
Use of remote sensing and GIS to determine recharge potential zones: the case of Occidental Lebanon

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Abstract Water recharge from land surfaces into subsurface media is an essential element in the hydrologic cycle. For a small-scale assessment, experimental approaches are usually followed, however, on a regional scale, this assessment needs to be made into a comprehensive picture where spatial data of the different contributing factors are treated. The case of Occidental Lebanon, with an area of around 5,000 km², was studied by the integration of all factors influencing this hydrologic process. Contributing factors are: lineaments and drainage frequency density, lithologic character, karstic domains and land cover/land use. The determination of these factors was carried out mainly by the application of remote sensing. Satellite images (Landsat 7 ETM & SPOT) and aerial photos were subjected to several treatment processes using a miscellany of software, mainly ERDAS Imagine and ESRI's Arc View software. Furthermore, exogenetic data, such as topographic and geologic maps, were utilized. The extracted information for these factors was plotted on maps. The integration of the maps in a GIS allowed deciding their interactive effects. However, each factor had its own degree of effect, i.e., weight, which was also determined in this study.

This study is an approach to better estimate and provide qualitative assessments of recharge potential (RP). The resultant map shows the highest recharge potentials towards the elevated regions where karstification is well developed. It was found that around 57% of the study area is terrain with very high to high recharge rate values, which a considerable amount of precipitated water is allowed to percolate into subsurface rocks.

Résumé La recharge de agua desde la superficie de la tierra a la subsuperficie es un elemento esencial del ciclo

hidrológico. Generalmente se utiliza un enfoque experimental para una asesoría de escala menor. Sin embargo, en una escala regional, esta asesoría tiene que ser incorporada en una visión global donde los datos espaciales de los diferentes factores contribuyentes son tomados en cuenta. Se estudió el caso del Líbano Occidental, con un área de aproximadamente 5,000 kilómetros cuadrados mediante un enfoque que consideró la integración de todos los factores que influyen el proceso hidrológico. Los factores contribuyentes incluyen lineamientos y la densidad de frecuencia de drenajes, el carácter litológico, la ubicación de dominios kársticos y la cobertura de vegetación/uso de la tierra. La determinación de estos factores se llevó a cabo mediante el uso de sensores remotos i.e., la aplicación de imágenes satelitales (Landsat 7, ETM & SPOT) y fotos aéreas que fueron procesadas mediante el uso de varios tipos de software, principalmente ERDAS Image y ESRI Arcview. Adicionalmente se utilizaron datos exogenéticos tales como mapas topográficos y geológicos. La información extraída para estos factores fue ploteada en los mapas. La integración de los mapas en el GIS permite decidir sus efectos de interacción. Sin embargo, cada factor tiene su grado de efecto (peso), el cual fue determinado en este estudio también. Este estudio es un intento de poder estimar mejor y proporcionar evaluaciones cualitativas de potencial de recarga (PR). El mapa resultante muestra que el potencial de recarga más alto se encuentra en las regiones elevadas donde la karstificación está bien desarrollada. Se encontró que aproximadamente 57% del área estudiada es terreno con un potencial de tasa de recarga que va de muy alto a alto, donde un monto importante de agua de lluvia puede ingresar a las rocas de subsuperficie. HJ-2004-0008-R3 Utilisation de la télédétection et de SIG pour déterminer les zones de recharge potentielle: cas du Liban Occidental.

Resumen La recharge à travers les surfaces du sol vers les zones de sub-surfaces est un élément essentiel du cycle hydrologique. Pour un modèle de gestion à petite échelle, l'approche expérimentale est habituellement utilisée; par ailleurs, à une échelle régionale, cette gestion nécessite d'être comprise dans un cadre compréhensif où sont traités les données spatiales et le traitement des différents facteurs contributifs. Le cas du Liban occidental, avec une superficie approchant les 5000 km² a été étudiée en intégrant la plupart des facteurs influençant les

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processus hydrologiques. Les facteurs contributifs sont: les linéaments et la fréquence de la densité de drainage, les caractères lithologiques, les domaines karstiques et l'occupation des sols. La détermination de ces facteurs a été menée par l'application de la télédétection. Les images satellites (Landsat 7 ETM et SPOT) et des photos aériennes ont été soumises à différents processus de traitement sur différents logiciels, principalement ERDAS Imagine et Arc View d'ESRI. De plus, des données exogènes telles que des cartes topographiques et géologiques ont été utilisées. L'information extraite pour ces facteurs a été cartographiée. L'intégration des cartes dans un SIG a permis de décider de leurs effets interactifs. Cependant, chaque facteur a son propre degré d'effet, un poids par exemple, qui a aussi été déterminé dans cette étude. Cette étude est une approche pour améliorer l'estimation et fournir des évaluations qualitatives du potentiel de recharge (PR). La carte résultante montre les plus grands potentiels de recharge vers les régions élevées où la karstification est bien développée. Il ressort de l'étude qu'environ 57% de la zone d'étude est constituée de terrains présentant des valeurs de taux de recharge élevées à très élevées, au niveau desquelles une part considérable des eaux de précipitation peut percoler à travers les roches de subsurface.

Keywords Recharge potential (RP) · Remote sensing · GIS · Occidental Lebanon

Introduction

The area of Occidental Lebanon (Fig. 1), with about 5,000 km², is a coastal mountainous region with a rugged topography. It is characterized by a high rate of precipitation, either from direct rain or from snowmelt. Annual precipitation ranges from 700 to 1,500 mm, with an average rate of about 985 mm from the coast up to the mountainous area. An estimated volume of around 4,900 million m³ of water is precipitated annually. The distribution of carbonate rocks (~70% of the study area), which are characterized by fracture and karst systems, permit recharging of considerable amounts of water into subsurface strata. Unfortunately, no reliable studies have been made to estimate the amount of this recharged water. This study aims to create an approach to estimate qualitatively the recharge of water into the subsurface media, and to produce a map showing different zones of recharge potential (RP).

The application of remote sensing in studying recharge properties is different from that applied to surface water. The study of recharge deals with indicative elements at the surface that reflect hidden hydrogeologic characteristics, which are reflected by water levels in wells. Remote sensing is supported by geographic information systems (GIS) due to the fact that the recharge property is a function of a number of interactive factors, which can be manipulated in the GIS system. In different studies, however, such as Bradbury and Muldoon (1994), Gustafsson (1994), Teeuw (1994), Per Saner et al. (1996), Edet et al. (1998) and Travaglia and

Ammar (1998), these factors vary from one study to the other, in fact, none includes a complete list of them.

In this study, a complementary integration of the influencing factors is applied to estimate the recharge potentials. These factors are: lineaments, drainage, lithology, karstification and land cover/land use. Normally, in groundwater exploration, most studies rely on locating the higher recharge zones as a first step, thus determining the groundwater flow regime, i.e., directions of flow and flow conditions. An RP map can be also helpful to determine sources of groundwater pollution, i.e., pathways along which pollutants move from surface to subsurface media (Shaban 2003). Therefore, producing a RP map would be very beneficial to Occidental Lebanon, the region, which occupies more than 70% of the country population and still suffers from water shortage and groundwater pollution problems.

Factors influencing recharge potential

Lineaments

The term "*lineament*" is a commonly used word in geological remote sensing studies in connection with fractures or tectonic analysis. Nevertheless, it is still not well defined, as shown by different interpretations created from similar features on satellite images or on aerial photos. O'Leary et al. (1976) defined a "lineament" as a mappable, simple or composite linear feature of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship. This usually is the accepted definition, even though a data set will initially include geological, cultural (man-made) and spurious (e.g., system artifacts) features, but the unfavorable features would be eliminated in geological interpretations. Only those linear features, which are observed on the image or aerial photo and are attributed to rock fractures, are considered in hydrogeological studies.

Drainage

Another input to help evaluate the recharge property can be realized by detailed morphometric analysis of the drainage network. This character is determined fundamentally by the underlying lithology, and thus provides an important indication of water percolation rate. Many workers combined only the lineament map with drainage map to presume the target areas of groundwater potential areas (Tomes 1975; Edet et al. 1998).

Normally, the most important morphometric properties of a drainage system are: drainage density, frequency of intersection of drainage lines, length of the 1st order streamlines, bifurcation ratio and drainage pattern. It is well known that the denser the drainage network, the less recharge rate and vice versa. Nevertheless, in Occidental Lebanon, this approach was found to give erroneous results in certain instances (Shaban et al. 2004). For example, within the known high recharge rock formations, notably those of the karstified dolomitic limestone, dense drainage

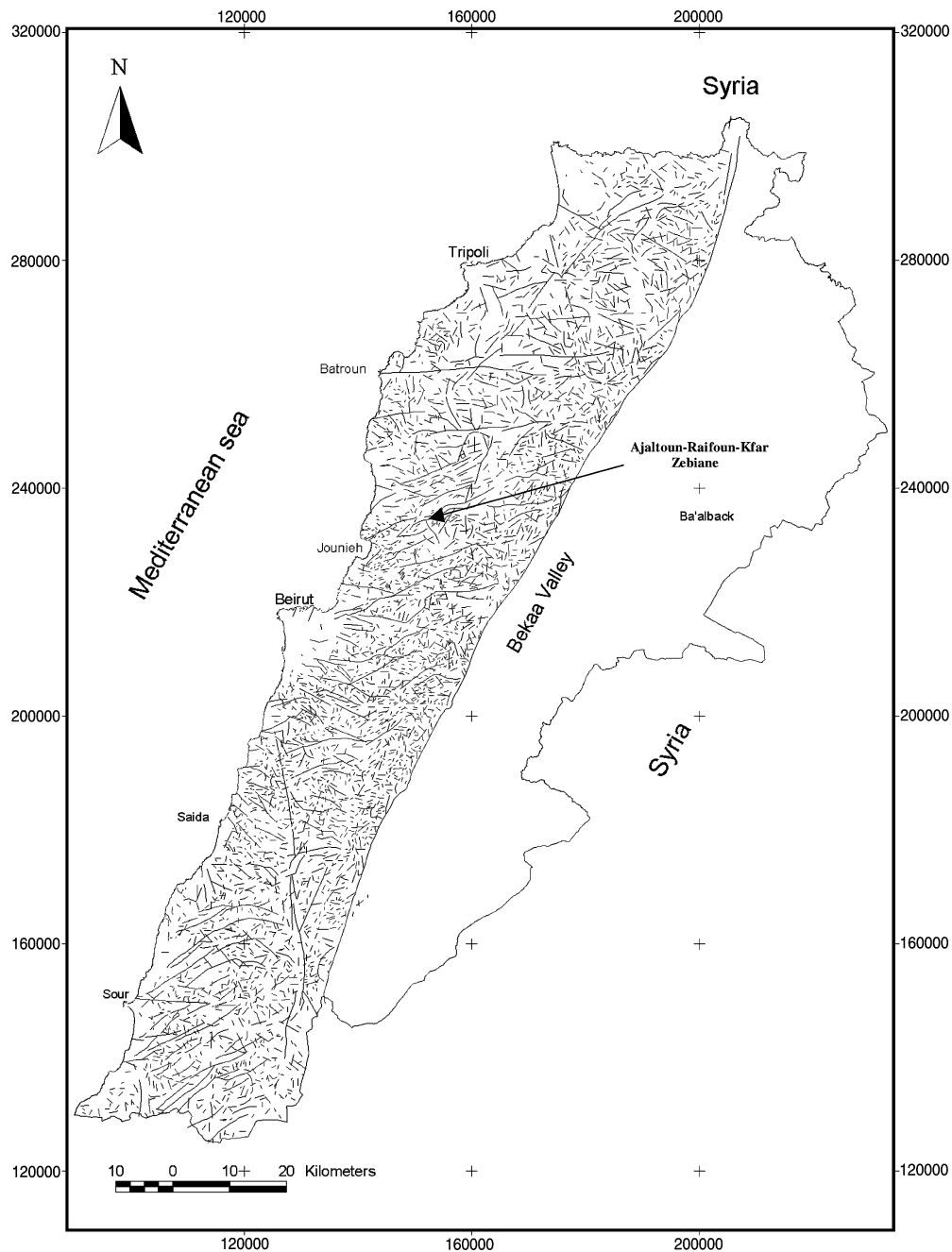


Fig. 1 Location of study area and lineament map of Occidental Lebanon as obtained from satellite image Landsat 7 ETM

networks are originated. This can be attributed to the presence of highly competent rocks. This in turn creates a number of flow paths, usually with relatively short lengths at the surface.

However, a comparative study was applied to find out the relationship of coincidence between the known recharge rates of different rock formations in the study area and the most relevant morphometric property. It was found that the drainage number (frequency) has the strongest relationship with the recharge property (Shaban 2003). The higher the frequency in the number of stream tributaries, the more recharge occurs.

Lithology

Of course, the lithologic character of the exposed rocks is significant in governing recharge. Some studies neglected this factor once they use the lineament and drainage (El-Shazly et al. 1983; Edet et al. 1998). This is because they consider the lineaments and drainage characters as a function of primary and secondary porosity, thus providing information on the lithology. But others (Salman 1983; El-Baz and Hamida 1995) incorporate the lithology factor because of its strong influence on water percolation. In this paper, the lithology is used to serve confirming and supporting assessment of recharge factors. This will tend

to minimize erroneous interpretations that may result from using lineaments and drainage factors alone.

Karstic domains

Karst terrain encompasses a variety of landforms, such as solution channels, sinkholes, lapies and many other irregular shapes. Normally, it is developed largely by chemical dissolution of carbonate rocks. The dissolution process often begins in and extends from existing geologic structures. This interrelation is quite well defined; therefore, it reflects a remarkable implication on water recharge from land surface. Almost all workers failed to account for the effect of karstic terrain in their studies, while others consider that effect as a very important element. Field reconnaissance in the study area reveals the significance of the surface karstic features. These are usually exposed within specific geographic domains, and hence four major types of karstic landforms were recognized. There are: (1) areas with distinct sinkholes, (2) areas with distinct lapies, (3) areas with developed karsts such as karrens and other surface dissolution features with relatively small exposures; and (4) areas with non-apparent karst, which are covered by thick soil accumulations (Bou Kheir et al. 2003).

Land cover/land use

Land cover/land use is a significant factor affecting the recharge process. This factor involves a number of elements but the major ones are the soil deposits, human settlements and vegetation cover. The major effect of soil deposits on water percolation into the subsurface media is attributed to its clayey content, as it controls the retention capacity of water. It is usually related to the terrain slope. Their geographic distribution in the study area is obviously different. Isolated thin soil deposits can be found in the mountainous regions, while thick and well-developed soil deposits are located on relatively flat areas. However, thick accumulations of soil deposits reduce the rate of water percolation.

The human settlement has a definite role in retarding the recharge process. Man-made constructions, such as concrete embankments, buildings, hangars, roads, etc. create a compacted terrain that seals the ground surface, thus preventing water to recharge easily (Bou Kheir et al. 2003). Vegetation cover can be considered as an enhancing one, notably in the Mediterranean extreme climate (Darwich et al. 2003). In this respect, the higher the vegetation cover, the higher the evapotranspiration rate and this implies less chance for percolation to the subsurface layers. But the density of the cover has to be considered as well as its geographic extent. Nevertheless, these processes are contradictory. First, the biochemical disruption of the terrain surfaces, whether it is soil or rock, by the roots and organisms. Second is that the vegetal cover helps in confining the water under the vegetal zone (in an umbrella scheme), therefore preventing water from direct evaporation. The third is the ability of plants to hold soil in place rather than to erode with an increase in water

run off. In summary, it can be assumed that the vegetation cover is an effective factor in the enhancement of recharge rate.

Methods of identification, analysis and classification

The applied method to assess factors influencing the recharge rates is based on studying a large region via remote sensing application (such as in the case of this study, i.e., 5,000 km²). This method has carried out along with the aid of topographic and geologic maps (1:50000 scale), as well as from previously related data collected on water resources in the study area. All were followed by field verification on several selected sites. The interpreted and resultant information were analyzed in spatial data. However, each factor was studied independently, thus five major categories were plotted to arrive at qualitative recharge rates.

Lineaments

Identification of linear geologic features was done on satellite images of *Landsat 7 ETM* (30×30 m resolution). *ER-DAS Imagine* software was used for this purpose. It has the advantage to detect “edge” features, e.g., lines of faults, which facilitate image interpretation. In this connection, the interpretation was applied both visually on screen and automated. The automated interpretation was achieved by using the special application in the software used, especially in enhancing linear features. This application includes various steps, notably, directional filtering, contrasting and sharpness. In addition, single and multi-band enhancement was carried out by interrelating each of the three bands as one set. Accordingly, interpretation from the thermal band, i.e., band 6 (120×120 m resolution), was an added value because it provided information by detecting wet horizons, which detected fracture zones. The interpretation of lineament features in this study followed plotting of all linear signatures on the image. The lineament map was then produced. It shows all linear features of different sizes and orientations regardless of their origin. An error ratio is inevitably created in this case, because some of these features are not geologically related. To minimize the error ratio, topographic maps, with special reference to linear objects such as roads, pipelines and terraces were overlapped on the produced lineament map to eliminate all non-geologic linear features as much as possible.

The final lineament map (Fig. 1) was analyzed. Usually, this analysis followed three principles. Some hydrogeologists deal with the connectivity of lineaments, which is only an indicative phenomenon to the groundwater transport, since the connected lineaments create an underground route for groundwater flow (Shaban 2003), while others involve only the length density (Teeuw 1994). The number of lineaments is another applied criterion of analysis El-Baz and Himida (1995). The latter is more indicative for the effective fracturing of rocks; thus it was applied in this study.

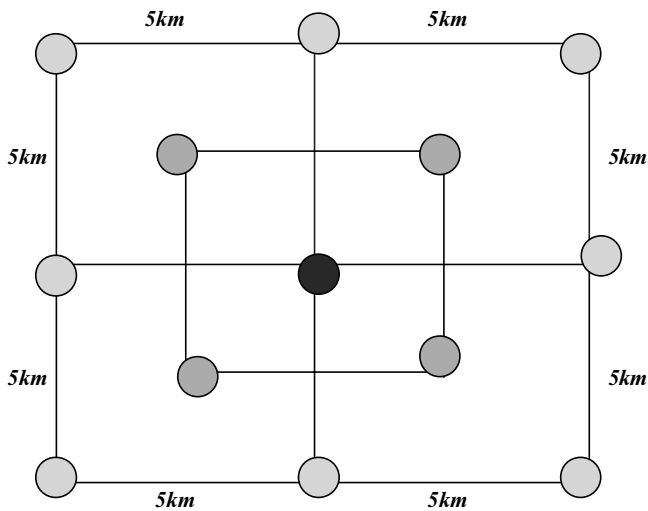


Fig. 2 Example of “Sliding Windows” method to calculate the frequency densities of lineaments, using a frame of specific area

Therefore, the frequency density of lineaments L_f is the visible number of lineaments per unit area (Greenbaum 1985). Its increase mainly is a function of high fracture zones, hence high RP capacity. It is expressed as:

$$L_f = \frac{\sum L_n}{A}$$

Where $\sum L_n$ is the total number of lineaments, and A is the area in km^2 .

To attain an optimum interpretation of the lineament map with reference to frequency, a *Sliding Windows* method was applied (Fig. 2). This was done by dividing the area of study into grids from which a frame was produced. The size of this frame depended on the distribution appearance of the linear features. In this study, a cadre of 5×5 km was used. The number of lineaments in each cadre was counted. Each obtained value was plotted in the middle of the frame. Therefore, for each four neighboring frames, the average value was again calculated, and then plotted again in the midpoint of the “conjunction” resultant frame (Fig. 2). From the plotted values, a contour line map was obtained for evaluating the lineaments frequency density (Fig. 3a).

Drainage

The extraction and analysis of the drainage network was used either from field data, topographic maps, aerial photographs, satellite images, or any combination of these. Over the past decade, much work had been done on automating the extraction of drainage networks, although almost all algorithms use digital elevation models (DEMs) as basic data (Chorowicz et al. 1992). However, there is still disagreement on the reliability of drainage extraction either manually from topographic maps or via automated approaches. Almost all workers in this concern pointed out that manual extraction involves more subjectivity than the

automated ones (Jenson and Domingue 1988; Tribe 1991; Ichoku et al. 1996; Martinez-Casasnovas and Stuver 1998; Abdallah et al. 2002). Therefore, in this study, a drainage map of Occidental Lebanon was created manually from the topographic map (1:50000 scale) in order to calculate the drainage frequency.

For this purpose, the counting of the tributaries followed the stream-order manner, i.e., number of 1st order, 2nd order, etc. This means that for each stream order, the number was counted and the total number of different orders in the specific area was summed. The same methodology of “sliding windows” used in the previous section was applied in this section, thus a drainage frequency map was produced (Fig. 3b).

Lithology

The distribution of the lithologic formations was taken from geological maps of 1:50000 scale (Dubertret 1953). They were used as base maps for further modifications by remote sensing. It is significant to mention that the use of remote sensing in geologic mapping provides a great deal but must be combined with fieldwork and laboratory investigations (Drury 1993). In this study, via the application of remote sensing, additional information on the lithologies was obtained from Landsat 7 ETM satellite images. The combination of bands 7, 4 and 2, as well as the application of different digital advantages of filtering and contrasting distinguished the image units, which combined the textural and pattern attributes of the terrain surface. Thus, visual tracing of many lithological patches and their boundaries were plotted, notably, assessing the moisture content in the argillaceous-exposed units through their clayey mineral content.

Basically, the information from image treatment is the creation of rock categories based on perviousness character, regardless of their age and even their similar descriptive lithology. The perviousness of rocks depends, in a broad sense, on clayey content, porosity and permeability. However, the majority of the exposed rocks in the study area reveal carbonates, marly rocks, basalts and sandstones, from which five categories were created.

The description of lithology on the geologic maps reflects only the major-rock constituents. Sometimes the exposed units show totally different character in terms of lithology, hence the permeability. In addition to plotting many lithologic boundaries, differentiation was done between the merged rock units on the geologic map such as C_{4-5} (Cenomanian–Turonian), which in some localities are lumped on the geology map as one rock unit, while in fact they have different lithologies. A final map was then produced to show zones of different lithologic character with respect to water recharge (Fig. 4a).

Karstic domains

The determination of the four known karstic domains was done directly from geologic and topographic maps

Fig. 3 (a) Lineament frequency map and (b) drainage frequency map of Occidental Lebanon

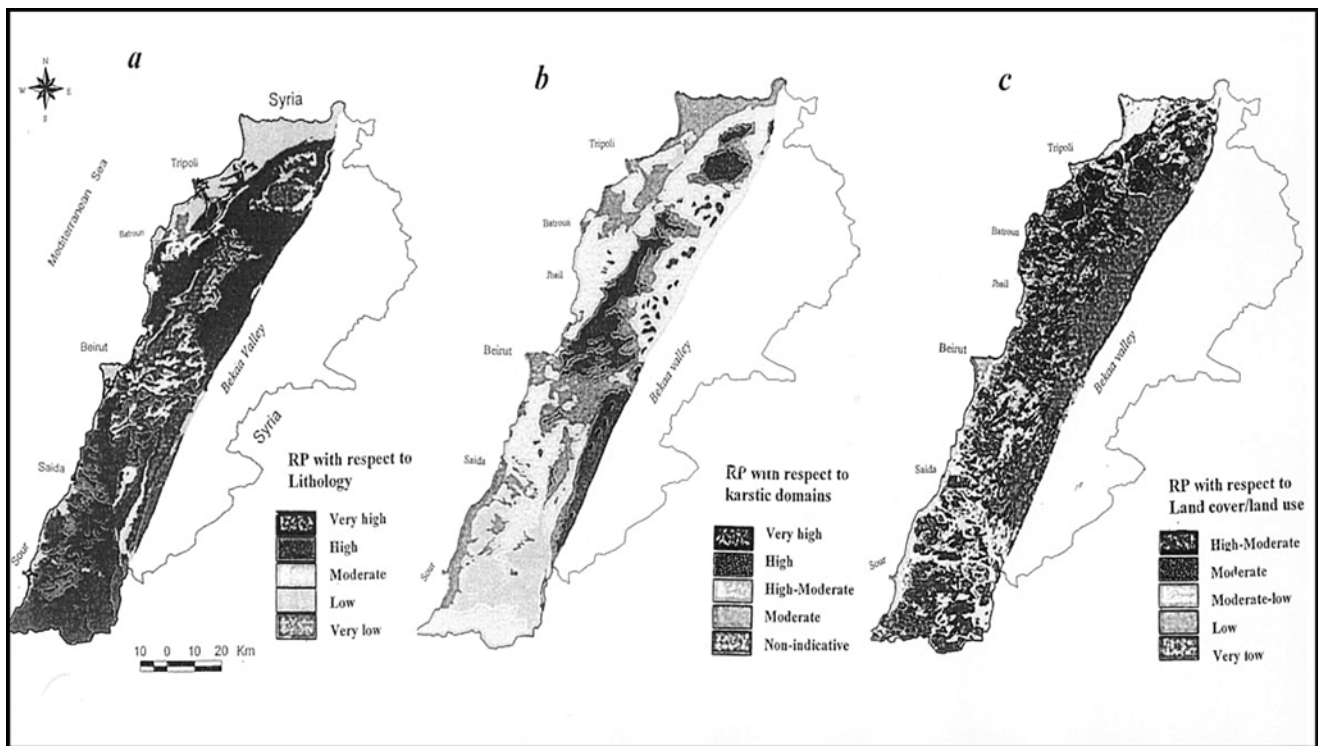
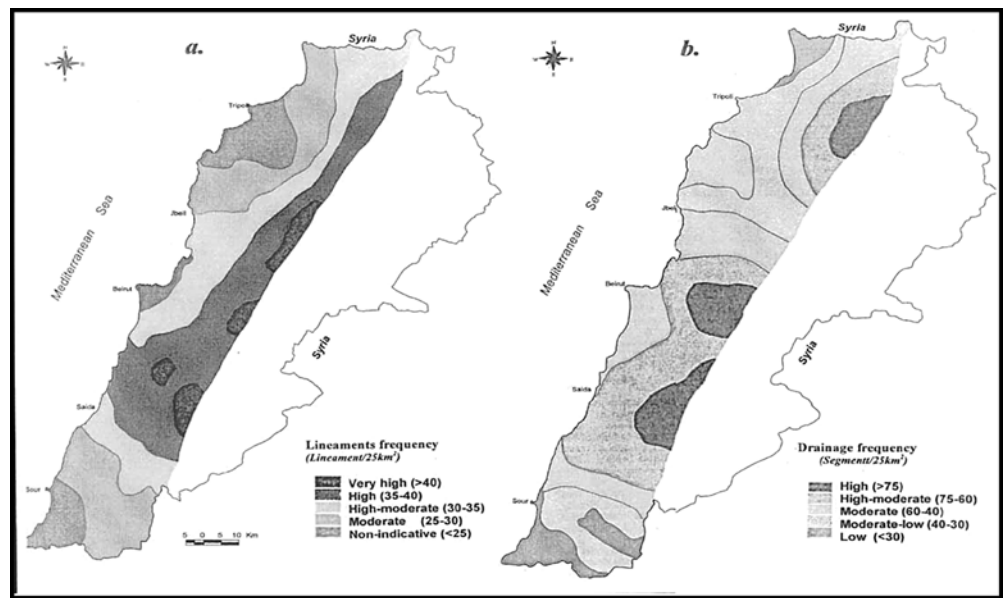


Fig. 4 Classification of (a) lithology, (b) karstic domains and (c) land cover/land use, as obtained by the aid of remote sensing with respect to recharge potential

(1:50000). In addition, the areas with no karstification were plotted. The concept of identification relies on two factors:

1. A specific determination of the sinkholes and lapies directly from topographic maps. The sinkholes appear as rounded to semi-rounded cluster contour lines, while the lapies always follow irregular and non-uniform contour lines (Bou Kheir et al. 2003). These two surficial karst features are well developed in the Jurassic and Cenomanian rocks in the study area.
2. From field observations, it was clear that areas with developed karst occur in the Cenomanian rocks of relatively moderate to low altitudes, i.e., less than 500 m (Shaban 2003). While the non-apparent karsts are restricted mainly to the Tertiary rocks, notably those in the south. This can be observed directly from the geologic map.

In addition to the above, remote sensing proved effective in identifying the karstic landforms, which are readily

recognized by a distinctive pitted surface (Ford 1998). It can be used accurately when no vegetation cover exists to hide these features. This was the case for the lapies in the Ajaltoun-Raifoun-KfarZebiane region (Fig. 1), which were too obscure to be traced from satellite images due to extensive vegetation. However, the karstic terrain, as bare carbonate rocks, in the elevated high altitude areas could be clearly delineated from Radarsat and aerial photos. This was confirmed with field verification to assure the mappable data, as well as to estimate the criteria relating the karstic type domains with water recharge. According to Shaban 2003 and Bou Kheir et al. 2003, a map showing different karstic zones according to water recharge was produced (Fig. 4b).

Land cover/land use

The main objective in assessing the land cover/land use is to classify the land surface into a number of land cover/land use units related to water recharge. In each unit, a spectrum of conflicting elements exists. Such as in the case of soil, which might contain a high clay content or may be sandy. Both have a different level of effect on recharge. In the land cover/land use classification, a wide number of classes can be obtained, but for the purpose of this study, only principal zones of similar response to recharge were encountered, thus only five zones of land cover/land use were defined. This classification was based on treating satellite images of two types. The availability of satellite images of merged Landsat 7 ETM⁺ (2000) pan sharpen and IRS-1 could produce a clear visualization of color and resolution. Therefore, a visual discrimination was established depending on optical differentiations and several polygons were obtained. Field verification was accomplished to recognize the different units of the land cover/land use in these polygons. Within each zone, different units were plotted, but all had relatively the same degree of effect on the RP rate (Su 2000 and Shaban 2003). The selection of various units to be categorized in specific zones lead to a Supervised Classification on the used image, thus a land cover/land use map was done to express different water recharge zones (Fig. 4c).

Data manipulation and results

From the obtained maps, and as noted above, a synoptic classification of five categories was plotted for each factor (Table 1). The level of effect of these factors are either expressed in *numerical* value ranges, such as for the lineaments, drainage and lithology, or in *descriptive* forms such as for the karsts and land cover/land use. For the numerical values, the ranges are based on the resultant domains, i.e., the difference between the maximum and minimum values.

For example, the drainage frequency from the obtained lineament map was found to be from 87 to 23 segment per 25 km², so that the selected domain was between >75 and <30 segment per 25 km², and five class ranges were built

upon this domain (Table 1). Accordingly, the description of each factor's effect depended mainly on its influence on the recharging process. For example, the high frequency density of lineaments indicates very high RP potential, while the low frequency density of lineaments does not indicate very low RP potential, but it was non-indicative for RP potential (Table 1). Therefore, the domain of RP potential for the lineaments in this case was from very high to non-indicative effect. While, for example, the lithology domain can work from very high to very low. This implies that once fractured, karstified dolomitic rocks and compacted clayey rocks are exposed; respectively. Of course, these descriptive levels were built upon field observations and the previous known quantitative estimates of RP capacity of terrain surface obtained by the UN (1967).

Therefore, five major descriptive levels were plotted, ranging from very high to very low, thus including sometimes interrelated levels, e.g., high-moderate, in addition to non-indicative levels (Table 1). Proposed rating of these levels starts from 10 points, i.e., *Very high* = 10 pts, and the minimum level *Very low* = 1 pt. Whilst for the non-indicative levels, which may play either positively or negatively in RP, was given a neutral rate, i.e., 5 pts (Shaban 2003).

Assessing the effect of each factor alone on RP did not give the required complementary picture. The integration of all factors together was necessary in order to obtain a RP map. Since these factors do not have the same degree of influence on the RP, a weighting approach was followed to incorporate these interactively. Obviously, the different factors as discussed in the previous sections have different weights. In order to estimate the weights of the involved factors, the effect of these factors on each other must first be presented. This was done through an applied schematic sketch according to Shaban et al. 2001 (Fig. 5).

According to the above sketch, and to arrive at a relative value for comparison in the rate evaluation, 1 major avenue of effect was given 1 point, while the minor avenue effect was given 1/2 of a point. The sketch shows that the lithology

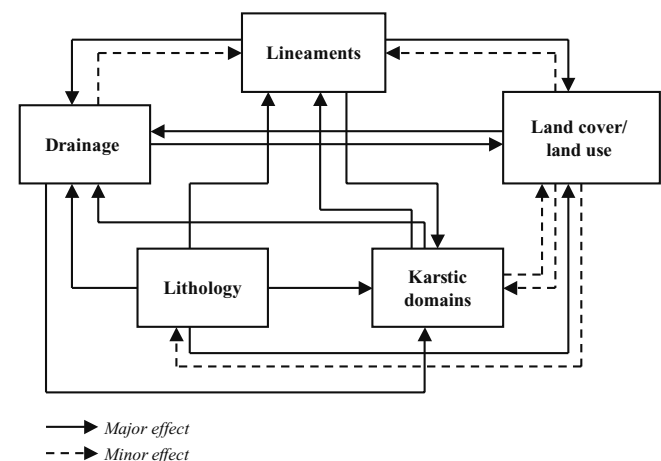


Fig. 5 Schematic sketch showing the interactive influence of factors concerning recharge property

Table 1 Categorization of factors affecting recharge potentials in Occidental Lebanon

| Factor | Descriptive level | Proposed weight of effect | Domain of effect |
|---------------------|-------------------|---------------------------|--|
| Lineaments | Very high | 10 | >40 (lineament per 25 km ²) |
| | High | 8 | 35–40 |
| | High–moderate | 6.5 | 30–35 |
| | Moderate | 5 | 25–30 |
| | Non indicative | 5 | <25 |
| Drainage | High | 8 | >75 (segment per 25 km ²) |
| | High–moderate | 6.5 | 75–60 |
| | Moderate | 5 | 60–40 |
| | Moderate–low | 3.5 | 40–30 |
| | Low | 2 | <30 |
| Lithology | Very high | 10 | 40–50% |
| | High | 8 | 28–35% |
| | Moderate | 5 | 10–20% |
| | Low | 2 | 5–10% |
| | Very low | 1 | <5% |
| Karst | Very high | 10 | Distinct with lapiez |
| | High | 8 | Distinct with sinkholes |
| | High–moderate | 6.5 | Developed karst |
| | Moderate | 5 | Apparent karst |
| | Non indicative | 5 | No karst |
| Land cover/land use | High–moderate | 6.5 | Dense vegetation, rural and excavated land |
| | Moderate | 5 | Sparse vegetation |
| | Moderate–low | 3.5 | Scattered settlements, thin soil cover |
| | Low | 2 | Moderately thick soil |
| | Very low | 1 | Dense human settlements, compacted soil |

Table 2 Weight evaluation of factors influencing RP capacity

| Factor | Descriptive scale | Weight (a) (1–10) | Rate (b) (1–4) | Weighted rating (a × b) | Total |
|---------------------|-------------------|-------------------|----------------|-------------------------|-------|
| Lineaments | Very high | 10 | 3 | 30 | 104 |
| | High | 8 | | 24 | |
| | High–moderate | 6.5 | | 20 | |
| | Moderate | 5 | | 15 | |
| | Non indicative | 5 | | 15 | |
| Drainage | High | 8 | 2.5 | 20 | 63 |
| | High–moderate | 6.5 | | 16 | |
| | Moderate | 5 | | 13 | |
| | Moderate–low | 3.5 | | 9 | |
| | Low | 2 | | 5 | |
| Lithology | Very high | 10 | 4 | 40 | 104 |
| | High | 8 | | 32 | |
| | Moderate | 5 | | 20 | |
| | Low | 2 | | 8 | |
| | Very low | 1 | | 4 | |
| Karstic domains | Very high | 10 | 2.5 | 25 | 87 |
| | High | 8 | | 20 | |
| | High–moderate | 6.5 | | 16 | |
| | Moderate | 5 | | 13 | |
| | Non indicative | 5 | | 13 | |
| Land cover/Land use | High–moderate | 6.5 | 2.5 | 16 | 46 |
| | Moderate | 5 | | 13 | |
| | Moderate–low | 3.5 | | 9 | |
| | Low | 2 | | 5 | |
| | Very low | 1 | | 3 | |

was the most influential one having 4 major avenues of effect, i.e., it had an effect on lineaments, karst, drainage, and land cover/land use.

Accordingly, the relative rates for each influencing factor as expressed in points as follows:

- Lineaments: 3 major = 3(1) = 3 pts
- Drainage: 2 major + 1major = 2(1) + 1(0.5) = 2.5 pts
- Lithology: 4 major = 4(1) = 4 pts
- Karst: 2 major + 1 minor = 2(1) + 1(0.5) = 2.5 pts
- Land cover/land use: 1 major + 3 minor = 1(1) + 3(0.5) = 2.5 pts

However, to attain a comprehensive evaluation of each factor on RP, the rates and weights must be integrated. This can be done by refereeing approaches followed by Khawlie (1986) and Shaban et al. (2001) (Table 2). Therefore, the total weighting assessment, after rounding off values, is shown in Table 2.

The grand total weight in this case was equal to:

$$= 104 + 63 + 104 + 87 + 46 = 404$$

This leads to the following percentages of factor effect on the RP capacity as follows:

- Lineament = $104/404 \times 100 = 26\%$
- Drainage = $63/404 \times 100 = 16\%$
- Lithology = $104/404 \times 100 = 26\%$
- Karstic domains = $87/404 \times 100 = 21\%$
- Land cover/land use = $46/404 \times 100 = 11\%$

However, the obtained maps for each factor were considered as layers. The overlaying of these layers, each with its own weight together in a GIS system resulted in different polygons of special characteristics with respect to the overall RP for the area.

The ESRI's Arc View software was applied to manipulate the above data, through superimposing of the different layers of RP after considering the weight/rate assessment. The final map was produced to reveal major zones of RP potentials with five descriptive levels (Fig. 6). These are: *very high*, *high*, *moderate*, *low* and *very low*. About 57% of the studied area has a high to very high RP. The resulting map (Fig. 6) was compared with that obtained by the UN (1967), and these levels equate to the following values:

- Very high = 45–50% of precipitated water is recharged to the subsurface strata.
- High = 30–35% of precipitated water is recharged to the subsurface strata.
- Moderate = 10–20% of precipitated water is recharged to the subsurface strata.
- Low = 5–10% of precipitated water is recharged to the subsurface strata.
- Very low = <5% of precipitated water is recharged to the subsurface strata.

The resulting measures revealed optimistic values of RP. However, in order to measure the quantity of recharged

water to subsurface media in Occidental Lebanon, a simplified calculation for the proposed recharge rates (adapted from UN 1967) and areal extent of RP zones obtained in this study (Table 3): a quantitative estimation of recharged water was obtained as follows:

As the volume of precipitated water is around $4,900 \times 10^6 \text{ m}^3/\text{year}$ (Climatic Atlas of Lebanon. CAL 1982; Mudalal 1989; Jaber 1995; METAP 1995; Shaban 2003), the volume of recharged water (W) will be:

$$W = \text{Precipitated volume} \times \text{Recharge ratio} \times \% \text{ of area}$$

This was applied to the five RP zone as follows:

$$\begin{aligned} W &= 4900 \times 10^6 \{0.475 \times 0.11 + 0.325 \times 0.46 \\ &\quad + 0.15 \times 0.15 + 0.075 \times 0.22 + 0.025 \times 0.06\} \\ &= 1187 \times 10^6 \text{ m}^3/\text{year} \end{aligned}$$

This means that around 24% of precipitated water in Occidental Lebanon is percolating downward to recharged the groundwater reservoirs, whilst the rest either evapotranspires or runs off the surface.

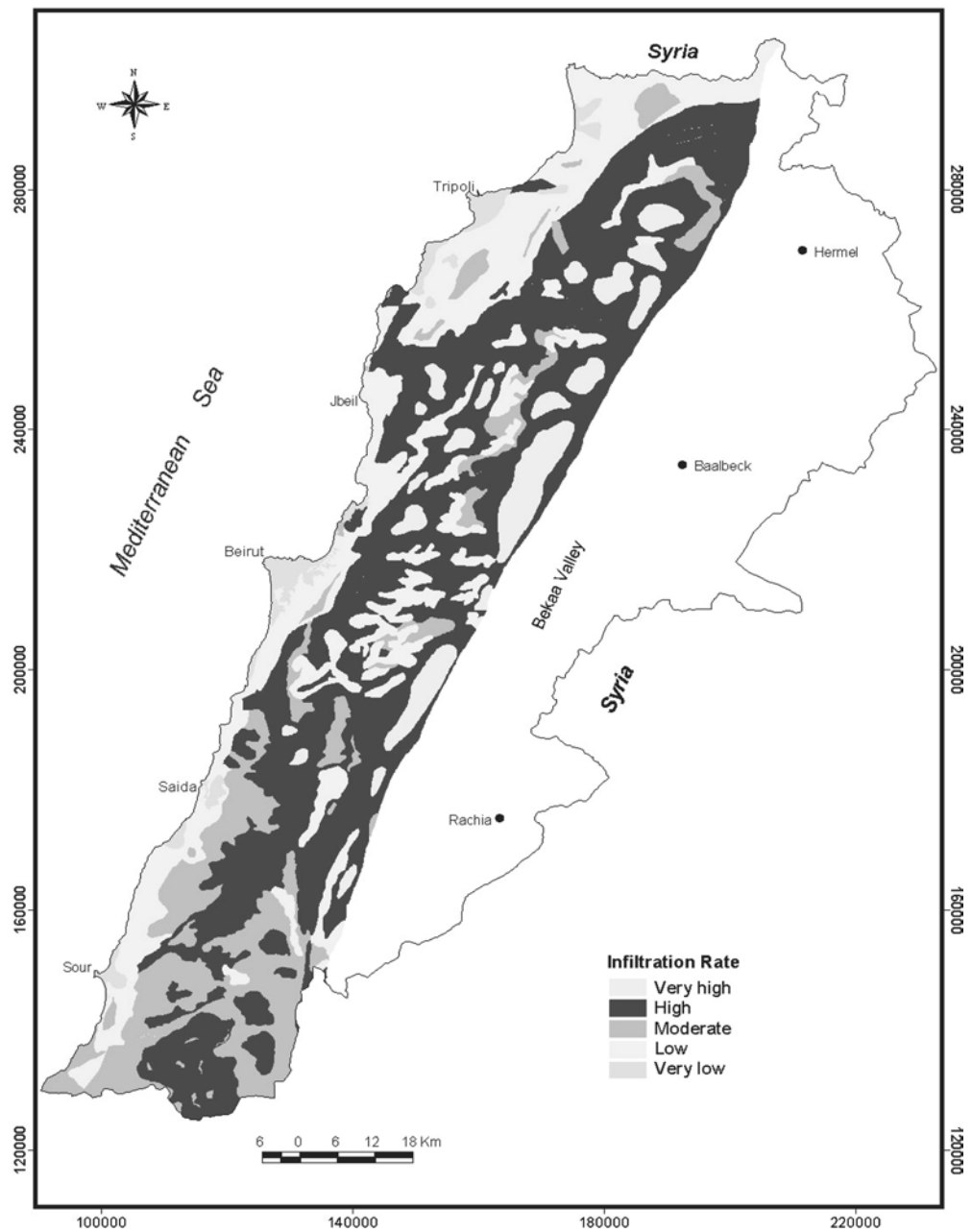
Conclusion

In many hydrogeological studies, notably those concerned with groundwater exploration, defining zones of different recharge potential RP is the first step, followed by assessing subsurface flow direction and trapping conditions (Shaban 2003).

In addition, assessing the RP also plays a role in several agricultural and environmental issues. This property represents the transmission rate of water flow from ground surface into deeper water-bearing strata, so it is very important. However, until recently, and for a regional-scale assessment, no definite approach is known and all studies are still initiatives.

Remote sensing application proved to be an effective way of studying such hydrologic measures. It can cover relatively large areas in a short time of assessment. Via remote sensing, RP cannot be directly estimated, but relies on defining the influencing factors, thus essential thematic maps must be produced. Namely lineaments and land cover/land use maps, in addition to substantial modifications made on geologic and karstic maps. The integration of remote sensing with its relative sector of Geographic Information System GIS fulfills the scope of this hydrological need. Occidental Lebanon was assessed in this study. However, the integration of influencing factors in a GIS system was applied. These factors have an increasing or decreasing effect on RP, but each of them has its own degree of effect (i.e., weight). Therefore, a weighting approach must be created for factor integration. Field verification was applied, in many instances, in order to confirm the extracted data (i.e., attributed to influencing factors) from the satellite images. The involved factors on RP are different from one area to another. Such as the karstic

Fig. 6 Recharge potential zones in Occidental Lebanon as obtained by the integration of different influencing factors



domain, which exist in the study area and may not exist elsewhere.

The resulting map shows that about 57% of Occidental Lebanon is a terrain with very high to high RP. Moreover, the most effective RP is found on regions of hard, fractured and karstified limestone and dolomite of the Jurassic and Cenomanian rock formations. These formations are located on the elevated areas of Occidental Lebanon, where complicated structures are situated. Whereas, the least effective

RP is in localities of dense human settlements and in relatively flat areas covered by soft materials. The obtained map of RP can be utilized in groundwater exploration, as it will give first hand information on groundwater recharge. Furthermore, such thematic maps are valuable for assessing the vulnerability of groundwater to pollution, as high recharging zones are the most effective to transmit pollutants to groundwater.

Table 3 Recharge potential categories and their quantitative estimates

| RP Category | Very high | High | Moderate | Low | Very low |
|-----------------------------------|-----------|--------|----------|-------|----------|
| Estimates according to FAO (1967) | 45–50% | 30–35% | 10–20% | 5–10% | <5% |
| Average (%) | 47.5 | 32.5 | 15 | 7.5 | 2.5 |
| Area extent (km ²) | 551 | 2,306 | 752 | 1,103 | 301 |

This study introduces an approach to best qualitative estimates on RP and needs to verify it through an instrumental application. It is recommended to apply such a study for the whole Lebanese territory and with a smaller scale in order to gain more precise information about surface signatures that governing the RP potentials.

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