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THE ROLE OF SINKHOLES IN GROUNDWATER RECHARGE IN THE HIGH MOUNTAINS OF LEBANON

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Groundwater recharge is an essential hydrologic property that must be considered while determining potential zones for groundwater storage and protection. However, concerns in groundwater assessment are often given to other hydrologic elements, such as the fracture systems and stratigraphic characterizations of the existing lithologies. In Lebanon, karstification is a dominant geomorphologic phenomenon that occurs either on-surface or subsurface, and plays in both cases a major role in the water flow regime and accumulation. Sinkholes are one of the surficial karst features that are widespread landforms in the mountainous regions of Lebanon, notably at higher altitudes, where hard carbonate rocks exist in a region with a high precipitation rate exceeding 1500 mm and covered by snow for more than nine months a year. The regular melting of snow cover results in considerable amounts of surface water that percolate downward into sinkholes and feed the Cenomanian limestone formation, the major groundwater reservoir in Lebanon. This study discusses the formation and geomorphologic orientation of sinkholes, with a special emphasis on the mechanism of groundwater recharge. The study benefits from field observations and testing. It aims, in a broad sense, to focus on the role of sinkholes in recharging groundwater to aquifers in Lebanon, and it highlights the necessity to protect these features from human interference.

INTRODUCTION

Lebanon, the mountainous terrain with the highest peaks in the Middle East region, is characterized by remarkable topographic features due to the intensive geological setting as well as the development of remarkable geomorphologic features in many parts of its terrain. Karst is one of these features, which is very well developed in the carbonate rocks. Thus, there is an obvious concern about the karstic landforms in Lebanon, which are often merely considered from the landscape point of view. However, they have another role with respect to water resources, notably for groundwater flow and storage regime. Karstification is well pronounced among the limestone and dolomite rocks in the Lebanese territory, and it is developed in the subsurface media as much as on the ground surface.

There are several studies done on the karstic phenomenon in Lebanon, with major features on karst as a hydrologic parameter to be considered (Guerre, 1969; Hakim, 1985; Edgell, 1997; Somma et al., 1998; Shaban et al., 2000; and Azar, 2000). However, subsurface karstification (e.g. conduits, galleries, etc.) is tedious to deal with due to unidentified behavior and the difficulty in tracing them at depth into the ground. Nevertheless, they play an essential hydrologic role and need investigation in order to identify their routes, which determine their influence on the groundwater regime.

In many studies however, hydrologic elements and related processes that account for water resources assessment have been recently given much more attention than before. This has been developed in accordance with water supply shortages, notably in the light of climate change and population increase. Therefore, it is a must to investigate the geologic and geomorphologic terrain features in depth and reach a more perfect knowledge on their influence on water resources. One of these features is the “sinkhole”, which is a karstic landform developed in two major regions on the high mountain ridges in Lebanon. According to Dubertret (1953) and Shaban and Khawlie (2006) they occur on: 1) the Cenomanian rocks in the upper-middle part of Lebanon (along Jabal Sannine - Qournet Es-Sawda-Jabal Akroum) and 2) in the southeast of Lebanon where Jurassic rocks exist in Jabal Haramoun (Figure 1). In this study, concern is with the sinkholes of the upper-middle part, since they are developed on the Cenomanian rocks, which compose the principal aquifer in Lebanon. In the selected region, these rocks extend along the elevated region, which is adjacent to the coastal zone, thus forming a natural reservoir to the neighboring urban coastal areas. In addition, this area contains much of the Lebanese heritage, such as the Lebanon Cedars and other natural reserves.

The study area, in particular, is a rugged and inaccessible region with no human settlements, except for a few tourist activities. It is located at an altitude of more than 2850 masl, and occupies the most elevated crest in the Middle East region, where Qournet Es-Sawda (3086 m) the highest peak is situated. The area of the Cenomanian rocks with dominant sinkholes is located within the following geographic coordinates (Figure 1):

- Latitudes: 33° 22' 00" and 33° 54' 20" N
- Longitudes: 35° 49' 17" and 36° 11' 00" E

The Cenomanin rocks in the study area are composed largely of highly fractured and karstified limestone, dolomite and dolomitic limestone, with some intervening marly limestone. These rocks are almost always exposed, and soil occurs only in the depressions and among the existing

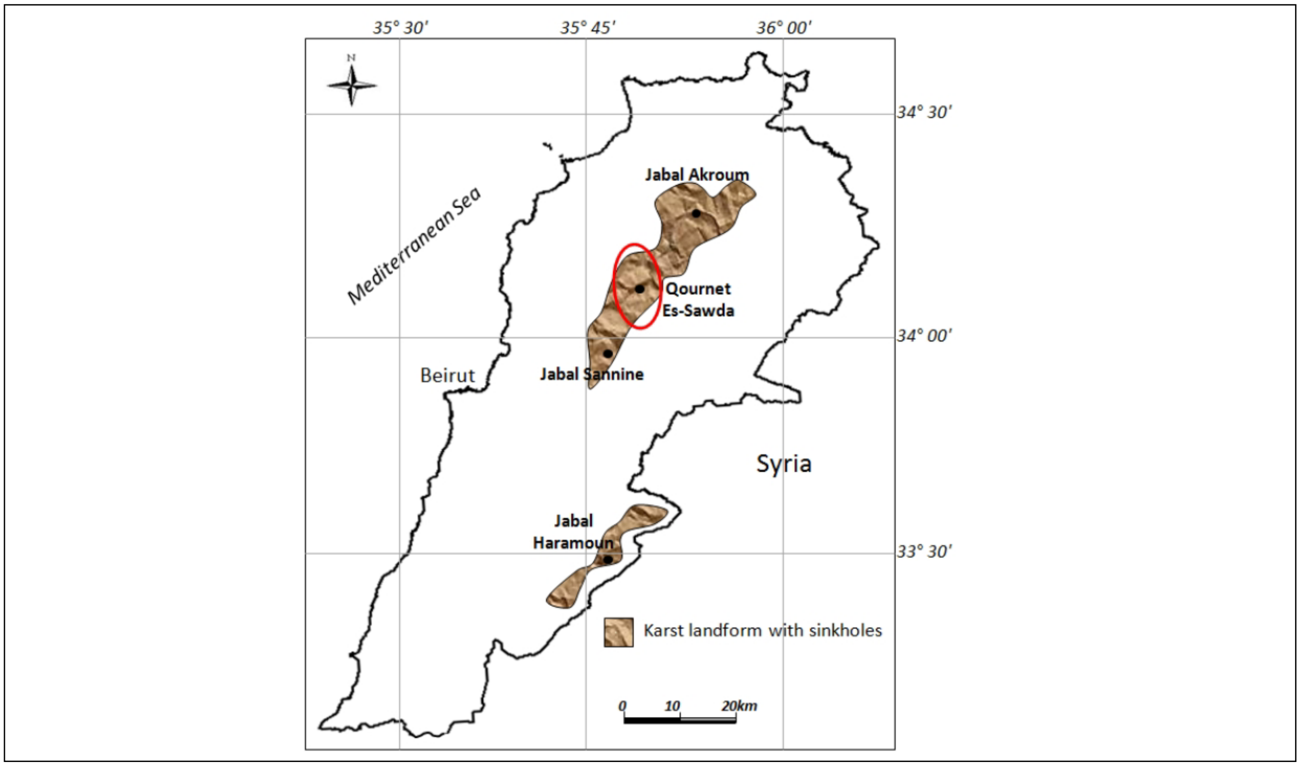

Figure 1. Location map of the study area.

sinkholes. In addition, the exposures of these rocks show intensive fragmented rocks almost of gravel size.

From a geomorphic point of view, the area of concern comprises a piedmont land feature, at a considerable altitude, where it is covered by snow for about ten months per year, and the snow patches remain in some valleys and depressions as well as sinkholes to the middle summer season as the last snow patches on the Lebanese terrain.

This study aims at characterizing the existing sinkhole systems in the area of concern and identifying their orientation and dimensions, and thus recognizing their influence in transporting water from the melting snow into the Cenomanian aquifer. This in turn will highlight their importance from an environmental point of view, in order to conserve these geomorphic features, which are believed to be the major channel system in feeding the groundwater reservoir in the region.

MATERIALS AND METHOD

Identification of sinkholes

In addition to the field survey and the obvious identification of sinkholes as almost rounded depressions into the carbonate rocks, the identification of karstic landforms was done by analyzing the available geologic (1:50000) and topographic maps (1:20000). They appear as closed, rounded to semi-rounded clustered contour lines as in Figure 2a. Moreover, aerial photos and high resolution satellite images (e.g. IKONOS, and Aster) are useful in identifying sinkholes, thus they were utilized in this study. According to Barrett and Curtis (1995), sinkholes can be visually detected from satellite images and aerial photos as distinctive pitted surfaces. Figure 2b shows an example of sinkholes from Lebanon as observed from Aster satellite images, with 15m spatial resolution.

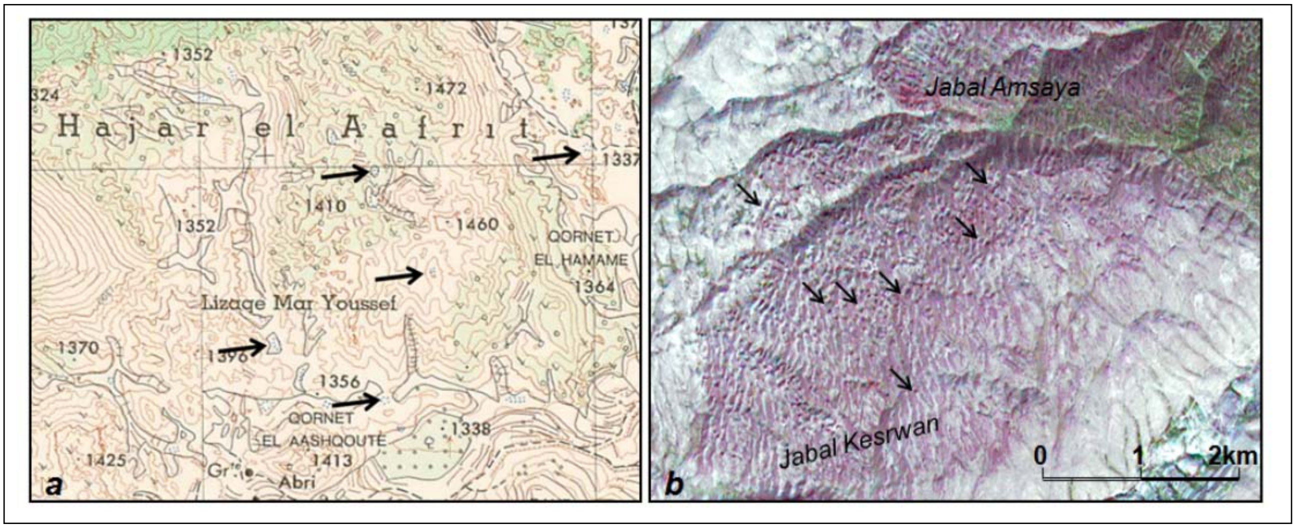

Figure 2. Identification of sinkholes from topographic maps (a) and from satellite (Aster) images (b).

The use of spatial tools (i.e. maps, aerial photos and satellite images) can also be used to calculate the number of the existing sinkholes in different regions. This will help to analyze their density per region. Also, aerial photos and satellite images can contribute to identifying the relationship of sinkholes with respect to geologic structures (if they are located on the intersection of fracture systems, or they occur along certain alignments). Hence, these tools were used in this study and the results were interrelated with a field reconnaissance for further confirmation.

In many instances, measuring the actual depth of depressions, in particular the sinkhole landforms, results in erroneous values. This is common when these depressions are filled with soil and rock debris (colluvium) that derived from the surrounding regions and subjected to hydraulic and/or aeolian erosion.

In this study, the analysis of topographic and geologic maps as well as the aerial photos and satellite images was a prerequisite step to determine the areas to be investigated. Thus, in many instance sinkholes of special interest were determined from these spatial tools and their location was identified. This facilitates the application of field surveys in these areas. For this purpose, global positioning system (GPS) tools were used for the exact location of the investigated sinkholes.

Formation and orientation of sinkholes

There is no debate on the definition of sinkholes or dolines (used interchangeably), but there is still some uncertainty on the mechanism and the orientation they have, with respect to the regions where they are formed, and the time needed to develop their actual size. Thus, the term sinkhole has many explanations characterizing mainly the physical dimensions, with little attention to the geologic process controlling their occurrence. For example, Sweeting (1973) described sinkholes as closed hollows of small or moderate dimensions; they can be cone-or bowl-shaped with rocky or vegetated sides and have a circular or elliptical plan. He also stated that their diameter is often greater than the depth and average sinkholes vary in size from about 2-100 m deep and from 10-1000 m in diameter.

In a broad sense, karst landforms result mainly from carbonate rock dissolution, but the dissolution process is controlled fundamentally by the existence of weak surfaces, spacing between bedding planes, and fracture systems, whether these systems exist as fissures/or fractures, and normally the fracture systems play an essential role on the formation of sinkholes. Hence at troughs and crests of folded structures fractures systems often occur due to the acute bending in rock stratum. This is more well developed at troughs of folded structures than at crests, where water accumulates, and thus tends to percolate to groundwater in sufficient quantities (Figure 3). Therefore, sinkholes are usually anticipated to form in depressions more or less on crests. However, each of them has specific geomorphic sinkhole aspect (e.g. rounded, semi-rounded, oval, conical, etc.), as well as different dimensions (depth and width).

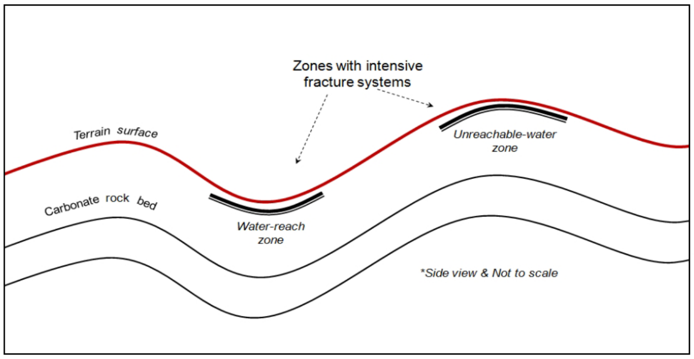

Figure 3. Usual sites to form sinkholes and their relation with fracture systems.

In many studies, the classification of sinkholes has been obtained and comparative analysis to the relationship between their dimensions was established considering different geometrical aspects. They were viewed as a principal type of karstic landform where sinkholes and other surficial depressions and holes exist. In this regard, White (1988) proposed an empirical classification of karstic landforms (Table 1).

In Lebanon, karst landforms are well exposed and they can be identified from field reconnaissance and analysis of topographic and geologic maps, as well as the observations on high spatial resolution satellite images that reveal the karstic landforms often occur within specific geographic domains (Shaban, 2003).

Accordingly, a preliminary classification was followed to characterize the karstic landforms in Lebanon (Shaban and Khawlie, 2006). They are fundamentally correlated to altitude, rock lithology and terrain characteristics. These are: 1) distinct sinkholes, 2) distinct lapies, 3) developed surficial karst (open karst), and 4) areas with nonapparent (covered) karst. However, the first distinction is closely related to water regime from surface to subsurface, and this is the reason in tackling it in this study. These distinctions were found to occur in certain areas, since sinkhole formation is controlled by several physical factors, which are attributed mainly to altitude and geology of the area where they exist.

In-situ investigation

Since the major objective of this study is to assess the role of sinkholes in water recharge from the surface, mainly from collected snow in depressions and sinkholes (Figure 4), into groundwater

Table 1. Geometrical classification of karst landforms (White, 1988).

Dimensions	Length to width ~ 1	Length to width > 1
Width to depth ? 1	Dolines (sinkholes) Compound and valley sinks poljes	Cutters Solution corridors Solution canyons
Width to depth ? 1	Solution chimneys Vertical shafts Subsidence shafts	Solution fissures

Figure 4. A sinkhole retains snow in middle summer, thuu serves in water recharge in the studied area.

reservoirs, field reconnaissance was carried out to apply in-situ investigation methods. These include mainly soil properties with respect to water infiltration processes, as well as the local geomorphic characteristics of terrain in the context of sinkholes. This required soil sampling and testing. In addition, dimensional measurements were taken at the located depressions, channels and rills around sinkholes, as well as the existing geologic structures.

RESULTS AND DISCUSSION

Sinkholes in the studied area show distinguishing and predominant geomorphologic characteristics, which are in turn reflected on the hydrologic regime of surface/subsurface water interaction. Other than the rocky terrain with highly fragmented rock debris, the entire region forms a pediment geomorphologic feature where a flat, slightly sloping surface is situated on the mountainous region. However, occurrence of sinkholes with different scales characterizes the flat surface of the area. Thus, the geomorphic and structural characteristics of sinkholes, as well as the fill materials govern the mechanism of water recharge from surface into substratum.

Dimensional aspects

The existing sinkholes compose a variety of shapes and dimensions, but they are almost all of medium to small scale type, which exhibits the early maturity stage of karstification. Thus, they were classified into two types as follows:

1. Small-scale sinkholes, which are characterized by a diameter of less than 10 m, and sometimes less than one meter, which compose almost a conical shape, thus a depth of about one tenth of the diameter (Figure 5a). Therefore, they are considered solution chimneys, vertical shafts and subsidence shafts according to the White (1988) classification in Table 1.

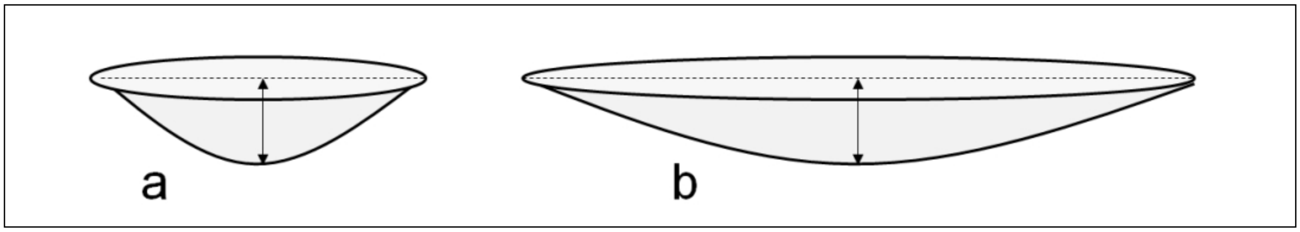

Figure 5. Schematic illustration for small-scale (a) and large-scale (b) sinkholes.

2. Large-scale sinkholes. This is a relative dimensional description according to the sinkholes existing in the area of study. They are often of diameter of 15-20 m, and depth of about 2.5-3 m, thus forming asymmetrical conical shape (Figure 5b).

Schemes of distribution

The common understanding on the formation of sinkholes (or dolines) is the fracture zones, which are developed by the effect of water dissolution on the carbonate rocks. However, several concepts account for sinkhole formation at the intersection of fractures as the most important criterion, or zones with dense joints (Deike, 1969). However, this may be controlled by the physical properties of the region where sinkholes are developed, notably the altitude, terrain characteristics, precipitation regime, and the lithologic character.

Accordingly, in the area of concern there are two dominant aspects of sinkhole distribution, these are:

1. Sinkholes in depressions: This aspect is attributed mainly to the large-scale ones. They often found along a unique alignment, which is mainly a fault trend (Figure 6).

2. Sinkholes on hillsides: These found to be of small-scale type. This aspect is almost found in chaotic schemes, and do not follow a specific trend like those in depressions. Thus, their formation is mainly due to local dissolution of calcium carbonate.

Figure 6. Existence of large-scale sinkholes along an alignment (assumed fault).

Sinkhole fill materials

The existing sinkholes, for both mentioned scales, are found to be totally filled by colluvial deposits. Hence, the type of the filling material depends mainly on the lithologic character of the surrounding terrain, as well as it is also dependent on the slope gradient of this terrain. Thus, some sinkholes where hard limestone rocks occur are filled by fragmented and flat, thin limestone rocks (Figure 7a), even though the surroundings of such sinkholes is totally covered by the fragmented rocks. Other sinkholes are filled by soil deposits (Figure 7b), but in both cases (sinkholes with fragmented rocks or with soil) have similar soil type, as indicated by in-situ field observations.

Hence, the majority of soil composition located in the sinkholes consists of well structured, strong shape, non-calcareous, sticky and plastic soils. Almost all the investigated soil samples in the existing sinkholes are characterized by hard consistency, which are hard when dry and form a soil sealing layer (1-2 cm) when dry. The texture is mainly of clayey to silty clay. Also, these deposits are common with mud cracks and joints (Figure 7b). The soil material under the sealed layer is composed of moderately strong structure, fine and moderate polyhedrons with high interstitial porosity allowing fast vertical water movement, and thus preventing water stagnation upon melting.

Water recharge regime

Recharge zones are still a matter of concern in many areas worldwide, thus several factors are involved to regulate the recharge potential from terrain surface downward to deeper stratum (Shaban et al., 2006). However, in some cases, the recharge property is merely governed by a dominant and highly influencing factor such as is the case in the area of concern. Hence, the studied pediment region of Qournet Es-Sawda is almost homogeneous and all occurring terrain features have similar influence. However, the existence of sinkholes plays the major role in water recharge regime. Therefore, the dimensional aspects, schemes of distribution and filling materials of sinkholes occupy the majority of recharge of the vertical water route. Notably sinkholes can retain snow for a long period of time that sometimes reaches the middle summer season (Figure 4).

Accordingly, the dimensions of the sinkholes serves capturing water in the form of snow and thus the snow melting process helps percolating water move uniformly into the depressions of sinkholes. The larger diameter large-scale sinkholes, with relatively shallow depth, have good a

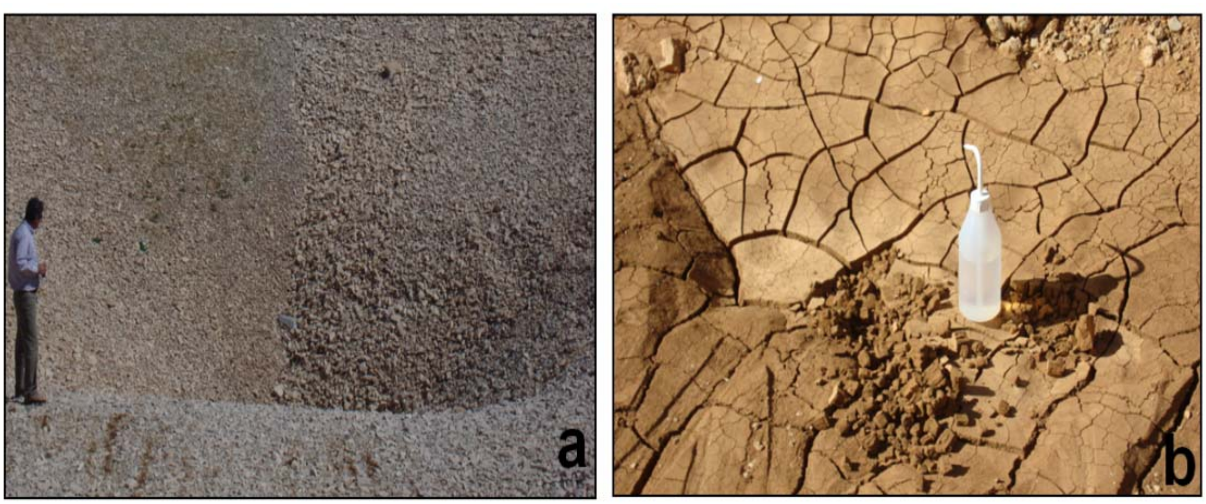

Figure 7. Sinkholes materials either as fragmented and flat, thin limestome (a), or soil deposits (b).

potential for water recharge, since the surface area is higher. In this respect, the density of sinkholes (number of sinkholes per unit area) also plays an important role, and thus the denser the number of sinkholes, the higher the recharge process and vice versa.

The scheme of distribution is also an influencing factor in water recharge, especially for those sinkholes along a predominant alignment, because these alignments are usually faults that create high permeability and porosity zones in the areas where they exist. Therefore, joining sinkholes can join these terrain pockets with their high recharge rate and increase their percolation to the substratum.

The materials included among the sinkholes have an important role in the infiltration rate into these conduits. Hence, impermeable layers, if they exist, will prevent water transfer downward. Nevertheless, the materials found in the sinkholes of the studied area were either filled by fragmented rocks, with extremely high permeability rate, or they are filled with soil characterized by relatively high infiltration rate, as discussed in the previous section.

CONCLUSION

Water resources assessment follows different approaches of analysis either with surface water or groundwater. However, sometimes the interaction between both is much more important. It is of utmost importance to identify the mechanism of water flow from the surface downward to a deeper stratum, notably in regions with considerable precipitation rate. This is absolutely the case of the Lebanese terrain where rainfall is high at the high mountains, which are dominated by fractured and karstified rocks that easily permit water to percolate into groundwater reservoirs.

The Cretaceous rocks of Lebanon, with a special attention to the Cenomanian ones, constitute the majority of the exposed rocks. The Cenomanian, with hard, massive fractured and karstified limestone and dolomite, represents the major aquifer in Lebanon. It has an integral role in storing groundwater with sufficient quantities. This rock formation is situated adjacent to the coastal zone of Lebanon, forming an elongated mountain ridge, thus receiving rainfall and snow with considerable amounts reaching more than 1800 mm on some crests. In other words, the Cenomanian rock formation in the coastal zone of Lebanon represents the water reservoir of this zone. For this reason, the recharge zone, which is situated on the pediment of this formation, must be given attention, and this study is an example of assessing the criteria of recharge of the Cenomanian formation in this area.

This study presents an empirical procedure to diagnose the mechanism of water recharge among a distinguished karstic landform. It depends mainly on analyzing the existence of sinkholes; their formation and the interrelation to each other, as well as their hydrologic related components. The results show that the existing sinkholes play a major role in recharging huge amounts of water, mainly from the melting snow, to the Cenomanian rocks. The recharge process in the area of concern is being extended for a long time over the year, thus utilizing from all rainy periods when they occur, as well as from the accumulated snow, which is retained for more than nine months a year.

The existence of sinkholes was found to be related to fracture systems, which also enhances the recharge potential property of the carbonate rock, as well as the depressions of sinkholes themselves are coated by permeable layers, whether they are soil or rock debris. Therefore, all hydrologic components account for high recharge rates in this area. For this reason, it is important to conserve this region from any pollution-related factors, notably those related with anthropogenic aspects.

Even though the area of study is still virgin and human activities are quite negligible, there are a few activities taking place. This may be exacerbated with time if environmental controls are not anticipated and implemented. Field reconnaissance shows local pollution aspects in the study area, with a special emphasis on pasture and sludge accumulations in different sites. It is a fear that this could be a prelude for further contamination processes.

In addition, there are other activities that interrupt the hydrologic regime, especially those of snow extraction processes, as well as the diffuse of the melting water from snowpack from the area of study along sloping terrain to other regions.

Relying on field observations, and the investigation of the karstic landform of the study area, as well as considering the importance of conserving this region to protect the major groundwater reservoir, a detailed study is required, including the use of all available tools of analysis. It is of utmost importance to apply more research, notably related studies in this region to build a comprehensive hydrologic and environmental picture.

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