African Journal of Agricultural Research Vol. 1 (3), pp. 047-056, October 2006
Available online at http://www.academicjournals.org/AJAR
ISSN 1991 637X © 2006 Academic Journals

Full Length Research Paper

Lithological mapping of the unsaturated zone of a porous media aquifer to delineate hydrogeological characteristic areas: Application to Israel's coastal aquifer

A. Melloul*, J. Albert, and M. Collin

*Hydrological Service; POB 36118; IL-91 360 Jerusalem

Accepted 20 October, 2006

With water quality steadily decreasing, decision-making with regard to water supply must improve aquifer management models, which are based upon various assumptions. Amongst these are assumptions concerning subsurface aquifer lithology. The objective of this study is to present a means of improving information and assumptions, as well as providing guidelines to characterise the unsaturated zone media. This media integrates soils and the "parental material" of soils, which results in a more realistic picture of the surficial layers of the aquifer. This is a key factor for understanding the behavior of the upper border of coastal aquifers and simulation of their hydrogeological models. Developing a digital GIS unsaturated zone map enables 3-dimensional depiction by illustrating the varying permeability characteristics of the stratigraphic layers. The resultant map conveys information about areas having low to high permeability and areas in which perched aquifers might be found. This can consequently contribute to better understanding of the recharge process, and of the reasons for deterioration of groundwater quality in the aquifer. In the case of aquifers prone to stress from significant anthropogenic land-use, the map highlights areas whose vadose zone has the ability to convey liquids and pollutants to the aquifer below. The focus of this study is Israel 's Coastal aquifer, a resource of critical significance to the country's water supply, which underlies the most populated areas of the country. This aquifer has been chosen because of its variegated lithology and water quality, the quantities of water being pumped from it, the large amount of existing data, and the potential of water which can be readily stored in it. This aquifer would appear to be an appropriate example of coastal aquifers around the world, to demonstrate the utility of such unsaturated zone mapping. This mapping can prove a tool for developing recommendations with regard to irrigation, land-use planning, and aquifer management.

Key words: GIS mapping, unsaturated zone/vadose zone, lithology, confined aquifer, phreatic aquifer, Coastal aquifer.

INTRODUCTION

Anthropogenic activities on the ground surface of a coastal aquifer

Groundwater contamination resulting from anthropogenic sources has become an environmental issue of major concern and the focus of public attention in recent years (Burmaster and Harris 1982; Zoller and others 1998). In coastal areas, a combination of rapid population growth and poor long-term planning has led to inappropriate construction and industrial siting (McHarg 1969; Appleyard 1995). These regions can contain wastewater treatment, storage ponds, and substantial number of operating and nonoperating effluent irrigation areas with large capacity solid waste dumps. Often, such areas host numerous potential industrial pollution sources, cities, towns, and villages, with major roads, and railway-lines (Bachmat and Collin, 1990; Collin 1995; Eitan 1995).

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*Corresponding author's E-mail: fmigliardo@unime.it, Tel. +390906765012; Fax. +39090395004.

The Buffering role of the vadose zone

The unsaturated or vadose layer, above a phreatic aquifer's water table, includes here the surficial soil layers and the vadose zone beneath the soils. Vadose zone media lithologies are the "parent materials" of the soils formed above them, and play a significant buffering role between the ground surface and the water table, as far as percolating liquid pollutants are concerned. Where undisturbed, these soils therefore reflect the unsaturated zone media lithology beneath them. The soils and the surficial unsaturated zone layers, their parent rock, strongly influence attenuation, routing, and time-of-arrival of percolating liquids moving through the unsaturated zone towards the water table. Physical and chemical attenuation processes can be active in this zone above the water table. They can include biodegradation, chemical reactions, dispersion, mechanical filtration, neutralization, and volatilization (Goldenberg and Melloul, 1994; Ronen and others 2000).

Direct aquifer recharge and vulnerability to pollution are therefore markedly influenced by the lithologies of these layers and their stratigraphic order. An accurate assessment of the various areas of the vadose zone is therefore an important step for hydrological characterization of the media overlying any aquifer, especially a coastal aquifer.

Importance of vadose zone assessment for hydrological and irrigation models

Owing to lithologic heterogeneity of the unsaturated zone, there is a consequent lack of accurate data as regards this media's permeability and/or coefficient of conductivity. A number of approaches have been undertaken worldwide to assess the vulnerability of groundwater quality to pollutant infiltration through the unsaturated zone. Beside mathematical models (Baum 1994), other approaches estimate groundwater vulnerability on the basis of maps, or aquifer vulnerability index tables. In most cases, groundwater vulnerability estimation has been mainly based upon a specific parameter, such as depth to groundwater or to an unpervious layer, the thickness of the sedimentary layers composing the unsaturated zone above the water table, and/or by general estimation of the hydraulic conductivity of these layers (Sotornikova and Vrba 1987; Andersen and Gosk 1989; Cramer and Vrba 1987; Van Stempvort and others 1993; Robins and others 1994; Hiscock and others 1995). However, owing to uncertainty regarding the use of each parameter, the U.S. EPA DRASTIC model can prove quite helpful in approximating vadose zone vulnerability to pollutants percolating from the ground surface by using the contribution of additional parameters. The drastic model incorporates a weighted,

parameters. The drastic model incorporates a weighted, additive formula, utilizing seven media parameters such as: depth to water table, recharge, aquifer media, soil characteristics, topography, impact of the vadose zone, and hydraulic conductivity. Some of them can be represented as a GIS layer based on point-source data, (US E.P.A 1985; Aller and others 1985; Rundquist and others 1991; Merchant 1994; Zhou et al., 1999; Chen and Fu, 2003). To augment the efficiency of such a DRASTIC model, parameters such as extensive use of anthropogenic sources including agriculture impact on groundwater have also been incorporated into it. This leads to the Composite DRASTIC model, augmenting the DRASTIC results by additionally appraising levels of potential risk and vulnerability of groundwater resources to pollution (Secunda et al., 1996; Melloul and Collin M. 1998). Despite these additional factors, it should be clear that such assessment produces relative rather than quantitative results, which remain approximate. The key concern being addressed when assessing a region utilizing a DRASTIC model is to pinpoint the key areas of highest hydrological vulnerability. On these areas more accurate quantitative assessment can then be utilized. This reduces the cost of attempting to fund an expensive quantitative monitoring system region-wide.

Inaccurate data in such assessment can result from unsaturated zone complexity, involving alterations of soil types and lithology, aquifer confinement, key sub-aquifers of the study area, depth to groundwater when referring to sub-aquifers and to the layer to which it belongs, etc. For that reason, hydro-geological cross-sections which are a result of synthetic and logical deduction as regards connection of lithology layers, can be considered relevant, improving the artifial intelligence at this regard (Chau W. 2006a,b).

Thus, considering the high importance of unsaturated zone lithology regarding assessment of the rate of downward percolation of water from the ground surface to the water table of the aquifer, this present study focuses mainly upon the mapping of such media.

Objective of this manuscript

The key objective of this study is to produce a map of the unsaturated zone between the saturated aquifer and above-lying soils, based on hydrological cross-sections of the aquifer in question. Such a map should delineate areas of varied permeabilities, and consequently highlight areas having a high degree of vulnerability to groundwater pollution. The resultant maps should be quite useful towards better assessment of the various properties of the aquifer media's upper boundary. Owing to its variegated hydrogeological characteristics, Israel's Coastal aquifer has been chosen as the case study for application of this approach.

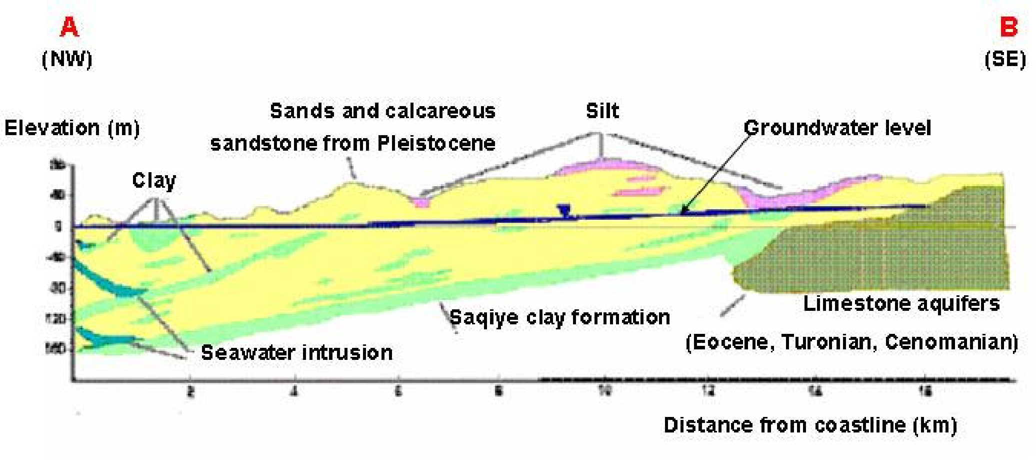

Figure 2. Hydrogeological cross-section of A-B transect from Figure **1**.

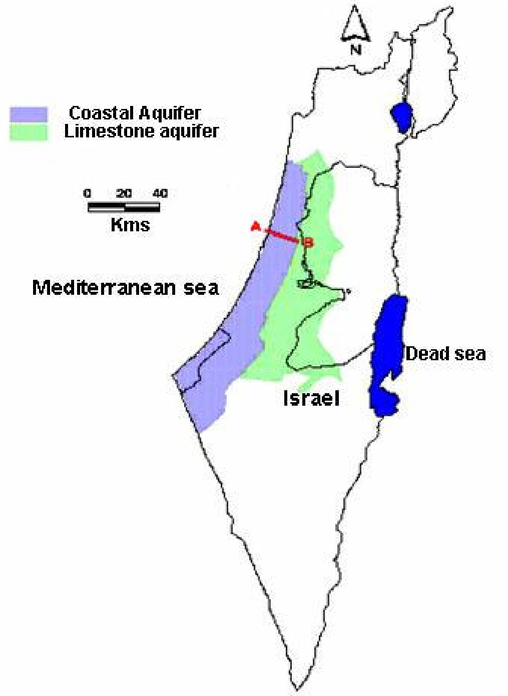

Figure 1. Location map and position of cross-section A-B.

Concepts of unsaturated zone mapping preparation

This study utilizes as example hydro-geolological cross-sections of Israel Coastal aquifer, obtained after deducing connections between various types of lithologic layers, based upon point-source well cross-sectional data (Figures 1 and 2). The objective is to update understanding and characterization of the unsaturated zone upper border of the aquifer. The results enhance empirical, and other models, augmenting artificial intelligence regarding the study area (Chau, 2006a). The greater the number of geological cross-sections, the more accurate the assessment of the unsaturated zone.

The aquifer's unsaturated zone lithologic variations are depicted as a digital geographic information system (GIS) map displaying the 2-D spatial distribution of the Israel Coastal aquifer's lithology (Figure 1) in the X-Y plane as determined from a series of hydro-geological cross-sections (in the X-Z plane ; Figure 2). Thus, to build such a map the key steps involved are:

- Conversion of the complete unsaturated zone lithology for each two-dimensional (X-Z) geologic cross-section into discrete segments based upon the two-dimensional (X-Y) hydrologic grid for the aquifer as shown in Figure 3.
- Digitization of the X-Y lithological cross-section, stored in a digital data layer with a grid and partial supporting topology. All digitization can be performed, using Arcview and/or other GIS programmes for system application.

Where lithologic transitions do not correspond to grid boundaries, a polygon grid structure should be built.

Individual cells can then be subdivided into sub-cells, to account for a lithological transition occurring in other portions of the cell. A colour table is necessary to distinguish basic material with gradations of individual colours used to convey layer thickness.

In the cases of cells having perched aquifers, once construction of the aquifer's polygon structure is complete, each individual cell or sub-cell can be encoded with four lithological parameters: upper layer material and thickness, and underlayer material and thickness. This mapping, both the pervious and impervious to semi-impervious underlying material (as well as its thickness) are depicted by a band of colour surrounding the cell or sub-cell in question. Otherwise, only a single lithological layer is displayed.

The final product is a digital 2-D map which supplies 3-D information. Such a map produces a more accurate assessment of the lithology between the aquifer's groundwater table and the ground surface. Information obtained by such maps can delineate geographic locations where the aquifer's unsaturated zone is "open" or hydrologically "phreatic", to highlight areas where the porous media coastal aquifer unsaturated zone acts as a filter to recharge the aquifer, as well as unconfined to semi-confined areas where the connection with the aquifer questionable.

Such mapping can lead to better understanding of this part of the aquifer; enabling more intelligent manipulation of data and better calibration of hydrological parameters. This can lead to more accurate assumptions and thus to more efficiency of the models, to resolve environmental and hydrological problems. In some way, this can be considered as an additional step towards understand a process to formalize the knowledge that provides a basis from which decisions can be made or pattern discerned. This mapping can also be a basis for construction of algorithms to be integrated in formatic programmes and numerical modelling for advancement of the artifical intelligence for optimal management of aquifers (Chau, 2006a,b).

Application of the approach to Israel's coastal aquifer

Hydrogeological situation of the Coastal aquifer

The Coastal aquifer is one of the most important groundwater resources in Israel. Annual exploitation of the aquifer has ranged around 500 MCM (Million Cubic Meters), a fourth of all Israel's consumption. It serves as an important component of the National Water Carrier System that conveys water from the northern to southern portions of the country. Furthermore, the aquifer acts as a key reservoir into which surface water, sometimes as treated wastewater, recharges the aquifer (between 100-120 MCM), either by direct injection or by surface spreading and infiltration (IHSR, Service 2000).

The Coastal aquifer is a Pleistocene granular groundwater formation extending from the Mt. Carmel horst in the north to the Gaza Strip in the south, and from the seashore to the limestone Yarqon-Taninim aquifer on the east (Figure 1). This aquifer has been subject of much geological research and study. Therefore, various geological cross-sections have been drawn for this aquifer (Issar 1968; Shachnai and Bein 1974). Between the years 1975 – 1980, the Hydrological Service revised most of these geological cross-sections and completed an entire set, containing 57 cross-sections: one for every two kms. Each cross-section extends from the sea coast to the aquifer's extreme eastern boundary. For hydrological purposes, an adequate code for the various subaquifers has been noted (Tolmach, 1977 to 1980). Modifications have also been made for some previous cross-sections (Sneh and Rosensaft 1994; Rosensaft et al., 1995). In this study, the Tolmach remodified cross-sections have been used, owing to the fact that they form a complete and continuous set, adapted for purposes of hydrological assessment (Figure 2)

Geologically, the aquifer is composed of wedge-shaped layers of dune sand, sandstone, calcareous sandstone, and silty loams, as well as intervening clay lenses. The top of the aquifer is covered by thin layers (of 0 to two meters) of sandy to silty and/or clayey soils. The aquifer's layers and aquitard lenses are at their thickest along the coast and feather out between two and five km from the sea, separating the aquifer into subaquifers. Within around 12 km of the coast, the aquifer is built upon the Saqiya sea clays of Neocene age. Further east, the aquifer rests upon limestone rocks of Eocene, Senonian, Turonian, and Cenomanian age

Steadily increasing urban population as well as relatively high frequency of drought years has led to sustained increases in pumpage as well as anthropogenic stress, particularly inland, due to urbanization. Industrial and agriculture leachates percolate from the ground surface to the water table (Ronen and others 2000). During the 1930's, before intensive exploitation of the aquifer began, the predominant direction of water flow was from east to west, with groundwater draining ultimately into the sea. Gradient levels varied between 0.1 - 0.3%. Since the 1930's, water exploitation has come to exceed natural replenishment, resulting in a steady lowering of the water table as well as accompanying alterations in direction of groundwater flow. Overpumpage of the Coastal aquifer has led in certain areas to the development of hydrological depressions, preventing outflow of contaminants from these areas to the sea, and leading to a deterioration of groundwater quality of the more inland zones of the Coastal aquifer (Melloul and Collin 1992; Melloul and Collin 2000; Melloul and Goldenberg 1997 Melloul and Zeitoun 1999; IHSR, 2000).

Artificial injection of freshwater into wells located between one and three kms from the seashore has been utilized as an important remediation measure to raise water tables in areas at highest risk of seawater intrusion. Since the 1970's, treated wastewater and water from other sources have been recharged into the aquifer, especially by spreading on the ground surface. Intensive

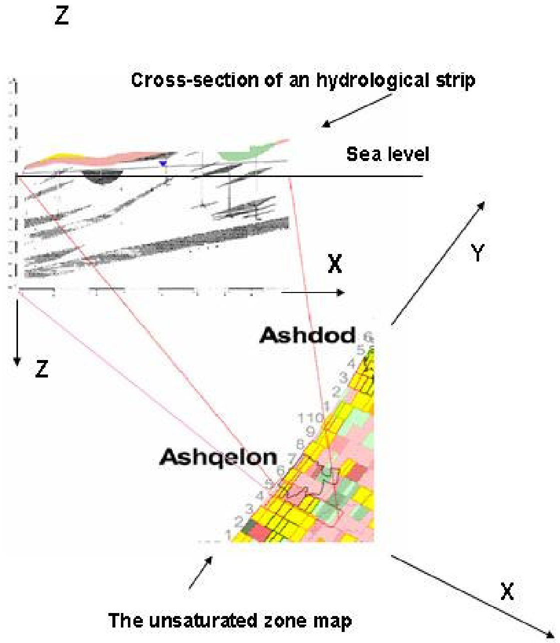

Figure 3. Blown-up cross-section of hydrogeological strip with local segment of map of aquifer unsaturated zone lithology.

irrigation with treated and partially treated effluents has become a key source of artificial recharge along the coastal plain. This has had the effect of moving the centre of the cone of depression away from the seashore.

The groundwater head of Israel's coastal aquifer lies between around 0 to 2 m between the coast and 5 km inland. This generally increases to around 30 m in the eastern portion of the aquifer, between 15 to 20 km from the seashore (IHSR, 2000). The topography in the area of the Coastal aquifer varies from 0 m at the seashore to around 150 m at the eastern edge of the aquifer. This leads to an unsaturated zone thickness that varies from 0 in the west to around 120 m in the east. The results of this lithologic unsaturated zone mapping can lead to improved delineation of areas having various percolation potential from the ground surface to groundwater table, and consequently to an assessment of the relative degree of vulnerability to pollution of the Coastal aquifer's goundwater.

Unsaturated zone mapping of Israel’s coastal aquifer

As an initial stage of the application of this approach to generate a map of the Coastal aquifer's unsaturated and/or a vadose zone media, the authors produced a digital GIS map displaying the 2-D spatial distribution of Israel’s Coastal aquifer's lithology in the X-Y plane as determined from the Hydrological Service’s revised series of 57 geological cross-sections (Tolmach, 1977 - 1980; Figure 2).

As mentioned above, the complete unsaturated zone lithology for each of Tolmach's two-dimensional (X-Z) geologic cross-sections (Figure 2) was converted into discrete segments based on the two-dimensional (X-Y) Hydrologic Service grid for the coastal plain (Melloul, 1988). The digitization of the X-Y encoding of the lithological data was performed using an existing digital data layer of the Israel Hydrological Service grid with partial supporting topology. All digitization was performed using ESRI's Arcview application (Version 3.2).

An example of the conversion from the X-Z orientation of the Tolmach cross-section to the X-Y orientation of this study is offered in Figure 3. This figure depicts as example the western portion of Row 105, at a distance of around 7 kms from the seashore, in the southern environs of the city of Ashqelon, in which clay and silts underlie sand layers.

In those circumstances in which sand is underlain by silt or clay, that cell is deemed to have a perched aquifer. Both the sand and the underlying material (as well as its thickness) are depicted on the map by a band of colour surrounding the cell or sub-cell in question. Otherwise, only a single lithological layer is displayed (Figure 3).

Since transitions in lithology do not necessarily correspond to the Hydrological Service grid boundaries, some editing of the polygonal structure of the grid has been required. Thus, as shown in Figure 3, some individual cells have been further subdivided, some into two, three or four sub-cells, in order to account for transitions in lithological type or thickness over the 2 km spread of an individual cell.

Once construction of the polygon structure was complete, each individual cell or sub-cell was encoded with four lithological parameters: upper-layer material and thickness, and under-layer material and thickness, as explained above in the "Methodology section". This yields two layers, each with a single permeability for a given cell and/or sub-cell. A yellow, pink, and green colour table was developed in which distinctions based upon material were established, with gradations of these individual colours used to convey layer thickness (Figure 3).

RESULTS AND DISCUSSION

The unsaturated zone map and assessment of natural recharge

The key results of this project are the mapping output given in Figure 4. According to the lithology and its stratigraphy, some categories have been delineated. As

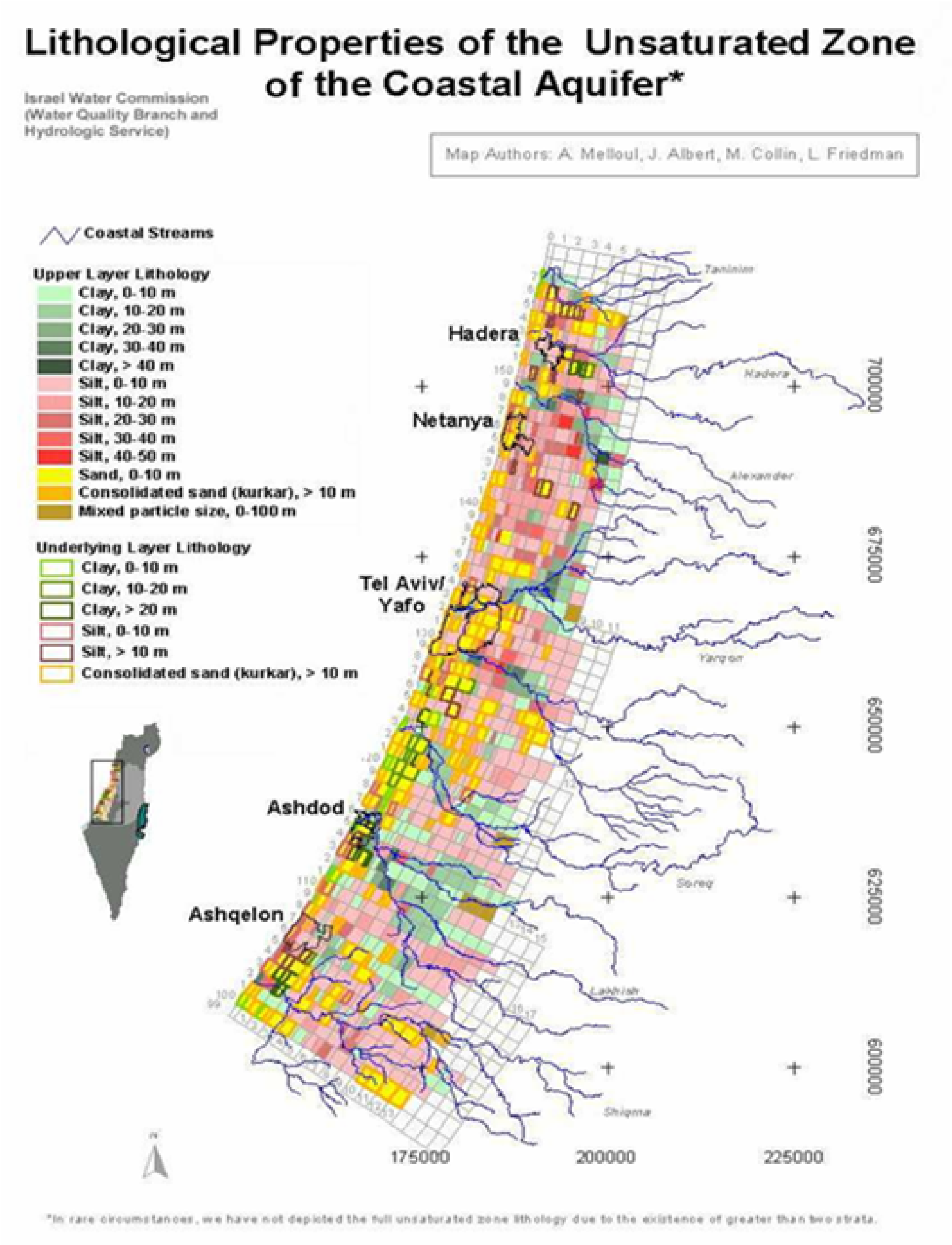

Figure 4. Lithological properties of the unsaturated zone of the Coastal aquifer.

illustrated in the graph in Figure 5, the vadose zone lithologies can reasonably be grouped into three categories. Each characterizes its own natural recharge capacity, such as:

Areas of relatively high lithologic permeability: these areas consist of calcareous sandstones ("kurkar") sands overlying calcareous sandstone and mixed-particle-sized sediments between the ground surface and the groundwater table.

These areas in Figure 4 are depicted in shades of yellow, in colour, or white, in black-and-white renditions, and cover approximately an area (A_p) of 370 km^2, representing about 16% of the total surface of the Coastal aquifer. In such areas the coefficient of infiltration (a_h) is estimated as around 0.35. For a multi-annual mean average rainfall, NR, of 0.5 m, the natural

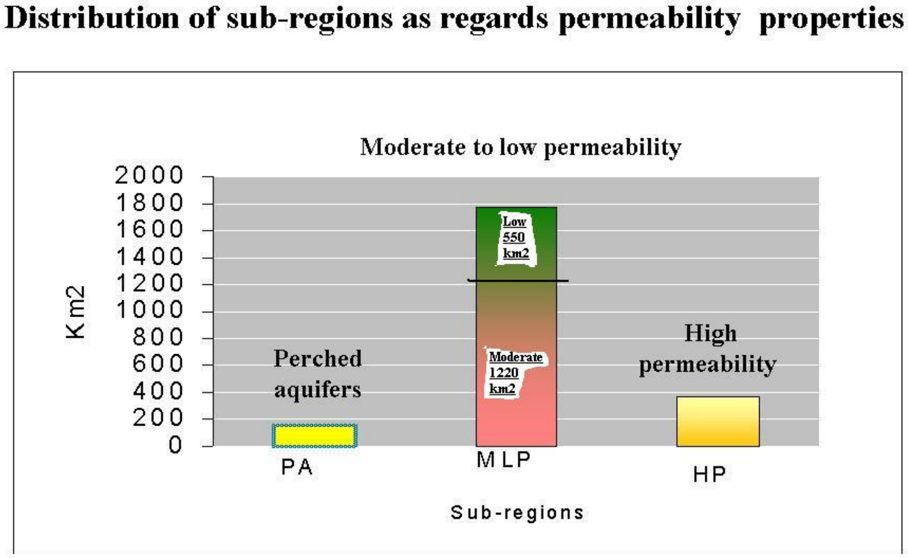

Figure 5. Distribution of sub-regions as regards permeability of the unsaturated zone in the Coastal aquifer.

recharge of the aquifer of these highly permeable areas (R_p) is assessed as:

$$\mathbf{R_p = a_h * A_p * NR = 0.35 * 370*10^6*0.5=64.7\ MCM/year}$$

Some of those areas are located beneath highly urbanized land-use, with streams conveying highly polluted effluents, such as the Yarqon and Ayalon streams in the Tel Aviv region (Strips 130 to 134 in cells 0 to 4, in Figure 4). In such cells, the appearance of high levels of pollutants such as organic and non-organic matter in groundwater testify to the "open" characteristic of these areas and their high permeability (p) or vulnerability to groundwater pollution (Melloul and Collin 1992; Ronen and others, 2000).

Areas of moderate lithologic permeability: These consist of areas of silts having low to moderate permeability, located above the groundwater table. They are shown respectively in shades of pink, in colour renditions, or grey in black-and-white renditions (Figure 4). The thickness of these layers can vary from a few meters to around 50m. Their relative lithologic permeability can change from one site to another owing to the thickness of the silts. The greater this thickness, the less pervious the unsaturated zone. These areas cover an area of approximately 1,220 km^2, representing about 53% of the total surface of the Coastal aquifer (Figures 4 and 5). Also in this category can be included cells, found in areas where highly permeable media layers are separated from the regional groundwater table by lenses or layers of silts and/or clays. These areas exhibit perched aquifer conditions, where downward infiltration to the regional aquifer table is impeded. Such areas are depicted with coloured borders in colour renditions, or grey or black borders in black-and-white renditions, in Figure 4 (in order to specify the material and thickness of the underlying lower permeability layer). They cover approximately 160 km^2, representing about 7% of the total surface of the Coastal aquifer (Figure 5).

In total, about 60 % of the areas which cover an area (Am) of 1380 km^2 can be considered as having a moderate coefficient permeability of natural racharge (NRm). Their natural recharge (Rm) for a multi annual average raifall value of 0.5 m lead to :

$$R_m = a_m * A_m * NR = \mathbf{0.2 * 1,380 *10^6*0.5= 138\ MCM/year}$$

Areas of silts having low to moderate permeability, found above the groundwater table are mainly located in the centre, between the western and the eastern cells of the aquifer. Most of areas exhibiting perched aquifer conditions are mainly located less than five km inland from the seashore. Typical representations of such areas of perched water are found in cells 1 and 2, and in strip 103 of Ziquim area, south to Ashqelon. There, during rainy years, perched groundwater as well as small ponds and marshes can appear on the ground surface. The regional groundwater is still of good quality, aside from certain cases where seawater intrusion already has caused adverse effects.

Areas with lowest lithologic permeability: These consist of clayey and/or heavy soil areas above the groundwater table. These areas are shown in shades of green in colour renditions, and black in black-and-white renditions, in Figure 4. They represent areas where the ground surface is relatively disconnected from the groundwater table. Such areas cover approximately an

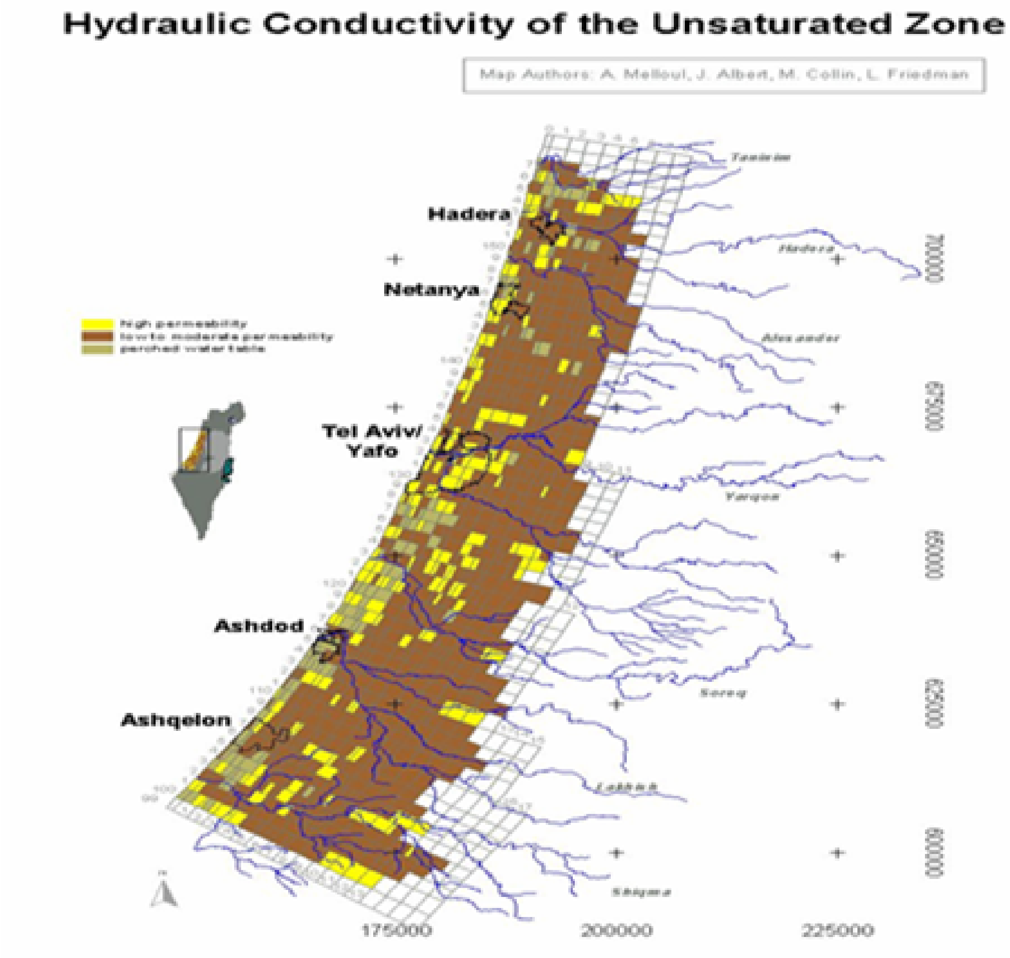

Figure 6. Permeability of the unsaturated zone in the Coastal aquifer.

area A_c of 550 km^2, representing about 24 % of the total surface of the Coastal aquifer (Figure 5). These areas have a very low natural coefficient of permeability of A_l of 0.05. The natural racharge (NRm) for a multi-annual average rainfall value (Rm) of 0.5 m leads to:

$R_n = a_n * A_n * NR$ **= 0.05** * 550 ***10^6*0.5= 13.75 MCM/year**

Most of these areas are located in the eastern cells, generally between cells 6 to 9 in hydrological strips 110 to 115 in the Ashdod area in the south, between strips 134 and 136 in the Tel aviv area in the centre; and between strips 145 to 149 in the northern portion of the Coastal aquifer, between Netanya and Hadera. Along the easternmost periphery of the Coastal aquifer, where it abuts the neighboring Eocene aquifer – which has more saline groundwater, the Coastal aquifer's groundwater can be found to have higher chloride concentrations, owing to lateral flow from the Eocene aquifer. Thus, despite the relative protection of unsaturated zone media, significant lateral flow from neighboring aquifers and also owing the presence of hydrological short cut may pollute the groundwater (Melloul, 1988; Melloul and Collin, 1992; Zoller et al., 2000).

Based on these above results given for each cathegory, the natural recharge for the total area of the coastal aquifer involves a total recharge of the aquifer of around (65+138+13) or 216 MCM/year. This approximative value is in the same range as the general values arrived at via various models, as well as the hydrologic water balance of the aquifer. This confirms the reliabiability of utilizing this type of mapping to calculate natural recharge of the aquifer, and verify assumptions as regards the unsatuarted zone, for various models.

CONCLUSIONS

The mapping produced by this approach can contribute towards:

Refining of aquifer models for management and improvement of monitoring systems

The findings noted above are quite significant for the various regions of the Israel's Coastal aquifer as regards monitoring and management of the aquifer, as shown in Figure 4. The results display the fact that most of the unsaturated zone of Israel's Coastal aquifer has moderate lithological permeability (respectively silts and perched areas). Based on Figure 4, 64 % of the total natural recharge of the aquifer from rainfall may be attributed to moderate to low permeability areas, whilst 30 % involves highly permeable areas, and only 6% includes very low permeability areas.

Also when considering the silt and clayey areas as one cathegory, as presented in Figures 6, it can be seen that only a small percent of the aquifer (16 %) can thus be considered completely open to the atmosphere. Thus, numerical modeling assumptions may consider approximately that 77 % of the aquifer are semi-confined to confined aquifer. Thus without considering that 7 % may be attributed as perched areas which can be also considered also as moderate permeability. This fact leads to the conclusion that most of the aquifer is not, in fact, "open" to atmospheric contact and can be considered a satisfactory filter to the phreatic groundwatater stored below.

Lithological changes provided by this study can be used for first-approximation estimates of permeability and/or hydraulic conductivity on the various portions of the upper border of the coastal aquifer. Figure 6 represents an initial step in this direction.

Lithological information provided in this study can lead to improved monitoring systems for calibrating numerical models by enhancing observation network monitoring, especially in such areas where the unsaturated zone has highest percolation characteristics and sources of pollution are evident. Examples would be areas where polluted leachates produced by highly industrialized land-use or polluted streams can threaten the groundwater. At such sites, density of observation facilities should be increased. Such mapping can thereby provide guidance towards enhanced monitoring in areas where special care ought to be taken to prevent pollution of underlying goundwater.

Such mapping can guide decision-makers and managers of coastal aquifers towards establishment of "protection zones". The results can additionally promote awareness as to locations where quality and quantity of water resources must be maintained and controlled for sustainable water management (Bachmat and Collin 1990).

However, in areas where the groundwater aquifer is overlain by low permeability lithology, but exhibits relatively high groundwater pollutant concentrations, such situations can also be explained as resulting from lateral flow and/or by hydrological short-cuts.

Digital lithological data and improvement of the data bank

Digital analysis and mapping enables easy editing of supporting data as well as improved data visualization. It allows more precise geological mapping than hand-drawn maps, with simplified presentation of stratigraphy and lithological permeability properties. This approach also enables additional supplementary and important GIS layering of other existing maps. A digital assessment of unsaturated zone lithology overlying the Coastal aquifer can serve as an integral component of any quantitative effort to determine the vulnerability of the underlying aquifer to pollutant inputs from above. This provides a further step towards integration with information programs for advancement of the artifical intelligence en route to better understanding and management of aquifers.

Further benefits of this approach

Israel's Water Commission is involved in the process of estimating the influence of wastewater irrigation upon the Coastal aquifer's salinity pattern and that of various soils, as a function of both space and time. A digital assessment of the aquifer's unsaturated zone lithology and of chloride and nitrate groundwater concentrations in wells can be effectively combined with information on distribution of land-use in order to establish basic statistical relationships, and construction of hydrological sensitivity maps (IHR, 2004).

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