}B and ^{87}Sr/^{86}Sr isotopic ratios in these areas would be beneficial and would reduce the areas labeled as “no information” in Fig. 6f.

6.4. Sensitivity analysis

An analysis was performed of the sensitivity of model results to assumed marginal/prior probability distributions (Table 1). All the data points were tested considering equal prior probability (0.5) for YES and NO states of each pollution source. These results were then compared with the results obtained after specifying certain prior probabilities. In 6 out of 101 wells the belief that a particular source of salinization exists improved/changed by 10%. Initially in those wells no dominant source of salinization was identified with 0.9 or more probability, and more information was needed to improve this probability level. In 17 out of 101 wells the most probable source of salinization remains the same, but the probability that another source exists changed by less than 10%. The results remained the same in the rest of the wells. Hence we can conclude that the results are not sensitive to prior belief assumptions in deciding the most probable source of pollution (see also Stiber et al., 1999).

Table 4 shows the sensitivity of the ionic ratios variables to the findings at the parent nodes. The objective of such an analysis is to identify those variables to which the results may be sensitive and thus to more carefully assign the prior probabilities on them. The last column in the Table 3 shows the percentage by which the variance of the ionic ratio probability distributions can be reduced based on findings at parent variables. A variance reduction implies that the values of a given variable can be made to concentrate more tightly about the mean value, and hence reduce the uncertainty about the state of the variable. The results in the table tell us that we should be more careful in assigning the prior probabilities at seawater intrusion, deep brine, and agricultural return flow nodes.

Table 4
Sensitivity of child nodes to the findings at parent nodes

Ionic ratios variables	Variables with prior probability setting (sources of salinization)	Variance reduction (%)
Na/Cl	Seawater intrusion	2.55
	Eocene rocks	7.03
	Deep brines upconing	13.0
	Wastewater seepages	5.90
	Agriculture return flows	0
SO_4/Cl	Seawater intrusion	6.81
	Eocene rocks	3.11
	Deep brines upconing	6.81
	Wastewater seepages	2.67
	Agriculture return flows	2.67
Ca/(HCO_3 + SO_4)	Seawater intrusion	4.08
	Eocene rocks	0
	Deep brines upconing	32.8
	Wastewater seepages	0
	Agriculture return flows	0
Br/Cl	Seawater intrusion	0.68
	Eocene rocks	0.77
	Deep brines upconing	0.69
	Wastewater seepages	1.68
	Agriculture return flows	18.1
Mg/Ca	Seawater intrusion	29.4
	Eocene rocks	1.49
	Deep brines upcoming	3.25
	Wastewater seepages	0
	Agriculture return flows	0

7. Conclusions

Salinization in the Gaza coastal aquifer may be caused by a single process or a combination of different processes, including seawater intrusion, upconing of brines from the deeper parts of the aquifer, flow of saline water from the adjacent Eocene aquifer, return flow from irrigation water, and leakage from the wastewater.

A Bayesian belief network was designed to utilize Na/Cl, SO_4/Cl, Br/Cl, Ca/(HCO_3 + SO_4), and Mg/Ca ionic ratios for understanding different salinization processes and sources of saline pollution. Although we have no information about δ^{11}B and ^{87}Sr/^{86}Sr isotopic composition they were included in the network to study their importance in this monitoring task.

Salinization due to wastewater leakages is found to occur with a very high probability in the areas north and south of Gaza, the Deir el Balah area, the Khan Younis area, and the Rafah area. These areas are characterized by improper disposal and treatment methods of domestic wastewater.

In the coastal zone, areas with a high probability of seawater intrusion were identified. Pollution from wastewater leakage also exists with a very high probability in the same locations. This tells us that seawater intrusion is not the only key issue in the coastal zone, and water managers should pay attention to other sources of pollution that could be more harmful. Some sampling for δ^{11}B and ^{87}Sr/^{86}Sr isotopic ratios is necessary in this zone to understand the contribution of each of these sources to the problem.

Although there are intensive agricultural activities in the Gaza Strip, the results of the model do not indicate salinization due to irrigation return flow. Limited availability of data in the areas of intensive irrigation activities could be the main reason for this. In these areas, additional data about Br/Cl, δ^{11}B and ^{87}Sr/^{86}Sr ionic and isotopic ratios is necessary.

In Zone 2 where deep brines are expected to be the most likely sources of salinization, only a few locations showed agreement with the expectations. The available data represent the shallow part of the aquifer and deep sampling is necessary to understand the extent of this salinization source.

Although literature suggested that Eocene water is a major potential source of the brackish groundwater that flows into the Gaza Strip, the model supported this argument in only a few locations. Again, lack of information in the eastern areas of the Gaza Strip near the boarders with Israel could be the reason for this disagreement.

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