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Case study

Combined land-use and environmental factors for sustainable groundwater management

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Abstract

Sustainable groundwater management must take into consideration pollution sources and the potential of fluid percolation which could convey pollutants to the aquifer. The objective of this paper is to highlight the relationship between environmental factors and land-use types, and the adverse effects upon groundwater quality which may stem from that relationship. A clear understanding of the significant impact of land-use can generate guidelines for sustainable groundwater management. Appropriate conservation and remediation measures, could then be suggested, taking in consideration land-use and intensity of percolation potential from the ground surface to the water table. Guidelines for operational measures can be suggested to mitigate and correct adverse trends in groundwater quality. Integrated with such guidelines, planned land-use activities should harmonize with needs of both ecological and sustainable groundwater management. Two study areas located in different regions of Israel's coastal aquifer have been considered in this paper. Erez-Shiqma represents a pristine region, whilst the Ra'anana area represents a region suffering from significant eco-hydrological stress.

Keywords: Environmental factors; Groundwater management; Land-use planning; Remediation measures; Sustainable development

1. Introduction

1.1. Environmental, land-use, and groundwater management stress factors

As a region's population grows, usage of land must be altered to accommodate burgeoning needs. Improperly planned land-use alterations adversely impact a region's environmental integrity. Inappropriate placement of industrial, commercial or high-intensity residential areas can significantly degrade regional environment. Intensive agriculture can potentially pollute groundwater with fertilizers, pesticides, and minimally treated effluents for irrigation. Polluted effluents could degrade surface water quality and vegetation.

Contributory natural environmental factors affect the limitation provided by the protective shield of soil and rock above the water table of phreatic aquifers. These include low slopes, shallow water table, high recharge and hydraulic conductivity, permeable soils, low natural groundcover, high coefficient of recharge, etc. Such natural aspects of the ambient environment can become unsustainability factors with regard to maintenance of groundwater quality.

In the steady-state situation of coastal aquifers groundwater drains towards the seashore. Excessive pumpage clearly has a severe detrimental effect upon groundwater reservoirs. Water tables drop, significantly altering groundwater flow-directions. Where excessive pumpage situations apply, saline seawater tends to intrude into the fresh water inland reservoirs, a phenomenon which can make salinisation almost irreversible (Goldenberg, Mandel, & Magaritz, 1986).

Further inland within coastal phreatic aquifers, foci of high pumpage can cause hydraulic cones of depression. Groundwater flows inwards towards these depressions in which chemical and biological parameters are concentrated and accumulated, a phenomenon leading to deterioration in groundwater quality and a danger to public health. Improper aquifer management, characterized by insufficient long-term considerations, can thus have significantly adverse consequences.

Urbanization in coastal regions is most often accompanied by a rise in anthropogenic pollution

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percolating to the water tables of coastal phreatic aquifers. The magnitude of percolation and subsequent pollution potential in such areas can be assessed by such empirical models as DRASTIC, AVI models, and others (Aller, Bennet, Lehr, & Petty, 1985; Andersen & Gosk, 1989; US EPA, 1985; Van Stempvort, Ewart, & Wassenaar, 1993).

Groundwater quality deterioration is a function of many factors. These include the ability of the intervening unsaturated zone and soil media to transfer fluids from the ground surface to the water table of phreatic aquifers. However, an equally significant concern is the potential of any specific land-use to contribute percolating pollutants.

Groundwater vulnerability assessment of Israel's coastal aquifer has recently been undertaken by the Israel Hydrological Service hydrologists. A form of the US EPA's DRASTIC model has been utilized to delineate the relative degree to which diffuse pollution might be able to alter groundwater quality as well as the character of soil clay components (Secunda, Collin, & Melloul, 1998). The results of this study highlight areas having higher pollution potential or higher vulnerability to groundwater pollution. Some of these results have been validated by the appearance of raised levels of chlorides and nitrates in groundwater, as indicated by an index of aquifer water quality, utilizing standard values of these parameters (Melloul & Collin, 1998). Detergents and other organic pollutants have been identified relatively deep within the vadose zone (Muszkat, Rosenthal, Ronen, & Margaritz, 1989; Zoller, Goldenberg, & Melloul, 1998). Urbanization has thus clearly amplified unsustainability factors in such stressed coastal aquifers (Collin & Eitan, 1999).

Alterations in aquifer media can also result in development of preferential flow paths that create hydrological short-cut phenomena which enhance the degradation of groundwater quality, lower the quantity of resources available for users, and thus impede sustainable groundwater development (Melloul & Collin, 1994; Zoller et al., 1998). It is therefore quite urgent to delineate and access the adverse influence of such factors which limit sustainable groundwater management.

Ideally, "time of arrival", as a numerical value, would be the ideal basis for vulnerability assessment with regard to the potential at any point for groundwater pollution. In fact, the unsaturated zone and soil act as the key factors determining percolation potential at any point. In the saturated zone, conductivity (K) values can provide key assumptions. However, within the unsaturated zone, owing to lack of meaningful conductivity (K) values in this zone, a theoretical time of arrival model is not presently workable. Only empirical extrapolation of field values can approximate time of arrival estimation. Therefore, the use of environmental and land-use impact considerations remains the most meaningful representation of true vulnerability of groundwater resources to potential anthropogenic pollution from the ground surface.

1.2. Ecological factors involved in harmonizing groundwater resource management with land-use planning

Attempts have been done in many countries to diminish the stress of ecological factors and harmonize land-use levels with natural terrain constraints. Intrinsic suitability for specific uses has been suggested and utilized in Boston, Staten Island, and Philadelphia, in USA (McHarg, 1969). This has been implemented by incorporation of harmonious compliance of land-use alteration with terrain restrictions and amenities.

One of the more interesting attempts to harmonize public land-use planning with terrain amenities has been carried out in Chicago throughout the 20th century. Earlier, the city had earlier turned its back on its waterfront. But following acceptance of the revolutionary Burnham Plan, the city bought up all of its lakefront, transferred the port and industrial center south of the city, and replaced these with beautiful parkland and open-space, accessible to the public (Burnham & Bennett, 1909).

A different type of challenge was faced by Baltimore. There, the city borders a labyrinthine embayment rather than a linear lakefront such as Chicago's. Disparate parties involved in its renovation planning process included local, regional, and Federal government agencies, private industry, and representatives of residential neighborhoods adjoined the harbour. Ultimately, port areas were transferred to more peripheral areas, public access was gained to the inner harbour, and environmental renovation was attained for the entire Baltimore region (Collin, 1973, 1975).

In Israel, similar innovative development has recently been made along its Mediterranean coast near Tel Aviv and Haifa. Here, long-term land-use planning and integrated ecological perspectives are increasingly becoming the norm for land-use alteration (Eldar, 1999; Lewy-Yanowitz, 1999).

Effective land-use and natural resource planning processes must ultimately be integrated. Sustainable development of groundwater is critical to urban planning. Integrated land-use and natural resource planning must simultaneously consider social and economic concerns and amenities, ecological and æsthetical requirements, in the context of sustainable groundwater development.

The objective of this paper is to note and combine environmental and land-use stress factors for ecological and groundwater resource purposes. The suggested approach can generate guidelines which could contribute towards groundwater sustainability.

2. Methodology

To mitigate non-sustainable factors and adverse effects upon long-term groundwater supply for future need, guidelines for sustainable groundwater management are necessary. These operational guidelines should be based upon such major eco-hydrological considerations as the potential of water infiltration under various environmental conditions, and the potential for pollution characterizing various land-usage factors. The greater the degree to which the guidelines can be quantified the better, they can be linked to numerical assessment of groundwater quality, aquifer rechargeability, and potential groundwater pollution by individual land-use types.

Key environmental components which affect aquifer rechargeability and land-use types which can pollute the aquifer are displayed in Table 1. On the vertical side of this table are components of the potential of environmental water recharge (PEWR) and on horizontal side are components of the Potential for land-use pollution of groundwater (PLPG).

These environmental and land-use components are presented with four levels of sensitivity weighting their different potential impact on groundwater. These levels are labeled as "H", "h", "l", and/or "L", "H" is for the case where the component has high potential of rechargeability of the aquifer; and/or high potential of pollution of groundwater from land use components. Intermediate, environmental and land-use impact upon groundwater quality are graded from moderately high (**h**), through moderately low (**l**) potential. The lowest potential impact for the both types of components being labeled as "L". The levels indicate the degree of potential impact a particular land-use may have upon the natural recharge ability of the aquifer and its groundwater quality for any study area.

In order to perform additive numerical assessment of environmental and land-use character of the area of concern, weighting has been assigned to each level. Although values attributed to each level are arbitrary, highest values are related to highest potential, etc., such as **H** = 4; **h** = 3; **l** = 2; and **L** = 1.

2.1. Assesment of the potential for environmental water recharge (PEWR)

The PEWR is presented in Table 1, utilizing four environmental categories: the hydrology, the land's physiography, soils, and ambient vegetation. Each environmental category is, in turn, subdivided into levels as regards specific conditions.

Hydrology involves such components as depth to water table, coefficient of recharge, and hydraulic conductivity of the vadose zone. Each of these components includes conditions labeled: "H", "h", "l", or "L". Here, "H" = high, "h" = moderately high, "l" = moderately low, and "L" = Low. The scale applies to either the relative degree of potential land-use impact upon groundwater quality or the relative potential for groundwater recharge – viz.: environmental sensitivity – at any particular location. Thus, in the case of depth to water table, shallow water table is labeled (H) when less than 5 m below the ground surface or labeled "L" when depth to the groundwater table is greater than 5 m; high recharge is labeled (H) for coefficient of recharge greater than 50%; and labeled (L) for lower values; high hydraulic conductivity is (H) for the case the media is characterized by

Table 1
Combining different levels of PEWR with PLPG

Environmental factors			Potential of land-use pollution on G.W. (PLPG) ⟹	Land-usage categories and intensities								
Categories	Components	Conditions		Conservation	Recreation		Agriculture		Residential		Industry and commercial	
					High	Low	Field crops	Orchards	High	Low	High	Low
			Rechargeability (PEWR) ⇓	L	h	L	h	l	h	L	H	h
Hydrology	Water table	Shallow	H	HL	Hh	HL	Hh	Hl	Hh	HL	HH	Hh
		Deep	l	lL	lh	lL	lh	ll	lh	lL	lH	lh
	Recharge coefficient	High	H	HL	Hh	HL	Hh	Hl	Hh	HL	HH	Hh
		Low	l	lL	lh	lL	lh	ll	lh	lL	lH	lh
	Hydraulic conductivity	High	H	HL	Hh	HL	Hh	Hl	Hh	HL	HH	Hh
		Low	l	lL	lh	lL	lh	ll	lh	lL	lH	lh
Physiography	Slope	< 20%	h	hL	hh	hL	hh	hl	hh	hL	hH	hh
		> 20%	l	lL	lh	lL	lh	ll	lh	lL	lH	lh
Soils	Permeability	Permeable	H	HL	Hh	HL	Hh	Hl	Hh	HL	HH	Hh
		Impermeable	L	LL	Lh	LL	Lh	Ll	Lh	LL	LH	Lh
Tree and other vegetation cover		Low	h	hL	hh	hL	hh	hl	hh	hL	hH	hh
		High		l	lh	lL	lh	ll	lh	lL	lH	lh

Key symbols: Very high – H; high – h; moderately low – l; low – L.

hydraulic conductivity values higher than 10 m per day and (L) for lower values; etc.

Physiography is subdivided into areas having slopes of 20% and more, labeled as "l", and those with less than 20% slope by "h" based on the fact that a lower degree of slope enables greater percolation from the surface to the water table.

Soils are subdivided into permeable or impermeable media. Label (H) applies to soils high in sand and "L" for soils richer in clay components.

Vegetation entails areas of high vegetation cover by label "l" enabling less water recharge than for the case labeled by "h", in which less vegetatie cover impedes percolation from the ground surface to the water table.

In this manner, any area of study can be characterized by its specific PEWR components. Therefore, for each area of study one averaged value of specific PEWR can be estimated by use of the following formula:

$$\text{Average PEWR} = \text{sum of PEWR components}/N, \tag{1}$$

where N is the number of component conditions which factor into the calculation of the average value. In Table 1, the total number of (PEWR) component, $N = 6$.

2.2. Assesment of the potential for land-use pollution of groundwater (PLPG)

Land-use components of five environmental categories are presented in Table 1. For each category, one or more components with two different intensities are considered.

The *conservation* land-use category implies minimal alteration compatible with preservation concerns (such as nature preserves), and is considered as (*L*) owing to minimal contribution to pollution.

The *recreation category* involves low intensity passive usage with generally low pollution potential. The category includes hiking paths and camping facilities, and is considered (*L*), while more active usage, such as sports facilities, marinas, etc., having higher pollution potential, are considered (*h*).

The *agricultural* category use can involve, on one extreme, field *crops* which tolerate and therefore receive high levels of pesticide and fertilizer applications, and are therefore considered (H) – thus having a higher potential contribution water pollution. At the other end of the scale, *orchards* are so sensitive to salinity that they restrict use of pesticides and fertilizers to minimal application levels and for these reasons are considered (*l*).

The *residential* land-use, category is considered (*L*), varying, as it does, from the low intensity usage of large, rambling estates to high intensity usage, and considered (*h*) for high-rise units in tight urban configurations.

The *industrial and commercial land-use category* can vary significantly in its potential for potential pollution. Low intensity usage includes small shopping centres, light industrial (research-development) parks, petrol stations, along with minor streets and roads, and can be therefore considered as contributing to intermediate to moderate high pollution, and considered (*h*). High intensity usage of major shopping malls, heavy industrial plants, oil facilities and spillage, and major transportation arteries can contribute to high levels of pollution, and can thus be considered (*H*) in Table 1.

Any area of study can be characterized by its specific PLPG components, estimated by the following formula:

$$\text{Average PLPG} = \text{sum of PLPG components values}/n, \tag{2}$$

where n is the number of component land-use categories and intensities which factor into the calculation of the average value. In Table 1, the total number of PLPG components, $n = 5$.

2.3. Recommended guidelines for sustainable groundwater management as regards potential for regional pollution

The combination of PEWR and PLPG values for any particular land-use category or environmental situation yields a variety of combinations of possibilities when assessing potential for groundwater pollution. At any specific location, percolation capacity of water from the ground surface to the water table and pollution potential from the variety of land-usages together characterize the area of study.

Fig. 1 presents levels of PEWR (Y-axis) and PLPG (X-axis). The presentation depicts 16 combinations or possibilities. Each combination represent a situation which can characterize any area of study.

Four extreme situations a, b, c, and d appear on this chart.

- a (= HL) represents an area having the highest PEWR and lowest PLPG. In such a situation sustainable groundwater management, guidelines may recommend use of fresh water recharge *from the surface* as an efficient and economic means of maintaining the area's water resources.
- b (= HH) represents an area having the highest PEWR and PLPG. Sustainable groundwater management guidelines may then give highest priority to measures which could mitigate and prevent further pollution. Recharge of the aquifer in such a situation is not efficient.
- c (= LL) represents an area having minimum PEWR and PLPG. Here, sustainable groundwater management guidelines would recommend groundwater recharge *into wells* with fresh water as a high priority. Measures would be recommended to maintain the area with minimum pollution.

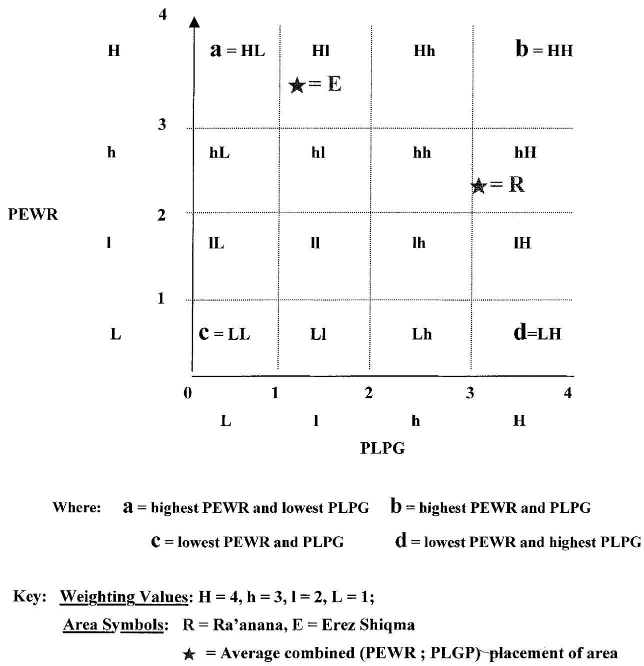

Fig. 1. Characterization of study areas as regards their PEWR and their PLPG.

- d (= LH) represents an area having the lowest PEWR and highest PLPG. Here, sustainable groundwater management guidelines might recommend in situ remediation of groundwater. Recharge of water directly to wells could be considered only if groundwater quality within the area remains satisfactory.

For any given study area, most situations would fall somewhere between these extreme possibilities. Appropriate operational measures would therefore vary accordingly.

3. Ecological and hydro-geological background of the study areas: Ra'anana and Erez-Shiqma

Israel's coastal plain extends from Mt. Carmel in the north to the Gaza Strip in the south, from the seashore on the west to the limestone aquifer on the east (Fig. 2). The aquifer is composed of layers of dune sand, sandstone, calcareous sandstone, silt, loams and clay lenses. These wedge-shaped clay lenses are at their thickest near the coast and feather out within around 5 km of the sea,

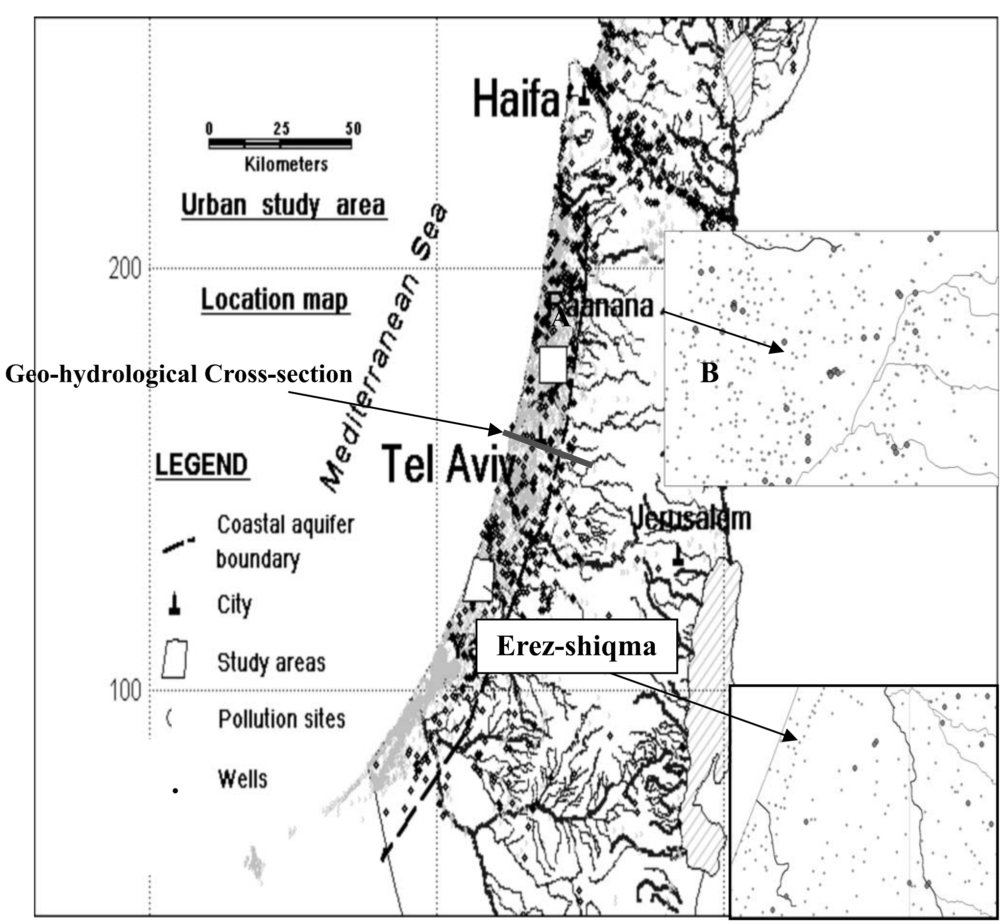

Fig. 2. Location map of the two study areas: Ra'anana and Erez-Shiqma.

effectively separating the aquifer into sub-aquifers. Within around 12 km of the coast the phreatic aquifer overlies sea clays of Neocene age. Eastward the aquifer rests mostly upon limestone aquifers (Tolmach, 1979; Fig. 3).

Since the 1970s, water pumped from the coastal aquifer has included treated water and water from other sources recharged into the aquifer. Treated and partially treated effluents have been used for intensive irrigation on the coastal plain (HSR, 1999). Anthropogenic activities introduce considerable amounts of pollutants into the environment. The degree to which contamination potential varies within the region was indicated in an assessment of vulnerability utilizing the DRASTIC Model (Secunda et al., 1998), and from use of an index of Aquifer Water Quality (Melloul & Collin, 1998).

Over the years, water exploitation has exceeded natural replenishment, resulting in a continuous lowering of the water table by a matter of several meters, and causing accompanying alterations in the direction of groundwater flow, as shown on recent water table level maps (HSR, 1999).

As a result of overpumpage, salinity sharply increased within 1–2 km of the coast due to seawater intrusion. As shown in Table 2, inland, Cl levels remain below the recommended standard of 250 mg l^{-1} Cl · NO_3 levels, on the other hand, are higher inland, and above the recommended standard of 45 mg l^{-1} NO_3, indicating active anthropogenic contamination (HSR, 1999). As a result of stress management, hydrologic short-cuts occur, enhanced by climatic variations which characterize these semi-arid areas. The effects of these processes are more pronounced contamination of groundwater in some portions of the aquifer than others (Zoller et al., 1998).

Two study areas have been selected for this paper. The first is the urban Ra'anana vicinity, northeast of Tel Aviv. The second is Erez-Shiqma, a low-density dune area enjoying low anthropogenic activities, extending between Ashqelon and the Gaza Strip, south of Tel Aviv (Fig. 2).

Data presented in Table 2 set forth the eco-hydrological background of these two study areas. The surface areas of both are roughly equal. Population density of the Ra'anana area is roughly an order of magnitude higher than that of the Erez-Shiqma area. Density of potential pollution sites of the Ra'anana area is more than twice that of Erez-Shiqma (Collin & Eitan, 1999). A far greater number of pumping wells are available for sampling in the Ra'anana area than in the Erez-Shiqma area. Utilizing chloride and nitrate data covering the past forty years, as available in the records of the Israel Hydrological Service (HSR, 1999), it is evident that chloride and nitrate levels, and their change over time, is markedly higher in the Ra'anana area than in the Erez-Shiqma area. Vertical profiles from chlorographs and nitrographs, indicate that degradation of groundwater quality from sources on the ground surface is more evident in the northern portion

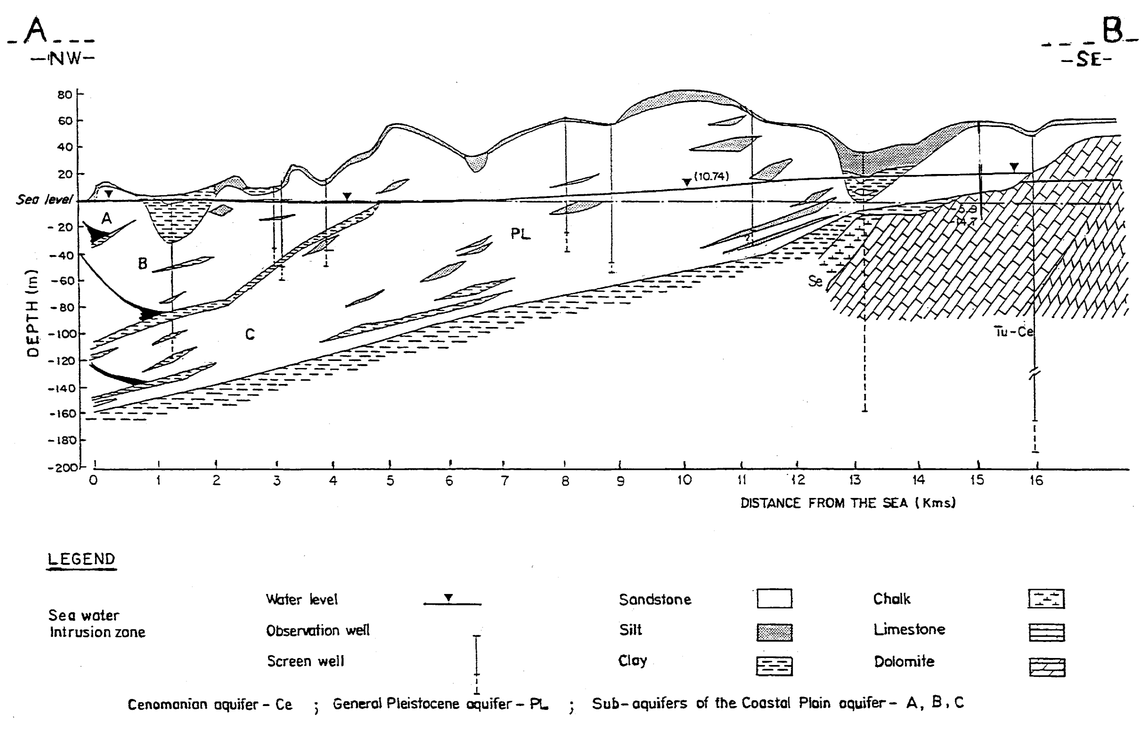

Fig. 3. Schematic hydrogeological cross-section of Israel's coastal aquifer.

Table 2
Ecological and hydrological data relating to the Ra'anana and Erez-Shiqma Study areas

Study areas names	Aquifer layer[a]	Surface area (km^2)	Nr. of wells in sample	Groundwater quality[b]				Socio-ecological data[c]	
				Cl mean 1996 ($mg\ l^{-1}\ yr^{-1}$)	Rate δ Cl ($mg\ l^{-1}\ yr^{-1}$)	NO_3 mean ($mg\ l^{-1}\ yr^{-1}$)	Rate δNO_3 ($mg\ l^{-1}\ yr^{-1}$)	Population density (nr./km^2)	Pollsite density (nr./km^2)
Ra'anana	Shallow	45	24	130	0.5	77	0		
	Medium	45	44	170	1.5	85	1.1	500	0.33
	Deep	45	40	135	1.0	75	0.8		
Erez-Shiqma	Shallow 1	58	5	85	0.2	47	0.2		
	Medium	58	17	83	−0.2	27	−0.1	50	0.14
	Deep	58	5	90	−0.3	23	0		

[a] Aquifer layer: (Shallow) shallow depth wells lower than 40 m below sea level; (Medium) medium depth wells between 40 and 80 m below sea level; (Deep) deep depth wells higher than 80 m below sea level.
[b] HSR (1999).
[c] Collin and Eitan (1999).

of the aquifer than further south (Melloul & Gliantschpigel, 1996).

3.1. Application to the Ra'anana and Erez-Shiqma study areas

Table 3 is a specific case of Table 1, refering specifically to the two study areas in question. This table delineates only components typifying the existing environmental and land-use situation of the two regions involved in the case study. It also presents the current combined situations of key environmental factors related to potential for water recharge together with potential for groundwater pollution of land-usage in the Ra'anana (**R**) and in Erez-Shiqma (**E**) study areas.

As explained in Section 2, averaged weightings of PEWR and PLPG for the two areas is obtained by use of formulas 1 and 2, and shown in Table 3. The arithmetic mean obtained for recharge factor PEWR (shaded column in Table 3) in the more developed Erez-Shiqma area equals 3.5, whilst that for the Ra'anana area is 2.1. The arithmetic mean for potential impact of land-usage factor PLPG (shaded row) for the Ra'anana area is 3.0, whilst that for the Erez-Shiqma area is 1.3.

These values represent the coordinates of average PEWR and PLPG for each study area, enabling locating the two areas on graph in Fig. 1. Their respective positions enable delineation of appropriate operational remedial measures to be implemented in each areas towards sustainable groundwater management. Thus in Fig. 1, the current combined PLPG and PEWR values (3.0; 2,1) for the Ra'anana area place it within the **hH** cell (starred **R**), whilst the current combined PLPG and PEWR values for the Erez-Shiqma area (1.3; 3.5) place it within the **Hl** cell (starred **E**).

4. Discussion

Table 3 gives the PEWR and PLPG component levels specific to the two study areas considered in this case. Fig. 1 indicates the position of these areas as regards their averaged PEWR and PLPG values. By locating the two sites of study in the same graph Fig. 1 illustrates the substantial difference existing between the Ra'anana and Erez-Shiqma areas as regards their respective PEWR and PLPG situation. It also indicates the extent to which these areas presently differ from desired situation or specific combinations. The implication of this deviation indicates the most effective management measures which could be taken in each area towards sustainable groundwater conditions. Thus, considered together, Table 3 and Fig. 1 can, respectively, delineate all the PEWR and PLPG components which characterize these areas, and generate appropriate guideliness for sustainable management in the target area. Areas characterized by high-intensity land-usages with potentially high environmental recharge, as indicated by HH, and hH in Table 3 and Fig. 1, are examples of highly stressed areas most susceptible to groundwater degradation, thus standing in greatest need of such conservation or remediation assessment.

The present case study area of Erez-Shiqma is characterized in Table 3 as an area having a shallow water table, moderate levels of rainfall for natural recharge aquifer, high hydraulic conductivity of the unsaturated zone, high soil permeability (sand and dunes area) soil, low slope, and low amounts of vegetative cover. The area is further characterized by low intensities of residential, commercial, and industrial land-use. Even recreational use is minimal. In Fig. 1, this area is located in cell **Hl** (starred as **E**). Sustainable groundwater management guidelines for such a "pristine" coastal area favour waterfront development for low-intensity recreation while maintaining open, sandy ground for maxi-

Table 3
Evaluating the PEWR and the PLPG from various land-usages types in Ra'anana (R) and Erez-Shiqma (E) study areas

Environmental factors			Potential impact (PLPG) ⇒	Land-usage categories and intensities								
Categories	Components	Conditions		Conservation	Recreation		Agriculture		Residential		Industry and commercial	
					Low	High	Orchards	Field crops	Low	High	Low	High
					Intensity				Intensity		Intensity	
			Recharge (PEWR) ⇓	L=1 (E)	L=1 (E)	h=3 (R)	l=2 (R)	h=3 (R)	l=2 (E)	h=3 (R)	h=3 (R)	H=4
Hydrology	Water table	Shallow	H=4 (E)	E	E				E			
		Deep	l=2 (R)			R	R	R		R	R	
	Recharge	High	H=4 (E)	E	E							
		Low	l=2 (R)		R	R	R	R	R	R	R	
	Hydraulic conductivity	High	h=3 (E)	E	E				E			
		Low	l=2 (R)		R	R	R	R	R	R	R	
Physiography	Slope	< 20%	h=3 (E,R)	E	E/R	R	R	R	E	R	R	
		> 20%	L=1									
Soils	Permeability	Permeable	H=4 (E)	E	E				E			
		Impermeable	L=1 (R)			R	R	R		R	R	
Tree and other cover	vegetation	Low	h=3 (E,R)	E	E/R	R	R	R	E	R	R	
		High	l=2									

Key symbols and values: (Very high) H = 4; (high) h = 3; (moderately low) l = 2; (low) L = 1.
Average environmental components (PEWR) for each area: (E) = 21/6 = 3.5; (R) = 13/6 = 2.1 (see shaded column).
Average land-use components (PLPG) for each area: (E) = 4/3 = 1.3; (R) = 15/5 = 3.0 (see shaded row).

mal natural surface recharge from seasonal rainfall. The area can thus be utilized as multi-annual freshwater reservoir. The artificial recharge to groundwater from storm runoff and from a planned nearby desalinization plant can be implemented both from the ground surface as well as by wells. Owing to this area's proximity to the seashore, hydrological measures should be taken to combat seawater intrusion. Land-use alterations should be carried out in accordance with rational and ecological planning guidelines so as to maintain the areas's pristine ecological character and safeguard relatively low levels of pollution, while providing for economic and residential needs.

Table 3 characterizes the second study area, Ra'anana, as having deeper water tables, moderately low coefficient of aquifer recharge, moderately low hydraulic conductivity and soil permeability, with low slope and low amounts of vegetative cover on the land. In contrast to Erez-Shiqma, the Ra'anana region is characterized by significant anthropogenic alteration, with accompanying stress upon residents' quality of life. Environmental components must thus be actively employed to mitigate the high potential pollution of groundwater from the high-stress land-usuage which characterizes the area. In Fig. 1, the area (starred as **R**) is sited as **hH**. For such an area, groundwater management guidelines must focus upon lowering potential pollution by improved long-term land-use planning. It is necessary to minimize contamination of groundwater pollution, while employing such mangement measures as water treatment and recharge by means of in situ injection into wells. Remediation measures could significantly diminish pollution generated by land-use. To accomplish this, renovation and improvement in the character of the urbanized environment would be required.

5. Conclusions

Presently, "pristine" regions yet unaltered by the hand of human beings, are increasingly rare. Where they exist, serious thought must be given to prevent land-use alteration which could degrade them, and to utilize them as long-term multi-annual subsurface reservoirs. On the other hand, highly stressed, polluted aquifer areas endanger the remaining surrounding groundwater resources. This study presents an approach which can enable delineation of "pristine" or stressed regions, offer appropriate operational measures and guidelines, and attain optimal land-use and environmental utilization and balance.

Specifically, such pristine areas as the Erez-Shiqma region should be managed by employing those remediation measures which could maintain this aquifer area as a long-term multi-annual groundwater reservoir for drinking water supply. Recommended measures thus include recharge from conventional and non-conventional water sources and strict land-use planning guidelines, in order to safeguard these groundwater resources for future generations.

Such environmentally stressed areas as the Ra'anana region should be managed utilizing measures for urbanized land-use renovation along with stringent ecological guidelines to maximize tree cover and ground vegetation, enable maximum public access to natural amenities, promote optimal life quality, and mitigate groundwater pollution. Land-use alteration planning should be carried out in a regional and national context, and includes appropriate hydrological expertise to ensure maintenance of groundwater quantity and quality. Intensive monitoring networks should be so located as to keep accurate track of local and regional trends.

By siting each one of two example study areas in Fig. 1, their situation can be visualized as regards PWER and PLPG factors. Discrepancies between the two areas, presented on the resultant graph, substantiate the gap between the two areas.

Guidelines for appropriate measures towards sustainable groundwater management are presented here. The approach taken in this study combines environmental and land-use components, as presented in Table 1. This approach enables development of a hierarchy of eco-hydrological situations for any particular area of study, which can lead to appropriate measures to mitigate and modify presently destructive trends and factors.

This approach is not intended as a quantitative model. The numbers which result represent the qualitative relative placement of any particular site with regard to environmental factors and land-use categories and intensities.

The study areas were intentionally chosen to point out sharp contrast. The "pristine" and stressed coastal aquifer areas are typical of such areas throughout the world. Thus, this approach can be applied to other aquifers on an international scale.

The objective of sound land-use water quality stewardship is to enhance the commonweal and promote sustainable groundwater management. The operational approaches recommended in this study could facilitate the efficient and effective fulfilment of this objective.

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