Protection Of Groundwater Resources in Karst At The Source: Application Of GIS And Policies Aiming For Water Sustainability For Qachqouch Spring

by

Jihad Othman

and

Lynn Tfayli

Supervised by Dr. Joanna Doummar

Date: December 2022

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Abstract

Freshwater resources are under unprecedented threats because of the increase in population, contamination, and climate change constraints; particularly karst aquifers. The estimation of recharge and assessment of vulnerability in these systems have become primordial to ensure their sustainable use. The forecasting and management of water availability and protection of water resources in the future can be better achieved with tools such as GIS. APLIS and COP methods are GIS-based methods generated to estimate distributed recharge and assess vulnerability respectively, taking into consideration the spatial distribution of all karstic and non-karstic features. The main parameters affecting the APLIS method are "Altitude", "sloPe", "Lithology", "Infiltration", and "Soil", while the COP method is accounting for all the karstic and non-karstic parameters of Autogenic and allogenic surface zones respectively represented by the "Concentration", the "overlying", and the "Precipitation" with many sub-factors for each. These two methods have been applied to the Qachqouch spring which is one of the main sources of water supply to Beirut's citizens that should be protected against contamination. Results show the spatial distribution of recharge and vulnerability with maps of resolution of 30×30 m of each cell. The underestimation of recharge using APLIS is linked to the over flooding of surface water after heavy rain events. However, the percentage of high recharge area is high and explains the dominant fast infiltration due to karst surface and subsurface features. Also, the resultant map of the COP method was highly affected by the concentration factor that takes into account karstic features such as stream sinkholes, dolines, faults, and the distance of every cell from each of the features.

Acknowledgment

First and foremost, we would like to give my warmest thanks to our supervisor Dr. Joanna Doummar who supported us through all the stages of accomplishing our project. Hydrogeological and geological field experience was the best part of my internship with you in the department of Geology (AUB) besides all the acquired writing skills.

Additionally, we would like to thank HAWKAMAA-EU, LEWAP, ACTED, and EU Regional Trust Fund for funding and contributing to achieving this success for the whole project in general, and for our study specifically. Thanks, Jasmine El Kareh for your assistance in completing the project on time and with perfection, despite so many challenges that cropped up during this process, Mira Zouhairy as well.

And of course, a special thanks to Maria Khesmatdinova for working on the geological cross-section of the catchment, and Jana's team and Ahmad Ezz Al Dine for the time spent discussing the methods used in both projects.

Introduction

Karst systems are the major water supply resources providing drinking water to the whole world's population (Kaçaro & Glu, 1999). The karst system is very dominant in Mediterranean countries such as Lebanon, Syria, and Turkey (Bakalowicz, 2015). The surface of Lebanon is dominated by highly fractured karst rocks originating from the carbonate formations of the Jurassic, Cretaceous, and Eocene ages (Edgell, 1997). Mainly, carbonate rocks that are characterized by the high dissolution of dolomite and limestone, an expansion of fractures, and the formation of sinkholes form the karst system in Lebanon (Ford & Williams, 2007). Thus, all these karst features cause groundwater recharge and vulnerability complexity (Ford & Williams, 2007, 2013).

Karst springs are considered a natural output of the karst systems (Bonacci, 2001). The outflow of any karst spring is highly related to the recharge process of the excess precipitation that doesn’t feed into the runoff and evapotranspiration, but into the subsurface through preferential flow pathways, sinkholes, and dolines (Bakalowicz, 2005; Ghasemizadeh et al., 2012). In general, karst systems contribute water into the subsurface through two main processes: direct (or concentrated) and diffuse (or slow) infiltration (Kiraly, 2003) as shown in Figure 1.

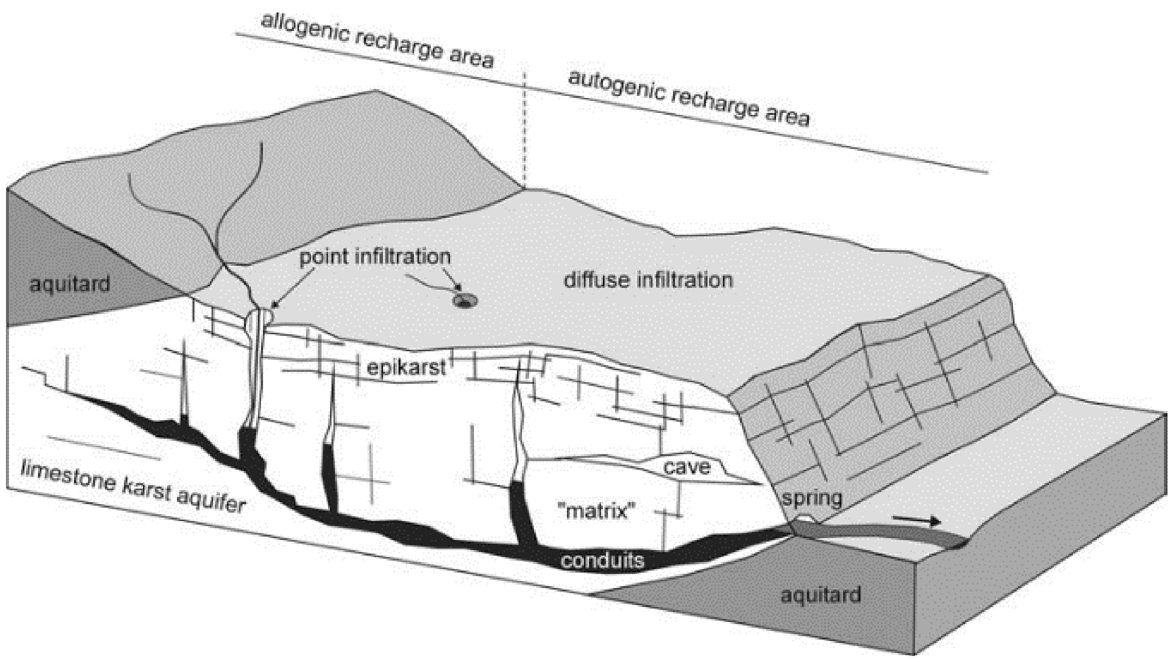

Figure 1: Schematic illustration showing recharge mechanism from autogenic and allogenic zones. Allogenic zone is the non-karstic surface contributing water superficially to the karst surface, the autogenic area, infiltrating the water into the subsurface (Benischke et al., 2007).

APLIS method was used to estimate the spatial recharge in karst aquifers using Geographic Information system (ARCGIS 10.3; Esri) overlaying the key parameters that have a high impact on the recharge process (Andreo et al., 2008). APLIS method was applied to different aquifers in different areas. Zagana et al., 2011, applied the APLIS method to estimate the groundwater recharge of evaporite and carbonate breccias aquifers in Greece. Also, Andreo et al., 2008, tested the method by estimating the recharge of eight aquifers in different regions in Spain. They stated that flow predition results of applied numerical, hydrochemical, hydrologic balance, and isotopic models were used to corroborate the validity of APLIS method. The obtained results of APLIS method matched these other methods results. Farfán et al., 2010, proved that the APLIS method should be considered by hydrogeologists for the estimation of recharge.

Karst aquifers are also considered very vulnerable because of their karst features, meaning that the groundwater is very sensitive to any surface contamination. Thus, assessing the vulnerability of karst springs is very challenging having their high recharge and flow complexity (Doummar et al., 2014). COP method is another method that uses GIS to classify the degree of vulnerability of karst surfaces (Hamdan et al., 2016). Estimating recharge and assessing vulnerability help protect our groundwater and provide water sustainability (Kazakis et al., 2018).

The study aims to reach water sustainability by protecting groundwater from surface contaminants. The project describes the application of GIS in the karst aquifer of the Qachqouch spring catchment area. Thus, APLIS and COP methods are used to spatially estimate the recharge and assess the vulnerability respectively using ArcGIS. The resultant raster maps will help us identify the high surface vulnerable zones and predict the accessibility and availability of the spring water to Beirut citizens in the future. Accordingly, new policies will be prepared and implemented emphasizing quantity and quality protection of the available spring water. They will follow a systematic approach directing stakeholders in providing the right actions to achieve this sustainability while taking into consideration already existing facilities and urbanization in the designated field. That being said, municipalities will have a clearer idea about the policies to be implemented by residents of the areas being studied. In turn, it will provide an opportunity for the community to engage in groundwater protection.

The Study Area: Qachqouch Spring

Qachqouch spring (Figure 2) is in the Keserwan area in Lebanon to the North of Beirut and at around 4.5 kilometers from the shoreline. It is the result of groundwater discharge at the lower boundary of the Jurassic karst aquifer at about 64 meters above sea level. The importance of the spring lies in using it to provide Beirut City and its suburbs with water during low flow periods. According to (Dubois et al., 2020), the discharge reaches an average of 45 Mm3 (range between 35 and 55 Mm^3) per year based on high-resolution monitoring of the spring from 2014 to 2019. The flow is maximum at 10 m3/s for a short time immediately after the flood event, 2 m3/s during high regular flow periods, and 0.2 m3/s during recession periods.

The upper (North) and the eastern boundaries of the catchment area of Qachqouch spring are delineated to the Nahr El Kalb River and 55 km^2 of mountainous nature at a maximum elevation of 1650 meters above sea level respectively (Dubois, 2017). Relying on tracer experiments, a relationship between the spring and the river was concluded through a sinking stream (Dubois et al., 2020). Karstified rock sequences are forming most of the area in Lebanon, around 67%. The Carbonate Jurassic aquifer forming the Qachqouch spring is composed of thick, more than 100 meters, massive fissured limestone(Dubois, 2017). Highly porous dolostones are found along the leaky faults and dykes because of the hydrothermal dolomitization and in the lower part of the formation because of the diagenetic dolomitization. The whole area is affected by tectonic deformation and fracturing caused by the major fault “Yammouneh Fault”. Karst features were developed during the Messinian salinity crisis and

Quaternary glacial events causing deep karst systems with features such as large dissolution conduits, dolines, sinkholes, and caves (Bakalowicz, 2015; Dubois et al., 2020). Rapid infiltration by point source infiltration in preferential pathways and diffuse recharge in bare fissured rocks are forming the dominant infiltration lines in this area. This area is characterized by point source infiltration along with fractures, faults, and dolines preferential pathways and diffuse recharge in simple fracture-unfeatured rocks (Bakalowicz, 2015; Martos-Rosillo et al., 2015).

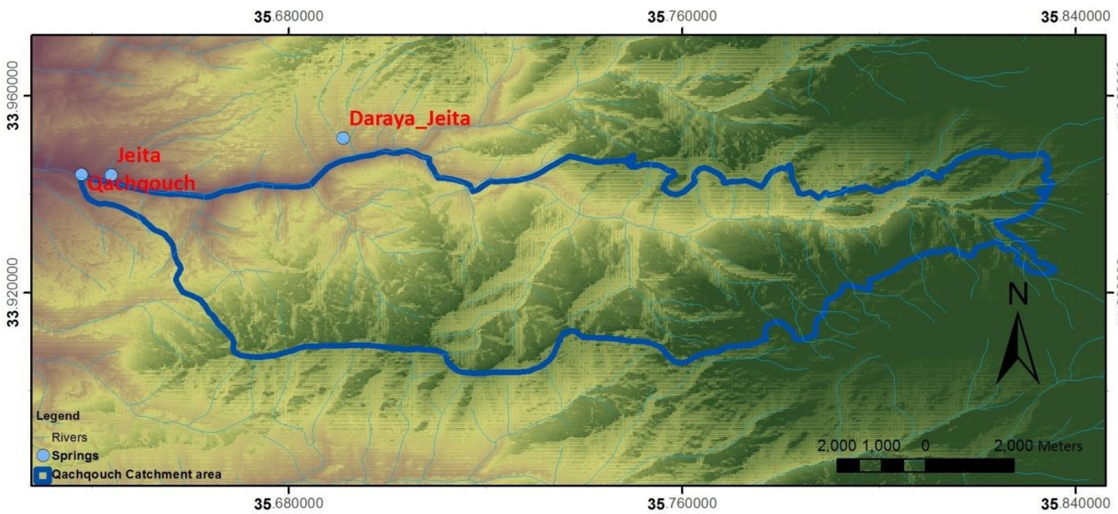

Figure 2: The catchment area of the investigated Spring (Qachqouch). Nahr el Kalb River acting as a boundary condition in the northern part of the catchment

Methodology

APLIS Method

APLIS method is one of the methods that assume a spatial distribution of recharge over all the catchment areas using mainly GIS. The multivariate analysis on many layers of information corresponding to known variables in the Mediterranean semi-arid climatic regions using the GIS was done in the above mentioned literature, and considered valid to be used in this project. Only five parameters were concluded to significantly affect the recharge. The bolded letters in the selected five parameters, “**A**ltitude” (A), “slo**P**e” (P), “**L**ithology” (L), “**I**nfiltration” (I), and “**S**oil” (S), form the term **APLIS** (Andreo et al., 2008; Farfán et al., 2010). More than that, it was noticed that recharge is highly sensitive to Lithology, moderately affected by infiltration, and less sensitive to altitude, slope, and soil information layers. Thus, the percentage of water from the total rainfall that reaches the aquifer as recharge is calculated using Equation 1 (Andreo et al., 2008; Hartmann et al., 2014):

$$\boldsymbol{R} = (\boldsymbol{A} + \boldsymbol{P} + 3\boldsymbol{L} + 2\boldsymbol{I} + \boldsymbol{S}) * \boldsymbol{Fh}/0.9 \qquad \textit{Equation 1}$$

where Fh is the correction factor that depends on the permeability of the aquifer depending on the hydrogeological characteristics of the material surface outcropping (Hartmann et al., 2014).

Investigating the APLIS parameters affecting recharge is required for the assessment of the recharge of the Qachqouch spring catchment. Therefore, all the surface features related to the geological and hydrogeological characteristics of the catchment area, including climatic data, land use land cover, soil, topography, lithology, and karst features were collected, processed, converted to raster datasets, and prepared to be overlaid to produce a final recharge map. Table 1 below shows the main prepared and investigated datasets to be used in the APLIS method:

Table 1: Datasets used to produce different layers of APLIS method

Shapefile/layer	Reference	Type of data	Resolution
Precipitation	Based on measurement (2014-2020) Assessment of historical data to determine the precipitation gradient	Time series	30-min; average yearly precipitation
*Topography	Digital Elevation Model (DEM) for Lebanon	DEM Raster	30 m resolution
Soil (texture and thickness)	Soil map for Lebanon (1955)	Polygon	1:50000
Geology	Dubertret (1955)- Hahne et al., 2011 Field mapping	Polygon	1:20000
Dolines (Point source)	Mapped on satellite imagery and validated in the field	Polygon	1:25000
*Base map resolution for the raster layers			

Various tools of ArcGIS (version 10.3), such as conversion tools to transform vector layers into raster layers, spatial analyst tools, and math tools for the calculation of raster layers according to the weight attributed to each attribute, were used to process shapefiles. The resultant raster layers were reclassified into classes based on the classification in Figure 3. The entire database was projected on the World Geographic System (WGS 1984) map projection. Also, the layers were first produced as vectors and then converted to a raster of a 30 m cell unit grid representing the cell size of the DEM. The given classifications follow the classification given to the different features by Andreo et al., 2008; Farfán et al., 2010.

Altitude (A)	
description	weight
<300	1
300-600	2
600-900	3
900-1200	4
1200-1500	5
1500-1800	6
1800-2100	7
2100-2400	8
2400-2700	9
>2700	10

SloPe (P)	
description	weight
>100	1
100-65	2
65-45	3
45-30	4
30-20	5
20-15	6
15-10	7
10-5	8
5-3	9
<3	10

Lithology (L)			
Description	Age	symbol	weight
Volcanics	Upper Jurassic	J5	2
Marly Limestone	Upper Aptian	C3	3
Sandy Limestone	Aptian	C2a	5
Limestone	Upper Jurassic	J7	5
Sandstone	Lower Cretaceous	C1	6
Limestone	Aptian	C2b	7
Dolomite-limestone	Cenomanian	C4	10
Limestone	Upper Jurassic	J6	10
Dolomite-limestone	Middle Jurassic	J4	10

Infiltration (I)	
description	weight
high impermeability (with or no vegetation)	3
low urbanisation (villages)+vegetation+karstificati	5
High vegetation + karstification	7
low vegetation+karstification (flanks bare rocks)	8
karstification (dolines, faults)	10

Soil (S)	
description	weight
grey soil	3
black soils (volcanics)	2
yellow-grey soils	3
sandy soils	9
mixed soils (sandy-marly)	4
mixed soils	3
terra rossa (calcareous soils)	10
landslides and mass wasting	3

Correction Factor (Fh)	
description	weight
J5/J6/J7/volcanics/C1/C3	0.1
J4/C2a/C2b/C4	1

classification of rate of recharge	
rate of recharge (%)	class
0 - 20	very low
20 - 40	low
40 - 60	moderate
60 - 80	high
80 - 100	very high

Figure 3: Weights assigned to attributes for APLIS layers according to available coverage information and literature

The precipitation/ altitude gradient reaches on average +20 mm per increment of 100 m in altitude (based on the comparison of rainfall amounts between 14 m and 805 m above sea level). Additionally, data from the climatic station at 950 m.a.s.l. from 2014 to 2020 shows an annual average of 1200 mm. A raster layer for precipitation distribution was generated from the clipped DEM based on the variation of altitude using Equation 2.

$$P(Z) = P(950) - ((950 - Z) * \frac{20}{100}) \qquad \textit{Equation 2}$$

Where P (Z) is the annual precipitation at an altitude Z on the catchment in [m]; P(950) is the reference precipitation collected on the catchment. 20 mm is the precipitation gradient per 100 m elevation. The spatial distribution of recharge in mm (R) is a product of the recharge (in percentage) and total precipitation distribution over the catchment area in mm.

COP method

The COP Method allows the assessment of the vulnerability of the catchment area of the Qachqouch spring and helps delineate zones contribution to recharge of high intrinsic sensitivity to contamination. The hydrological and hydrogeological factors, surface features, and catchment parameters are represented in the application of topography, soil, land use land cover, lithology, karst features, and the depth of the water table.

The COP method targets the surface of the groundwater (the water table) by assessing the ability of the overlying soils and unsaturated zone factor (O) to protect the groundwater, and by assessing the modification in the level of protection caused by diffuse or concentrated infiltration (C) and the climatic conditions (P) (Andreo et al., 2008). The method identifies the vulnerable areas by preparing these factors with Geographic Information System (ArcGIS) tools using different combinations between geological and hydrogeological datasets (Moreno-Gómez et al., 2018). Each factor is divided into several subfactors represented in an input map. The maps are finally compiled together for a final vulnerability index. The variables of the input are not real ones but are the variables shown in Figure 4 according to Vías et al., 2006 classification.

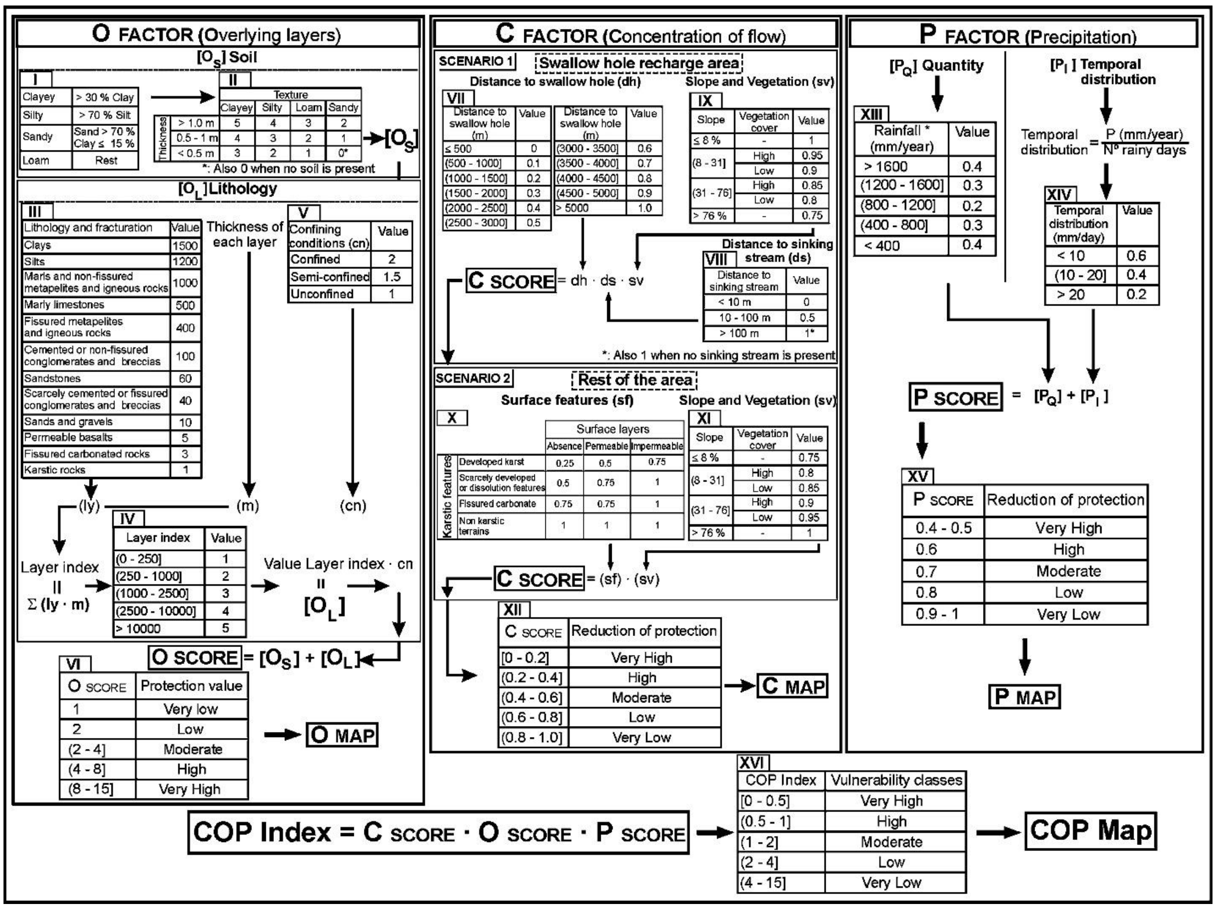

Figure 4: Main factors playing a role in the definition of the COP map (Vías et al., 2006)

Results

Each cell in the resultant map has a recharge ratio considering that only this ratio of total precipitation reaches the water table through this surface area of 30 meters resolution. These cells were grouped in classes based on the percentage ratio of recharge, thus the resultant map of the APLIS method in Figure 5 computes the total recharge percent per increment of 5% for the total area. The mean distribution map of precipitation is shown in Figure 6. The precipitation map in Figure 6 was multiplied by the recharge ratio in Figure 5 to compute the total mean recharge in each cell in the map of Figure 7.

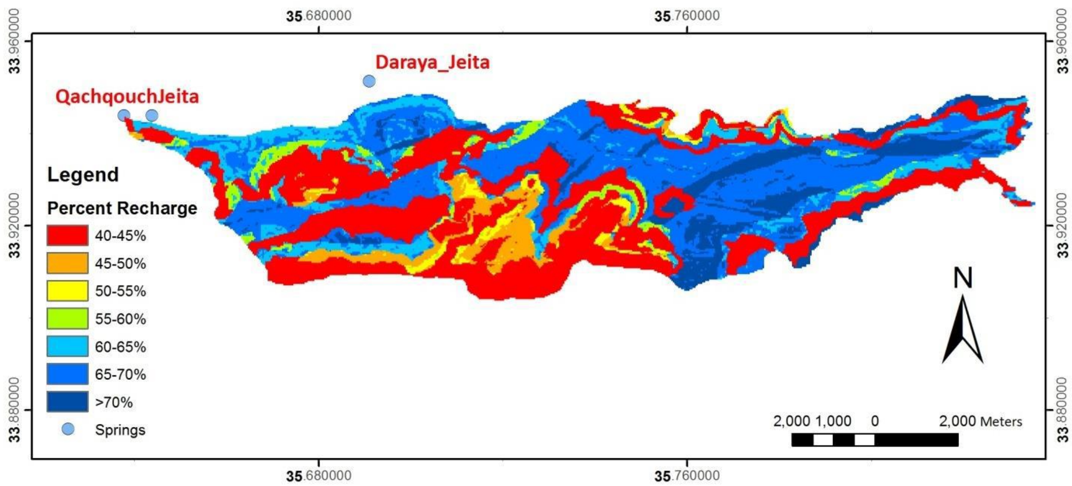

Figure 5: Percent Infiltration (in 5% increment) using the APLIS method

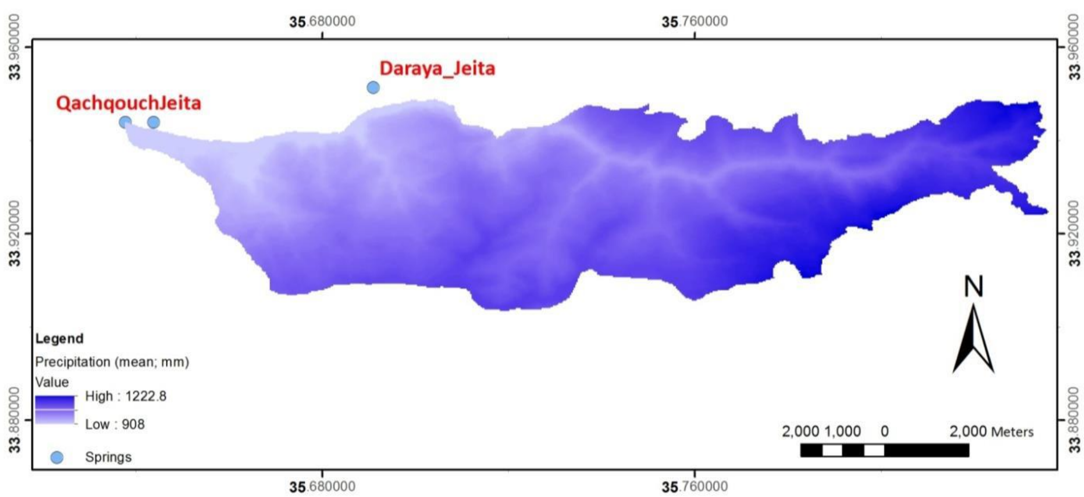

Figure 6: Precipitation distribution for an average year

The precipitation map in Figure 6was multiplied by the recharge ratio in Figure 5 to compute the total mean recharge in each cell in the map of Figure 7.

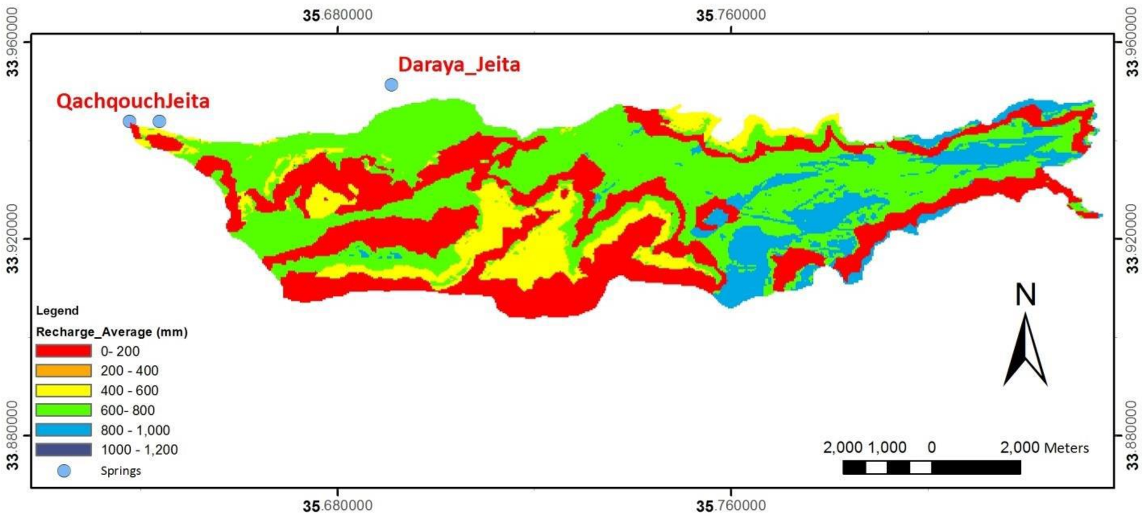

Figure 7: Final recharge map in mm (Using APLIS) for an intermediate year

The COP method resultant map in Figure 8classifies the catchment area from very low vulnerability to very high vulnerability. The red color zones are the most vulnerable areas that fit the exposed karst rocks to the surface.

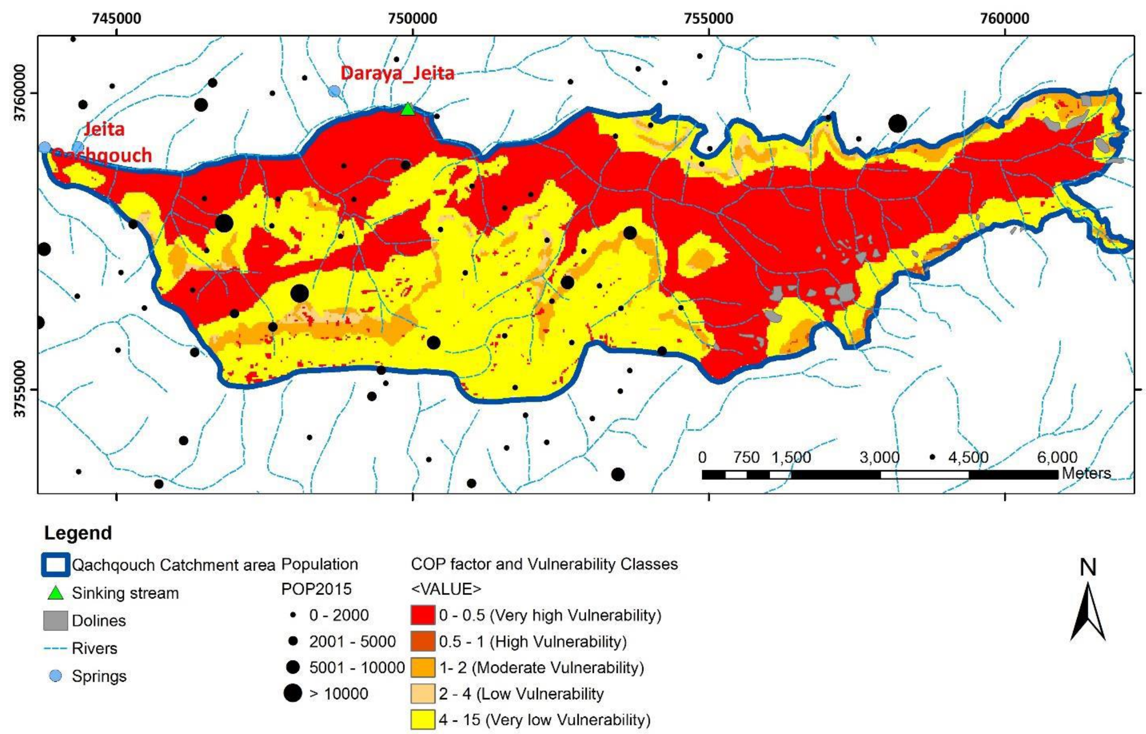

Figure 8: COP map showing the extent of vulnerability

Application to Policy

A brief history of existing policies

Walking through a brief history in time, all the way back to the beginning of the 19th century, the purchase of water springs was common. During the French mandate, legislations were set having the purpose to organize the water sector. They emphasized that the state is the only owner of water resources while allowing well digging on private lands only under pre-authorization. Wells can be drilled no more than 150 m in depth without a permit and following a flow of one hundred cubic meters per day. Considering the sharp increase of boreholes and private irrigations, legislation was set out to organize groundwater exploitation and use, a permit was replaced by a declaration for drilling less than 150 m while another permit is to be issued when wanting to go beyond that depth (Riachi, 2016).

In more recent groundwater regulations, the licensing process of wells involves the relatively new water authorities including municipalities and the ministry of energy and water. The process is mainly centralized at the ministry level. In addition, the externalization of some of the roles previously performed by the ministry was directed toward private companies that were in charge of technical studies and field visits to control well drilling. Companies requested fees from users in order to proceed with the studies and apply to the ministry. This created a disincentive for people to pursue legal wells. Moreover, when the civil war took place in Lebanon, much more exploitation hit the aquifers of Lebanon with no legal control or management (Riachi, 2016).

Focusing on Qachqouch, the area already contains established urbanization and human exploitation of the lands available. They form sources of influence on available water in the region. This adds more aspects for policy implementation and recommendation.

Starting with residential buildings and areas, the catchment suffers from poor infrastructures in Lebanon allowing leakages and sewage water to contaminate surrounding areas, specifically reaching water resources. In addition, an industrial zone, hospitals, and quarries lie within the designated area represented in Figure 9. The sources illustrated in this map explain the contamination concluded from the bacterial analysis data in table 2. The bacterial analysis was done mostly in 2020 for water samples taken from the Qachqouch spring. In the same year, the sources of contamination existed and they are positively linked to the type of bacteria shown in the bacterial analysis data. All of these combined contribute to water resource contamination which stresses the need for policies to modulate and preserve the water.

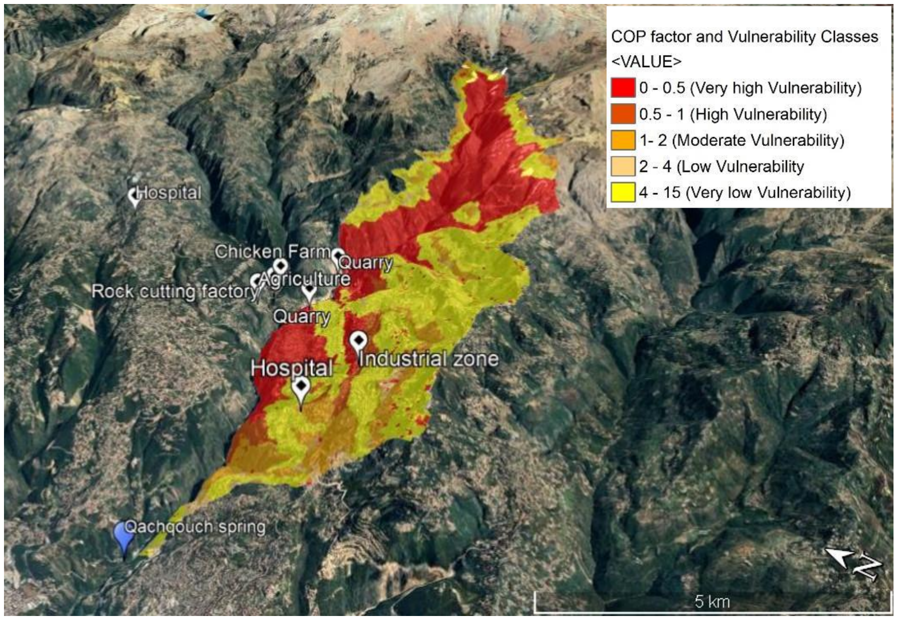

Figure 9: Sources of contamination lie within the catchment area of different classes represented in different colors

Table 2: Bacterial analysis of water samples taken from Qachqouch spring

date and time	Total Coliform	E-coli	Fecal Enterocoques	Pseudomonas Aerug
1/23/20 11:30 AM	3783	968	225	0
1/30/20 11:30 AM	1566	81	28	0
2/6/20 12:00 PM	1227	124	45	0
2/13/20 12:00 PM	2127	193	62	0
2/20/20 12:10 PM	419	44	25	0
2/27/20 12:30 AM	202	37	20	0
3/4/20 2:20 PM	560	46	27	0
3/12/20 11:30 AM	1088	92	48	0
7/14/20 10:10 AM	350	0	28	42
9/24/20 6:00 PM	300	38	20	0
11/5/20 2:00 PM	2000	700	220	0
12/29/20 11:00 AM	102	36	20	0
2/26/21 9:30 AM	136	30	6	0

Discussion of A Possible Solution

As mentioned before, legal historical background over the water has proven insufficient nor does it protect our valuable resources. In order to establish a well-comprehended protection, plan for the area, it is best to divide it into protection zones. The diversification of the area necessitates this approach due to its different occupations and spread over fragmentary lands. Equity should be prioritized in protection plans making sure to cover every aspect to the fullest potential and efficiency.

Furthermore, legal governance in Lebanon lacks spatial measures. The latter implies that strict measures cannot be applied on all grounds taking away some of their respective rights. The delineation of protection zones will help establish the balance where policies in one zone are not necessarily applied in another due to its relatively lower vulnerability. Moreover, it was observed that Lebanese laws neglected water quality focusing solely on quantity. In other words, laws targeted mostly regulations related to wells and imposed sanctions depending on the rate of groundwater extraction within one time frame. These policies only concern the quantity of the water leaving aside its quality whereas this project particularly addresses water quality emphasizing its deteriorating conditions if kept untreated.

The karstic nature of rocks in Lebanon makes them a perfect fit for the following protection zones:

Zone S1 mainly concerns the prevention of damage and pollution of groundwater and immediate surroundings. Wells, recharge installations, and sinkholes are important locations in this zone. Sinkholes are big surface holes similar to vertical caves but extend vertically and contribute in the very fast infiltration of surface water into the subsurface. They form the main entry points of surface water directly into the subsoil, where their immediate surroundings of geological structures play a big role in providing fast recharge especially if the surface water is a cumulative accumulation of water from different autogenic and allogenic areas and facilities. Within the catchment area, some of these facilities are hospitals, quarries, and even industrial zones as seen in the map of Figure 9. Hospitals bring in highly hazardous waste in case of leakages and accidents. As for quarries, there is a risk of water contamination due to minerals and dust. Industrial zones may have various water contaminants including hazardous waste containing harmful chemicals as well as other waste products. Policies are set to accommodate all these contaminants in order to preserve water quality. As for future constructions and land use, no activities should be permitted except those that aim for supplying drinking water.

Zone S2 is a zone where the pollution of groundwater is coming from excavations and underground work and installations. Many of these installations risk pathogen contamination of the waters so appropriate policies must be set in order to prevent and decrease this risk. Excavations causing change to the soil and protective layer should be strictly forbidden, in addition to wastewater infiltration. Fertilizer application should be very limited and monitored to not risk groundwater quality contamination.

Zone S3 intends to guarantee accidental pollutant substances have enough space and time for necessary measures before reaching the designated waters. Of course, any construction that put the water quality or quantity at risk should be prohibited. Moreover, storage tanks, pipes or any underground constructions that cause a risk of water quality deterioration should not be allowed (Swiss Federal Council, 2018).

Conclusion

To recap briefly, the steps followed to accomplish groundwater protection can be summarized into five big headlines. First, a perimeter should be installed for the zones we are covering. Second, the determination of the nature of the pollutant in addition to the cause of the pollution that comes in third place should be considered. Fourth, the effectiveness of possible measures should be determined. All of this is achieved within the last headline which is the legal framework.

Many stakeholders normally should take part in this process including the ministry of energy and water and municipalities. Starting with ministries, the ministry of energy and water partake the biggest role as it is responsible for planning and implementing water projects as well as regulating and monitoring those projects. Of course, keeping in mind a major responsibility, that is the protection of water resources against pollution. This will help achieve conservation and water resource management as well. To complement these responsibilities, the ministry of finance takes part in funding and laying out suitable budgets for project implementations. As for the ministry of public health, looking out for waterborne diseases and monitoring incidences plays a crucial role in contributing to epidemiological fields. In addition, the Water Establishment in Lebanon heavily contributes to the process by planning and distributing water resources within respective areas, implementing wastewater plans, and investigating water drinking quality.

In this case, municipalities play a complementary role in supervising all of these missions in designated areas on a closer scale. They will ensure residence of the area are applying measures aligned with groundwater protection policies. One of the aims of this project is not only to have clear guidelines to follow but also to facilitate operations on the field. One may take the numerous stakeholders as a limit to the project, but in fact, the policies are built in a way to facilitate operations and the clarity of the guidelines will ease off the coordination between all shareholders and constrict it to municipal supervision and follow-ups. The interaction between Science Investigation- Science Evidence-Stakeholders/Decision Makers and Policy is shown in Figure 10. This schematic approach can be applied on all the groundwater catchment units in Lebanon to help draft white papers that can further lead to protection laws based on the hydrogeological characteristic of specific high-yield springs used for local supply.

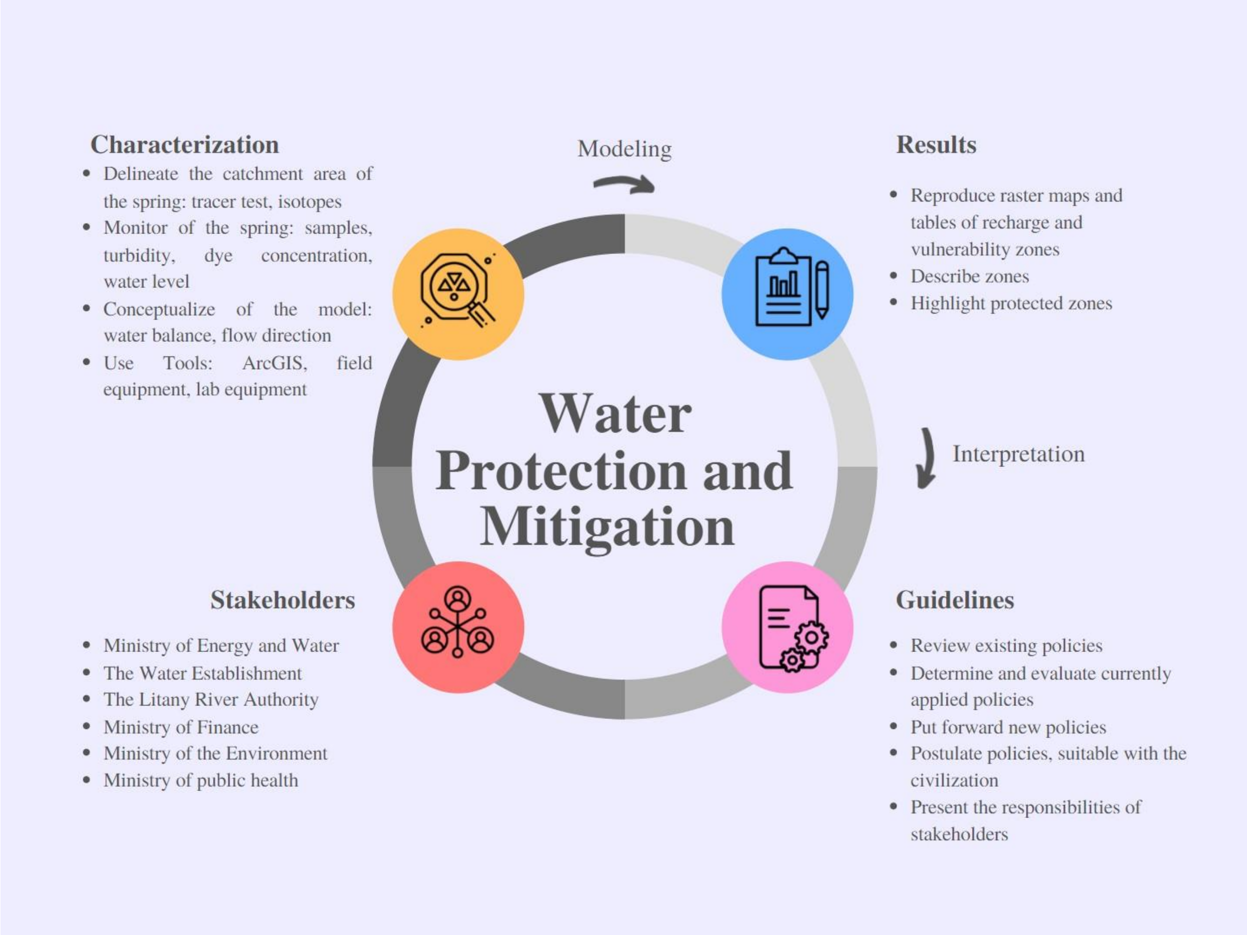

Figure 10: Graphical Abstract highlighting the interaction between Science Investigation- Science Evidence-Stakeholders/Decision Makers and Policy

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