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Application of GALDIT index in the Mediterranean region to assess vulnerability to sea water intrusion

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Application of GALDIT index in the Mediterranean region to assess vulnerability to sea water intrusion

by

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I dedicate my work to my parents who have been, and always will be there for me. I promise to always make you proud.

Sincerely,

Tracy

Abstract

GALDIT is a Vulnerability Indexing (VI) methodology that uses ranges, ratings and weights developed as a preliminary decision support tool to predict groundwater areas prone to Sea Water Intrusion (SWI). It has been only applied on porous coastal aquifers to date, in Mediterranean coastal regions, where SWI has become a growing problem. The present study tests the applicability of GALDIT VI in the Mediterranean region, by comparing the results of a porous aquifer in Akkar, Northern Lebanon to the results of a porous aquifer in Northern-East Greece. Furthermore, a feasibility of the application of GALDIT VI is done on a karstic coastal aquifer for the first time. The coastal aquifer selected for this purpose is located in Ghadir, Central Lebanon.The application of GALDIT VI on two different porous coastal aquifers shows that the theoretical ranges and ratings can always be adjusted to better fit the hydrogeological conditions of the study area. Moreover, GALDIT VI is not able to explain alone SWI evolution through time, at least not in the case of Akkar porous aquifer. Therefore, anthropogenic parameters, such as abstraction rate, should be taken into consideration.The results of the feasibility study on the karstic aquifer of Ghadir reveal the limitation of GALDIT VI in predicting sensitivity to SWI.

Consequently, GALDIT VI can be fine-tuned by modifying or replacing the non-sensitive parameters/indicators by sensitive ones.The modifications include taking into account the geological structures and introducing parameters that specifically characterize karst aquifers.

Finally, further investigations should be conducted to validate the solutions proposed in order to give the best possible outcome from a low resolution vulnerability assessment method as GALDIT VI.

Keywords: Sea Water Intrusion (SWI), Vulnerability Index (VI), GALDIT VI, porous aquifer, karstic aquifer, Groundwater.

Résumé

GALDIT est une méthodologie d'indexation de vulnérabilité (VI) qui utilise des intervalles, des classes et des poids développés comme un outil préliminaire de prise de décision pour prédire les eaux souterraines sujettes à l'intrusion d'eau de mer. Il a été appliqué uniquement sur les aquifères côtiers poreux à ce jour, dans les régions côtières Méditerranéennes, où l'intrusion des eaux salines est devenue un problème croissant.
La présente étude teste l'applicabilité de GALDIT VI dans la région Méditerranéenne, en comparant les résultats d'un aquifère poreux à Akkar, au Nord du Liban aux résultats d'un aquifère poreux dans le Nord-Est de la Grèce. En outre, la faisabilité de l'application de GALDIT VI se fait pour la première fois sur un aquifère côtier karstique. L'aquifère côtier choisi à cet effet est situé à Ghadir, au centre du Liban.

L'application de GALDIT VI sur deux aquifères côtiers poreux différents montre que les intervalles et les classes théoriques peuvent toujours être ajustées pour mieux s'adapter aux conditions hydrogéologiques de la zone d'étude. En outre, GALDIT VI n'est pas en mesure d'expliquer seule l'évolution de l'intrusion à travers le temps, du moins pas dans le cas de l'aquifère poreux de Akkar. Par conséquent, les paramètres anthropiques, tels que le taux d'abstraction, devraient être pris en considération.

Les résultats de l'étude de faisabilité sur l'aquifère karstique de Ghadir révèlent la limitation de GALDIT VI dans la prévision de la sensibilité à l'intrusion des eaux salines. Par conséquent, GALDIT VI peut être ajusté en modifiant ou en remplaçant les paramètres/indicateurs non sensibles par des messages sensibles.
Les modifications incluent la prise en compte des structures géologiques et l'introduction d'indicateurs qui caractérisent spécifiquement les aquifères karstiques.

Enfin, d'autres recherches devraient être menées pour valider les solutions proposées afin de donner le meilleur résultat possible à partir d'une méthode d'évaluation de la vulnérabilité à faible résolution comme GALDIT VI.

Mots-clés : Intrusion de l'eau de mer (SWI), Indice de Vulnérabilité (VI), GALDIT VI, aquifère poreux, aquifère karstique, eaux souterraines.

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Acronyms List

a.m.s.l: Above mean sea level

A*:* Aquifer hydraulic conductivity

ARAK: Aquifer Rechargeability Assessment in Karst

AVI: Aquifer Vulnerability Index

D: Distance from shore

DRASTIC: Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone and hydraulic Conductivity of the aquifer

EC: Electrical conductivity

EPIK: Epikarst, Protective cover, Infiltration conditions and Karst network development

EPM: Equivalent Porous Medium

G: Groundwater occurrence

GIS: Geographic Information System

I: Impact status of existing SWI

L: Groundwater level a.m.s.l

MCM: Million Cubic Meters

SWI: Sea Water Intrusion

TDS: Total Dissolved Solids

VI: Vulnerability Index

1 Introduction

Groundwater aquifers are the main source of freshwater used for drinking, industrial and agricultural purposes; however, groundwater scarcity and contamination have been the most popular topics in hydrology in the past decades, and continue to be (Pedro & Valley, 2001). Although it is seen as a natural process on a regional scale, on a local scale Sea Water Intrusion (SWI) is majorly a human-induced contamination in over-exploited aquifers. This phenomenon happens in coastal zones, where saline water from the sea diffuses into freshwater aquifers (Papadopoulou et al., 2005). SWI can be demonstrated by a remarkable increase in salinity values, consisting of chloride concentration, Total Dissolved Solids (TDS) and Electrical Conductivities (EC).

SWI is mostly seen in European Mediterranean and Middle Eastern Mediterranean countries, considered as semi-arid regions. Spain, Italy, Greece, Turkey and Lebanon, are examples where rain is almost absent during five months in the summer, impacting the continuity of recharge. These countries are also characterized by their dominant carbonate rocks that form major aquifers, and a number of alluvial and sedimentary aquifers which are sources of usable water as well (EUWI, 2007).
Lebanon, located on the Mediterranean Sea, has a serious water shortage in coastal areas, where the high density of people results in high water demand and therefore an extensive exploitation of groundwater. Consequently, the deficit in the water balance along the coast exceeding 150 Million Cubic Meters (MCM) (UNDP, 2014) is the direct cause behind SWI to coastal aquifers.

Over the years, a pronounced increase in SWI has been noted. Actually, the salinity measurements fall far beyond recommended national values for potable/domestic purposes. For example, chloride reaches 1500 mg/l in the capital, Beirut, and its suburbs, while water for domestic purposes, let alone potable purposes should have less than 500 mg/l of chloride. Salinity has indeed risen to 5,000 mg/L in 2005, which refers to an intrusion constituting 10% of the total groundwater in Beirut and its suburbs (Saadeh, 2008). This percentage is at least five times higher than the salinity limit where the contamination becomes irreversible and the water is inconsumable (Barlow, 2003).

Although many researchers tackled the problem of SWI in Lebanon, it has been difficult to find a definite solution for the affected coastal aquifers, due to their complex and heterogenic nature.

One of the most important steps towards ensuring groundwater sustainability in coastal areas is to evaluate the vulnerability of the aquifer towards SWI. The latter will allow for decision makers to outline sensitive areas prone to SWI where management practices, such as artificial recharge, can be applied or where further abstraction is to be limited or prohibited.

GALDIT (acronym for *G*roundwater occurrence, *A*quifer hydraulic conductivity, water *L*evel above mean sea level (a.m.s.l), *D*istance from shore, *I*mpact status of existing SWI and aquifer *T*hickness) is a qualitative spatial method developed by Chachadi & Lobo Ferreira (2005), to assess the vulnerability of coastal aquifers for SWI. This method has been applied in countries such as Greece and Spain.

The present research aims at testing the applicability of the GALDIT Vulnerability Index (VI) method on two pilot coastal areas in Lebanon characterized by varying hydraulic characteristics: 1) the alluvial unconsolidated porous aquifer of Akkar, Northern Lebanon and 2) the karstic fractured limestone aquifer of Ghadir, Central Lebanon. An evaluation of the method is done in order to study the sensitivity of each of the GALDIT VI parameters in the final vulnerability map. The results obtained on the pilot area of Akkar, Lebanon are compared and contrasted to a previous work done on a coastal porous aquifer in Greece. The present study also highlights the major missing parameters that should be considered especially in a fractured aquifer. It also proposes an alternative method to tackle the specific vulnerability of a site including the impact of anthropogenic activities that play a significant role in SWI.

Section 2 consists of a background review of the relevant concepts needed for this study, followed by a detailed definition of the adopted method GALDIT VI. The results of the application of GALDIT VI on the two pilot areas are presented in Section 6. These results will be discussed in Section 7 and amendments to the method will be proposed in order to address different types of aquifers and account for the different hydrogeological conditions. Conclusions are provided in the last section.

2 Background

2.1 Concept of Sea Water Intrusion (SWI)

Saltwater is mostly known as sea water, but also can occur as ancient water, called “fossil water”(AzoCleantech, 2009). This water may have been present between deep calcareous rocks for a long period of time and has been enriched with minerals from these rocks through time. However, this study focuses only on Sea Water Intrusion (SWI).

The first attempt to model SWI was at the end of the 19th century when Ghyben and Herzberg discovered that the freshwater-saltwater interface is estimated at a depth of 40 times the height of groundwater level above mean sea level (a.m.s.l), in the same area. In other words, when the water level, in a coastal aquifer, decreases by 1m, saltwater level will increase by 40 m (Liu, n.d.). However, it is valid when the interface between saltwater and freshwater is sharp (excluding the mixing zone), and the water pressure is the same for both at any point (hydrostatic equilibrium). The pressure is calculated by multiplying the specific weight of the fluid by the water depth. The above explanation is described with the following Ghyben-Herzberg formula:

Equation 1.1 $$z = \frac{\rho_f}{\rho_s - \rho_f} * h$$ (Wiest, 1998)

Or

Equation 1.2 $$z = 40 * h$$

where ρ_f is the specific weight of salt water (1.025 g/cm^3), ρ_s is the specific weight of freshwater (1.0 g/cm^3), h (m) is the height of groundwater a.m.s.l, and z (m) is the depth of groundwater below sea level.

This simple Ghyben-Herzberg formula to estimate the saltwater-freshwater interface, does not take into consideration the type of aquifer, its hydraulic properties (such as permeability, rechargeability and conductivity), and the external stresses affecting water level change (Satta, 2014).

In fact, hydrostatic equilibrium is not always conserved in coastal areas, where flow takes place, which might lead to a mixing zone instead of a sharp interface (Papadopoulou et al., 2005). Figure 1 illustrates the concept of equilibrium used in the Ghyben-Herzberg formula and that will be assumed for this study. It is worth mentioning that the flow taking place in coastal areas will have a direction towards the sea, if no stress is applied. This water flow direction prevents the intrusion of sea water to the groundwater.

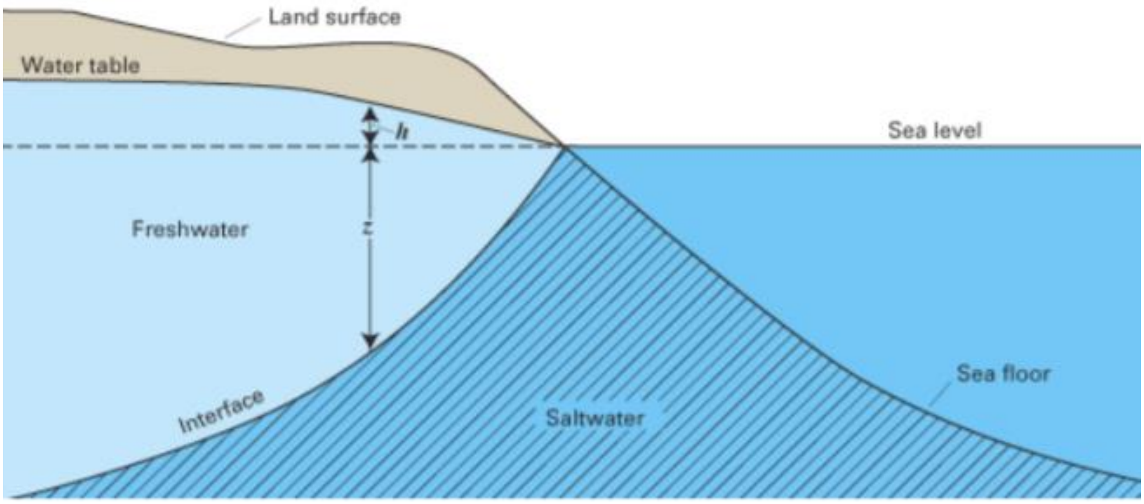

Figure 1: Hydrostatic equilibrium depicted by the sharp interface between freshwater and saltwater (Barlow, 2003).

The problem of SWI will only become noticeable to the population when well contamination occurs. This process begins when sea water intrudes as a wedge under the less dense freshwater. In a stress-free condition, freshwater head halts the advancement of saltwater by exerting pressure. However, under over abstraction conditions, the pressure of freshwater head will decrease allowing saline water to form a cone and advance towards the tapping well, which will be contaminated eventually. This phenomenon is known as *upconing* (Johnson et al., 2017).

2.2 Indicators of Sea Water Intrusion (SWI)

In order to identify SWI, one should first think about water chemistry. It is evident that saline water has a high concentration in salts and minerals whereas freshwater does not. Salinity represents all the dissolved salts in water and indicates whether SWI exists or not. According to Aitchison-Earl et al. (2003), the concentration in chloride, bicarbonate, sodium and calcium determine salinity. In fact, the result of their experiment showed that there is a high increase in chloride and sodium concentrations, where a small amount of saltwater exists, whereas bicarbonate and calcium are barely affected. Knowing that this relation can be much more complex in-situ, it is still valid to use chloride to bicarbonate and sodium to calcium ratios to detect an increase in salinity (Aitchison-Earl et al., 2003).

Another study, done on the coastal aquifer in Beirut, Lebanon (Acra & Ayoub, 2001) has found "diagnostic indicators" for SWI that add to the concentration in salts, the parameters of hardness and conductivity. Hardness measures the concentration of calcium and magnesium in water in mg/l. Typically freshwater has a total hardness ($CaCO_3$) between 15 and 375 mg/l and a magnesium hardness between 5 and 125 mg/l, which is half of calcium hardness (10 to 250). Whereas sea water hardness is higher than 6630 mg/l, consisting of a magnesium hardness around 5630 mg/l and a calcium hardness around 1000 (Johnson et al., 2017).

This high difference in values between fresh and saltwater can be a suitable indicator for SWI. In fact, hardness parameter not only detects SWI but also can give information about its severity, when freshwater values become closer to sea water values.

Another diagnostic indicator is electrical conductivity (EC). It is the ability of water in passing an electrical current. Since sea water is high in salts and minerals, it is then a very good conductor (high conductivity) whereas freshwater is not.

The conductivity parameter is considered to be the easiest and cheapest to test. Instead of doing a complete chemical analysis, conductivity measurement can be done in the field. Since it is easily done, it can serve as a monitoring tool to check the progress of SWI on a frequent basis. Conductivity measurements give reliable values; however, they can be affected by the minerals present in rocks, especially when it comes to carbonate rocks. Chemical analysis can then be complementary to conductivity measurements, for validation purposes (Aitchison-Earl et al., 2003). Based on previous studies and research, scientists have deduced a relationship between TDS, EC and chloride concentration:

Equation 2 **TDS (mg/L) = 0.64 EC (µS/cm) where EC>1000** (Evangelou, 1998)

Equation 3 **TDS = 1.8066 [Cl]** (Johnson et al., 2017)

2.3 Concept of vulnerability

When it comes to explaining vulnerability, different definitions can be found. However, all of them focus on the fundamental terms that form vulnerability: "harm, exposure, sensitivity, adaptive capacity, and recovery" (Runge, 2015). Vulnerability is seen as a wide and complex concept used in different social, economic, and especially environmental studies. Environmental vulnerability focuses on the interaction between human actions and nature, by integrating suitable, but complex, components (such as processes, indicators and factors) that are representative for assessing the vulnerability (Runge, 2015). First, when dealing with vulnerability, two main questions should be asked: "vulnerability of what?" and "vulnerability to what?" (Harter & Walker, 2001).

2.3.1 Vulnerability assessment

It is not evident whether to assess vulnerability qualitatively, or quantitatively. In fact, vulnerability is a theoretical concept that needs to be assessed by developing a methodology (Hinkel, 2011). Three different types of vulnerability assessment exist: statistical-based approaches (probability of contamination), process-based simulations (numerical solutions) and indexing methods (indicators mapping) (Mimi et al., 2012). Each methodology varies depending on the target and its conditions. Indicators, which represent theoretical variables resulting from observable variables, are the best approach to give a meaning and evaluate vulnerability (Hinkel, 2011). Furthermore, "an index-based method enables the translation of a complex reality into a single measurement"(Satta, 2014). However, choosing adequate indicators is a challenge. In fact, one should rely on deduction, previous studies, and personal expertise, until a logical result is obtained by trial and error.

By integrating several indicators, a theoretical composite indicator, called index, will be the measure to assess vulnerability (Hinkel, 2011).

Vulnerability Index (VI) is then an adequate tool to assess vulnerability. For a study area, exposed to any kind of hazard, VI measures the effect of that potential threat to the area. This method was proposed in 1990 (Koroglu, 2016). In fact, a researcher called Lino Briguglio, from the University of Malta has described the fundamentals of the method. VI is calculated by the cumulative score of the weighted indicators, where each of these indicators is assigned a value based on its relative importance for the specific situation (Koroglu, 2016).

2.3.2 Groundwater vulnerability

Many definitions can be found for groundwater vulnerability, some of them as cited in Harter & Walker (2001) are:

"The sensitivity of groundwater quality to anthropogenic activities which may prove detrimental to the present and/or intended usage-value of the resource." (Bachmat and Collin, 1983, quoted in Vrba & Zoporozec).

"The ability of a system to cope with external, natural and anthropogenic impacts that affect its state and character in time and space." (Sotornikova and Vrba, 1987, quoted in Vrba and Zoporozec).

"Vulnerability is an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts." (International Association of Hydrogeologists, Vrba & Zoporozec, 1994).

For the purpose of this study, the last definition, of 1994, will be adapted. Intrinsic vulnerability deals with the hydraulic, geologic, and geomorphological properties of an aquifer, which determine the sensitivity and adaptive capacity described above (Runge, 2015). Nevertheless, the intrinsic properties alone do not take into account the type of contaminant which has to be included in this study. In fact, contaminants can be of different types: diffuse and concentrated contaminants infiltrating from the surface into the aquifer, and saltwater intrusion entering as a wedge under the freshwater. Therefore, specific vulnerability is used to assign the appropriate indicators, taking into consideration the contaminant properties (Perrin et al. , 2004).

It is worth mentioning that extrinsic vulnerability deals only with external factors affecting the groundwater system such as human activities or natural disasters. Hazard and exposure are then included in extrinsic vulnerability. This study uses the intrinsic properties of an aquifer; however, the status of the existing contamination is taken into consideration.

Finally, the less vulnerable the area is, the more likely it will respond to recovery practices.

2.4 Vulnerability assessment of aquifers in the Mediterranean region

2.4.1 Types of aquifers

Aquifers are classified depending on confinement type first and geology second. Unconfined aquifers are the ones exposed to water infiltrating from the surface, and are usually shallow aquifers. Figure 2a presents an unconfined aquifer where the impermeable bedrock retains water from infiltrating deeper, and the water table shows the water level in the unconfined aquifer. It should be noted that these aquifers are highly exposed to contaminations from the land surface (pesticides, waste water, etc.) and thus are not a good source for domestic use (Michigan Environmental Education Curriculum, n.d.).

Confined aquifers (Figure 2b) are the ones that are overlaid by an impermeable layer and thus are under more pressure, especially if they are deep aquifers. Water enters this type of aquifer from places where the impermeable layer does not exist or is fractured (Michigan Environmental Education Curriculum, n.d.). Confined aquifers are the most exploitable, and are less exposed to SWI under normal conditions, due to the high pressure. However, under high abstraction conditions, confined aquifers become the most prone to SWI due to sudden drop in pressure and the significant depression cone (Chachadi & Lobo Ferreira, 2005).

a

b

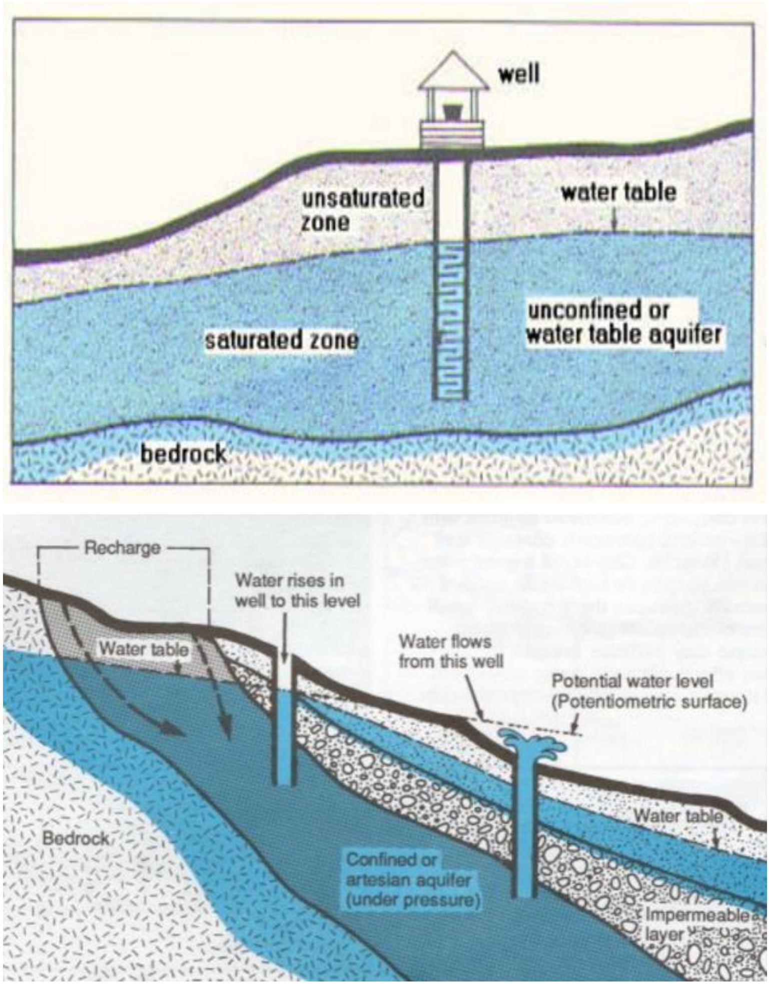

Figure 2: a) Showing an unconfined aquifer, where the saturated zone indicates the exploitable water zone, and the water table indicates water level. b) Showing a confined aquifer, and the recharge area that is not confined. The artesian well tapping the confined aquifer results from high pressure (Michigan Environmental Education Curriculum, n.d.).

Aquifers are then classified into two main classes depending on their geology: Karstic aquifers, and porous aquifers. In the Mediterranean region, porous and karstic aquifers are found in the following lithologies:

Porous aquifers are mainly formed of detrital sedimentary, found in coastal plains, and fluvial deposits found in valleys and deltas. Freshwater is stored in the pores; thus, the quantity depends on the size of the pores. Assessing the vulnerability of these aquifers has been frequently studied in previous works, due to their importance in providing freshwater for use, and their “easy to measure” hydrogeological properties.

Karstic aquifers are more complex and heterogeneous; thus, a more detailed description shall be given for the purpose of this research.

Karst is a natural feature mostly seen in carbonate rocks, mainly limestone and dolomite, which have undergone a dissolution process called “karstification”, leading to the progressive enlargement of pores. Karstic rocks form the bedrock of large areas on the Earth, which are ice-free, and most importantly, are the groundwater source for almost 25% of the whole population (Ford & Williams, 2007). For the Mediterranean countries alone, half of the population is dependent on karstic groundwater (Bakalowicz, 2005). These aquifers have been a challenge to characterize due to their high heterogeneity and duality of infiltration and flow. In fact, water infiltrates diffusively in fast source points, and in the subsurface it flows in small fissures of impermeable layers as well as in high permeable conduits and enlarged fissures (Bakalowicz, 2005). Despite being exposed to the same forces as other subsurface rocks, the flow in karstic rocks is different from all other types of flows. This fact is due to the process of karstification, mentioned above. Consequently, large conduits will be formed progressively, leading to turbulent water flow, instead of a laminar, parallel, flow that occurs in other subsurface rocks (Ford & Williams, 2007). Therefore, karst systems should be treated cautiously in hydrology, taking into consideration their distinctive geomorphology and hydraulic properties. For the above-mentioned reasons, studying karstic aquifers behavior is not an easy task, therefore fewer studies are found on their vulnerability assessment using indexing methods.

2.4.2 Vulnerability Index (VI) methods on coastal aquifers

All VI methods have the same principle of calculating a vulnerability index. It usually relies on choosing a number of parameters that is weighted and rated according to previous knowledge. A numerical value, index, is obtained by integrating the obtained field data. It is worth mentioning that all the methods applied on porous aquifers without modification may result in erroneous results when applied in karstic media, reversely as well. This is due to the specific hydraulic properties of the different geologies. However, some methods traditionally applied on porous aquifers can be applied on karstic aquifers with some modifications in the parameters used. Where karst systems are very complex, karst vulnerability assessment used to rely mainly on modelling approaches and the other two types of vulnerability assessment mentioned in Section 2.3.1. To be able to apply a VI, it is assumed that the karstic system is Equivalent Porous Medium (EPM) (Bakalowicz, 2005). The most used methods of VI are described below.

- **DRASTIC**

This is the first indexing method, developed in 1987 (Doerfliger, Jeannin, & Zwahlen, 1999), to assess the intrinsic vulnerability of a porous aquifer against contaminants diffusing from the surface. DRASTIC considers only the hydrogeological setting of the aquifer which includes the following parameters: "*D*epth to water, net *R*echarge, *A*quifer media, *S*oil media, *T*opography, *I*mpact of the vadose zone and hydraulic *C*onductivity of the aquifer" (Aller et al., 1987), from where comes the acronym DRASTIC. The higher the index, the higher is the potential of an aquifer to get contaminated. Although his method was only applied in porous aquifers, a modified version of DRASTIC was developed for the karstic aquifer of Ramallah District, Palestine by increasing the theoretical weight of aquifer media and hydraulic conductivity factors that highly affect the intrinsic vulnerability of karst aquifers (Mimi et al., 2012).

- **AVI**

AVI, or *A*quifer *V*ulnerability *I*ndex, is a simple and limited vulnerability indexing method in sedimentary aquifers, inspired by DRASTIC, but using the cumulative thickness of sedimentary layers above the aquifer and hydraulic conductivity (Luoma et al., 2016). This method has a number of limitations by ignoring some important parameters, such as water content, and making assumptions by considering only shallow aquifers for example (Stempvoort et al., 1993).

- **EPIK**

This is the first indexing method developed specifically for karstic aquifers. EPIK acronym stands for *E*pikarst, *P*rotective cover, *I*nfiltration conditions and *K*arst network development (Doerfliger et al., 1999). The higher the index, the lower the intrinsic vulnerability is. It is applicable at catchment scale and deals with any kind of diffuse contaminations from the land surface.

- **GALDIT**

The use of GALDIT VI to predict the most vulnerable areas prone to SWI, has started since 2005. Since then it has been used by researchers in different study areas, however not in Lebanon.

A detailed description will be given for GALDIT VI to justify the choice of using it as part of the methodology of this study.

A general explanation of the method:

GALDIT VI focuses only on classifying the vulnerability of an area in relation to SWI. In fact, GALDIT stands for "*G*roundwater occurrence (aquifer type; unconfined, confined and leaky confined); *A*quifer hydraulic conductivity; ground water *L*evel a.m.s.l; *D*istance from the shore, *I*mpact of existing status of SWI in the area; and *T*hickness of the aquifer" (Paulo et al. , 2005). This technique is relatively new and has been applied in porous coastal aquifers only. However, GALDIT VI has not been applied in karstic regions due to the complexity and heterogeneity of these aquifers.

This indexing method works as follows: value ranges of data are obtained after field measurements, then ratings will be given on a vulnerability ranking scale between 2.5 and 10 (10 being the most vulnerable) and weights will be assigned for each parameter/indicator (more details can be found in Appendix 2). Finally, according to Chachadi & Lobo Ferreira (2005), GALDIT VI is calculated by:

Equation 4.1 $$\textbf{GALDIT VI} = \frac{(\boldsymbol{W_1 \times G + W_2 \times A + W_3 \times L + W_4 \times D + W_5 \times I + W_6 \times T})}{\boldsymbol{\sum_1^6 W_i}}$$

Equation 4.2 $$\textbf{GALDIT VI} = \frac{(\boldsymbol{1 \times G + 3 \times A + 4 \times L + 4 \times D + 1 \times I + 2 \times T})}{\boldsymbol{15}}$$

The importance of parameters in assessing vulnerability to SWI:

Choosing suitable parameters/indicators that would have a negative or positive effect on the assessment and would give reliable vulnerability results, is a very delicate task. For example, if one considers saltwater density, it wouldn't be a good indicator, since it is a known constant that will not affect vulnerability. Therefore, a suitable indicator should be one that varies depending on the study area and that would influence the present state of vulnerability when it varies. The parameters chosen by Chachadi & Lobo Ferreira, (2005) to come up with the GALDIT indexing method, are explained by the following reasoning:

- *G*roundwater occurrence (*G*): Although a confined aquifer is more protected from SWI than an unconfined aquifer (due to a sealing impermeable layer), the larger cone of depression around the well, due to high confining pressure, makes it more prone to SWI. Accordingly, a confined aquifer will have a higher vulnerability (10) than an unconfined aquifer (7.5) (Paulo et al., 2005).

- *A*quifer hydraulic conductivity (*A*): It is a measure (in m/day) of the ability of water to flow in an aquifer. The higher the conductivity, the higher is the probability of sea water to flow inland. In other words, a high aquifer hydraulic conductivity suggests a high vulnerability (Chachadi & Lobo Ferreira, 2005).
- Groundwater level a.m.s.l (*L*): This parameter is essential for evaluating SWI because it is a measure of the hydraulic pressure that contributes in inhibiting the entrance of sea water. In fact, as explained earlier, Equation 1.2 demonstrates that for every 1 m of freshwater above sea level, there is 40 m of freshwater below sea level. At this level the freshwater- saltwater interface is found. In other words, this indicates that a sea level rise will result in less freshwater below sea level, leading to a decrease in hydraulic pressure and a higher vulnerability to SWI.
- *D*istance from shore (*D*): This parameter might be the easiest to compute. In fact, it indicates the perpendicular distance from the shoreline moving inland. It is naturally known that the farther one moves from the shoreline, the less impact from sea water there is. Therefore, the closer an area it is to the shoreline, the more vulnerable it is to SWI.
- *I*mpact of existing status of SWI (*I*): If the area under study is already affected by SWI, this parameter is very important to consider. The ratio of [Cl-] / [HCO3-1 + CO32-], called Revelle coefficient, is proposed by Chachadi & Lobo Ferreira (2005) as a criterion that determines the parameter I. In fact, chloride concentration is high in sea water and negligible in freshwater, while bicarbonate varies inversely. Therefore, the higher the ratio the more vulnerable is the aquifer.
- *T*hickness of aquifer (*T*): this parameter refers to the total thickness for a confined aquifer, and the water saturated thickness of an unconfined aquifer. It was proven by Chachadi & Lobo Ferreira (2005) that the thicker an aquifer is, the more vulnerable it is to SWI.

Being the only VI method that studies SWI, GALDIT VI will be tested in the study areas with the aid of GIS tools.

2.5 Geographic Information System (GIS)

Geographic Information System (GIS) is "the go-to technology"(Esri, n.d.) that allows the user to store spatial data in a structured and managed form (using a database), to manage and retrieve that data easily. By retrieving the spatial data, the user can visualize it, and perform different spatial analysis techniques that enable her/him to produce maps or other outputs. Thirteen open sources free GIS exist including Quantum GIS (QGIS) and Grass GIS (GISGeography, 2017). However, commercial GIS, such as ESRI's product ArcGIS, are more popular in the industries and professions relying on that technology. ArcGIS is formed from ArcCatalogue, where the data is stored, and ArcMap the interface where the data can be visualized. This latter is the main platform used in this study due to its developed spatial analysis tools and its well established support system in case of system failure (Dempsey, 2012). The data collected is stored in a structured database, and is retrieved from ArcCatalogue. Thematic maps are then produced to visualize the spatial distribution of the different parameters. These maps will be the input to generate a final vulnerability index map by using raster calculator and spatial analysis tools. Raster calculations assist in the computation of the vulnerability index by adding the different criteria weights that were used, in order to generate final vulnerability maps. Spatial analysis tools, such as classification, rasterization, interpolation, etc. enable the detection of the most significant parameters interfering and the delineation of the most vulnerable areas.

3 Research objectives and questions

Different approaches exist to assess vulnerability such as AVI, DRASTIC, EPIK, and more modified indexing methodologies (Luoma et al., 2016). However, AVI only focuses on the intrinsic vulnerability of sedimentary basins, whereas EPIK and DRASTIC are concerned with vulnerability of aquifers against diffuse and concentrated contamination. GALDIT is the only VI method developed to assess vulnerability of coastal aquifers to SWI. The closest application of GALDIT VI to Lebanon, on the Mediterranean Sea, is in Northern-East Greece. This method was several times successfully applied on the Greek coast, to assess the vulnerability of typical Mediterranean alluvial (porous) aquifers.

Nevertheless, GALDIT VI has not been tested yet on karstic aquifers. In fact, no indexing method has been developed so far to assess vulnerability to SWI in karstic aquifers. Actually, the challenge is choosing appropriate indicators suitable for the complex hydrogeological setting.

Therefore, the general aims of this study are to:

- Compare the results of GALDIT VI, successfully applied on the alluvial coastal aquifer of Northern-East Greece, to the results returned by a different alluvial coastal aquifer in the Mediterranean region.

- Assess the sensitivity of the key parameters in the mapping of vulnerability to SWI

- Evaluate the feasibility of GALDIT VI on a karstic aquifer.
- Propose modifications to GALDIT VI to suit the study areas and overcome the limitations of the parameters

The specific objectives, respectively to each aim, are to:

- Adapt the same criterions of GALDIT VI used in the study case of the alluvial aquifer in Northern-East Greece, to Akkar alluvial aquifer in Lebanon, using ArcGIS tools.
- Visualize the evolution of SWI through time and its impact on vulnerability.
- Identify the parameter(s) contributing to the highly vulnerable part of the aquifer and compare with the results obtained in Northern-East Greece.
- Adapt also GALDIT VI to Ghadir karstic aquifer, assuming it is equivalent to a porous medium.
- Evaluate GALDIT VI applicability in general.
- Discuss the limitations of the unmodified GALDIT VI in karstic aquifers due to the unsatisfying parameters used.
- Propose modifications to GALDIT VI parameters to suit the hydrogeological conditions. This can be achieved by evaluating the specific properties of the aquifers that interfere in vulnerability assessment or by studying hydrogeological controls present in the region (faults and folds).

The following research questions will be answered:

- Is GALDIT VI a consistent method to evaluate the most vulnerable areas in a Mediterranean alluvial aquifer?
- Can the evolution of SWI be detected by GALDIT VI?
- Does GALDIT VI return reliable results in a karstic environment?
- How can GALDIT VI methodology be modified to give the best results for each study area?

4 Study area

4.1 Geographical setting

Lebanon is located at approximately 34°50’N 35°50’E. The coast of Lebanon extends on the eastern part of the Mediterranean Sea. It runs for approximately 220 km from North to South, with a narrow width of around 3 km. This region is bound from the East by a range of mountains called “Mount Lebanon”.

Lebanon is characterized by a Mediterranean climate, having relatively warm, dry summers and slightly cold, but wet winters.

For the purpose of this study, two pilot areas are chosen on the coast of Lebanon.

Akkar alluvial plain, located in the Northern part, and Ghadir karstic basin in the Central part of the coast, near Beirut (Figure 3).

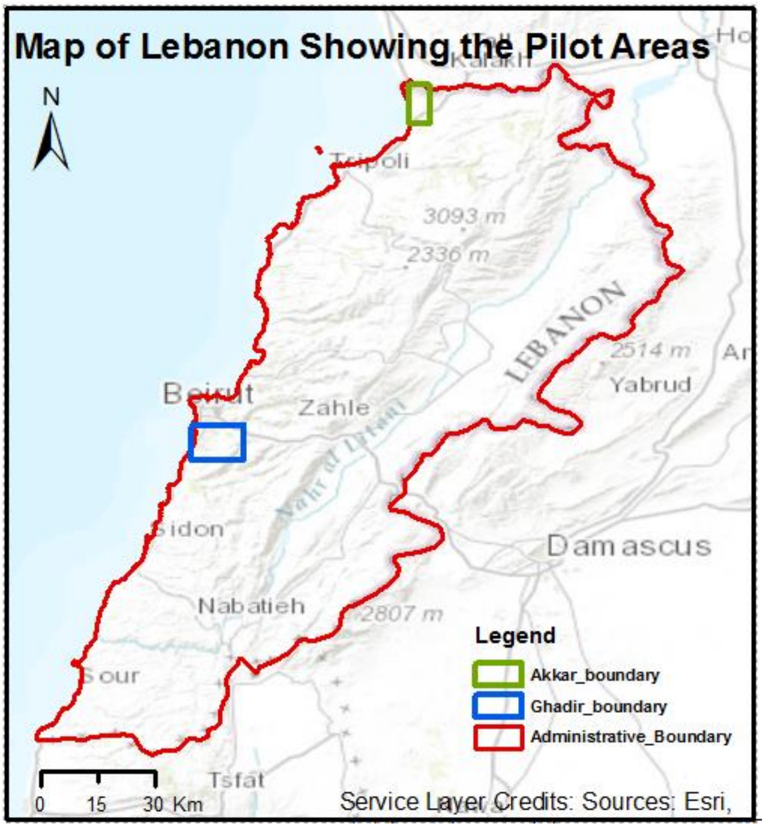

Figure 3: Map locating Lebanon and the pilot areas of this study.

Figure 4: Akkar plain in direct contact with the sea.

Akkar alluvial plain (Figure 4) is the largest plain located on the coast of Lebanon, highly important for its agricultural uses (ranked second in Lebanon). This plain is bound from the West by the Mediterranean Sea, and from the East by high mountains (El-Osmani et al., 2014). It extends around 136.75 Km^2, with a nearly flat topography varying from 0 to 7m asl at 1km from the coastline (FAO, 1997).

Ghadir aquifer system, which is constituted of different aquifers, extends beyond the Ghadir River surface water basin. Actually, surface water flow might differ from groundwater flow especially in fractured aquifers. Ghadir area lies on altitudes varying between 0 m a.m.s.l at the coast and 950 m a.m.s.l in the east.
For the purpose of this study, only the karstic aquifer of Ghadir, in direct contact with the sea, will only be considered.

4.2 Geological and structural setting

Lebanon is mostly formed of sedimentary rocks, which are dominated by carbonate. The lithostratigraphy of the coast extends from Mid-Cretaceous up to the Quaternary (Walley, 1997) (Appendix 4).

The pilot area of Akkar is mostly located on Quaternary unconsolidated porous alluvial deposits. The area comprises Quaternary marine and continental deposits overlying Pliocene and Miocene limestone blocks, marl, clay and gypsum, deposited horizontally (FAO, 1970).

In the pilot area of Ghadir, the Sannine formation (C4), of karstic nature is the major formation which has an important hydrogeological significance in the region. This rock sequence is of Cenomanian age (Walley, 1997), reaches a thickness of 660-700 m if not eroded (Elezian, 1985), and is made up of a thick and monotonous succession of carbonate rocks. C4 forms a block of three members that are overlaid by recent deposits along the coast. These members were named from oldest to youngest C4a, C4b and C4c respectively by Saint Marc, (1974), Walley, 1997 and Khadra, 2003. Appendix 4 shows the members in sequence, belonging to the Cenomanian age. The subunits C4a, C4b are 220 m and 180 m thick respectively. C4 strata are dipping towards the North-West at varying dipping angles between 0º and 52º (Figure 5).

The coast of Lebanon is affected by major structures that have disturbed its geology. According to Walley (1997), Mount Lebanon Anticline resulted in the dipping of the coastal strata towards the sea. In addition, many secondary faults running NE-SW and E-W have contributed in the disturbance of the geological sequence. In the Northern part of the coast, near Akkar alluvial plain, minor anticlinorium and synclinorium are also found along with a major fault called “Akkar fault”. In the Central part, including Ghadir study area, deformation is accommodated partly by two fault systems. The first consists of E-W to ENE-WSW striking structures while the second consists of lower order NW-SE striking ones (Figure 6) (Doummar et. al, 2015).

The structures found such as faulting and folding can form barriers or conduits for either groundwater recharge or SWI.

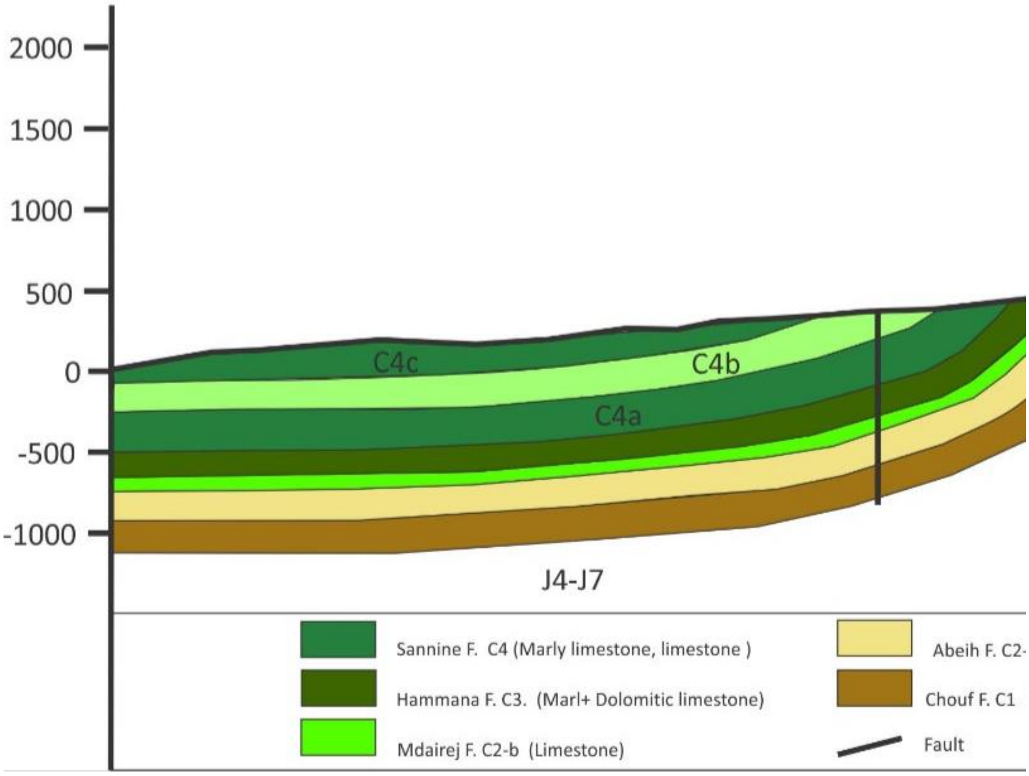

Figure 5: A W-E cross section, where the shoreline is on the West. The cross section shows the C4 members dipping towards the sea (Doummar et. Al, 2015; technical report).

4.3 Hydrogeological setting

There are four aquifers found on the coastal stretch of Lebanon going from Mid-Cretaceous to the Quaternary period (Appendix 4). This study focuses on the Cenomanian karstic aquifer and on the Quaternary porous aquifer.

4.3.1 Akkar hydrogeological setting

Three groundwater aquifers are distinguished under the Akkar plain (FAO, 1970). Being the only exploitable aquifer, the shallow Quaternary aquifer, consisting mainly of sand and clay deposits, will be studied. The boundaries of the studied aquifer are defined from the North by the national Lebanese boundary, from the West by the Mediterranean Sea and from the East by a volcanic layer creating a no-flow boundary.

This alluvial aquifer is the major porous aquifer of the Lebanese coast. It serves for irrigating the Akkar plain, and therefore has a great economic significance. Consequently, maintaining the water quality of this aquifer is vital.

4.3.2 Ghadir hydrogeological setting

Groundwater aquifers range from Mid-Cretaceous to Quaternary in this pilot area (Doummar et. al, 2015) (Figure 6). As mentioned earlier, the coastal karstic aquifer C4, which happens to be the largest, will be studied. The hydrogeological setting of C4 is more complex than Akkar. Ghadir karstic aquifer is chosen to depict the geological and structural complexities encountered in assessing karstic systems.

Characterized by a significant secondary porosity (fissured matrix and dissolution fractures), the upper and lower members of the Sannine Formation (C4c and C4a) are considered karst aquifers (Khadra 2003). The middle member (C4b) has a low permeability and therefore acts as an aquiclude, separating both aquifers (Khadra, 2003).

It should be noted that C4a (oldest Sannine/Cenomanian unit) is overlain by the marly C4b subunit and underlain by the impervious Hammana Formation (C3), therefore it can be considered a confined aquifer except in its recharge areas (Appendix 4).

However, C4a cannot be studied due to its unattainable depth at which it is located. Therefore, C4c will be the karstic aquifer under study.

The complexity of the geology and the structural settings play a major role not only in recharge but also in regulating the relationship between saltwater from the sea and freshwater aquifers. The structures found contribute either in enhancing water flow, or restricting it and have to be considered when dealing with vulnerability. For instance, The Northern boundary of C4c is defined by a sealing fault that constitutes a no flow boundary and makes this aquifer isolated. Furthermore, folding has resulted in the exposure of C4b on the Eastern part of the C4c aquifer forming a no flow boundary (Figure 6).

For the purpose of this study, the continuum approach is used. The highly fractured aquifer is considered EPM (Ford & Williams, 2007).

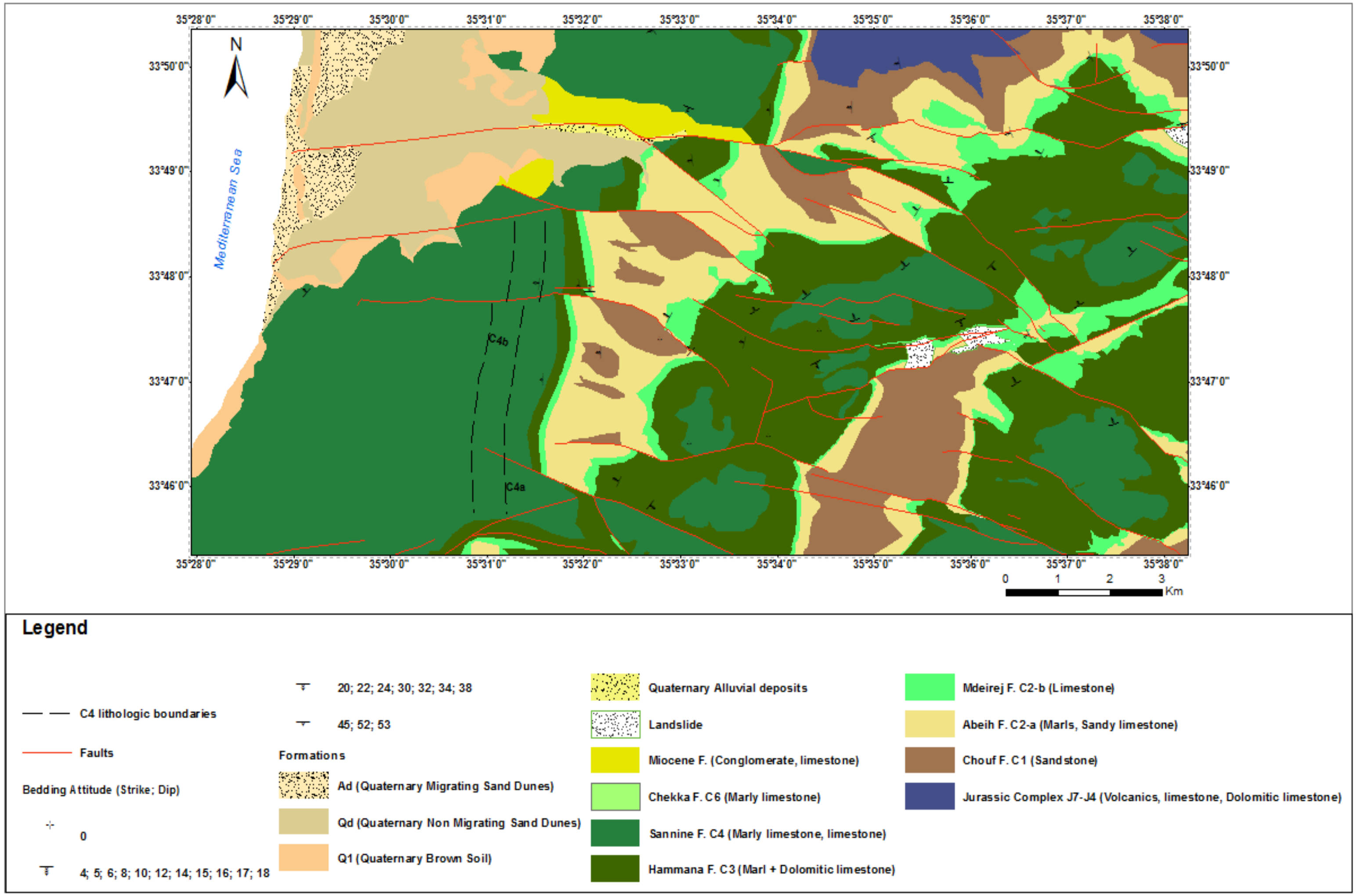

Figure 6: Ghadir area. The complexity can be seen from the different formations present, the change in dip and the faults present (data source from Doummar et. al, 2015).

5 Methods and materials

5.1 Overview

In this section, GALDIT VI will be applied on both pilot areas (Akkar and Ghadir) in order to assess its validity on Mediterranean porous aquifers and to identify limitations in assessing vulnerability to SWI in Ghadir C4c karstic aquifer.

As mentioned earlier, it has been very popular on the Greek coast, more precisely, in Northern-East Greece (Appendix 1 shows the location), where sand and alluvial deposits prevail. Two GALDIT VI applications were conducted in this area by Recinos et al. (2013) and Pedreira et al. (2014), on two typical porous aquifers. *D* and *I* have been modified in these studies to suit the existing conditions of the area. In fact, *D* uses different ranges to assign ratings, whereas *I* uses chloride data instead of Revelle coefficient. Moreover, the study done in 2013 considers the time factor as well by studying the change in vulnerability between 1992 and 2004.

GALDIT VI parameters and ratings will be adapted from the Greek study case of Recinos et al. (2013), sharing similar morphological, geological and hydrogeological conditions with Akkar coastal plain. In fact, the Greek study area is a plain located on the Mediterranean Sea and consists of a shallow Quaternary aquifer (30 to 110 m thick) used for irrigation purposes. Hence, the applicability of GALDIT VI through time, on another Quaternary aquifer in the Mediterranean region (Akkar, Lebanon), will be explored. Moreover, the sensitivity of GALDIT VI to the change in the *I* parameter between 1969 and 2013 will be tested. Also, GALDIT VI has not been used in any karstic environment. Therefore, its limitations will be evaluated on Ghadir C4c karstic aquifer to be able afterwards to evaluate this VI method and outline more significant parameters and propose modifications.

5.2 Workflow

The general methodology followed in this study is summarized in Figure 7. First, data collection is done (previous literature and field survey), followed by data processing that is constituted of: spatial distribution layers' generation, layers rating, computation of GALDIT VI. Finally, a discussion will be made to evaluate the applied methodology and its results. Each step of this workflow will be thoroughly described in the following sections.

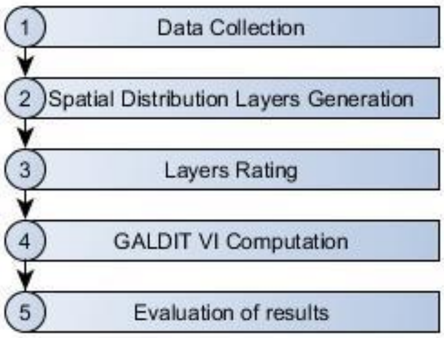

Figure 7: The general workflow adapted in this study.

5.2.1 Data collection

The first step in the GALDIT VI is to collect data characterizing the indicators/parameters used for this method. Most of the data needed were collected from previous studies on the pilot areas from 1969 until present.

- **Data for Akkar**

For Akkar Quaternary aquifer, a number of studies are found dating back to 1969 and 1970, where the hydrogeological conditions of the aquifer are described in detail by Chapond & Guerre (1970) . A more recent, general study, has been done also on this aquifer by UNDP (2014), where the groundwater *L*evel change is assessed between 1969 and 2013 and the salinity measurements were done on public wells in the area.

It should be noted that using available data from 1969 is not a problem for this kind of study, since four of GALDIT VI parameters describe the intrinsic properties of an aquifer, which will not change without the interference of external stresses. In fact, *G*, *A*, *D* and *T* are "static" parameters, considered unchangeable through time. However, *I* and *L* are "dynamic" parameters, always changing due to external factors, and need to be monitored through time (Recinos et al., 2013). Data for *L* are found in the UNDP study (2014). It was shown in this study that the water level has not changed significantly between 1969 and 2013 since a decrease in freshwater is compensated by sea water intrusion (UNDP, 2014). Therefore, only the change in the *I* parameter between 1969 and 2013, should be taken into consideration.

The data collected and the field methods used in previous studies to get the data are summarized in Table 1.

Table 1:Summary of the data and field methods needed to compute GALDIT VI for Akkar porous aquifer.

Porous Aquifer-Akkar		
GALDIT parameters	**Data available**	**Field methods used in litterature**
Ground water occurrence	Unconsolidated Quaternary deposits, unconfined shallow aquifer (FAO, 1970)	Lithological study from well samples
Aquifer hydraulic conductivity	Kh (m/day) =T/Ds with T: transmissivity (m2/day) and Ds: saturated thickness of the aquifer (m) spatial distribution maps: Paper map "Carte des transmissivites" (FAO,1970) and interval thicknesses map: paper map "Epaisseur de la nappe" (FAO,1970)	Pumping tests
Depth to Water Level	Contour lines for Water level: Paper map "carte des profondeurs jusqu'a l'eau" (FAO, 1970), (UNDP, 2014)	Water level meter and piezometer pipe
Distance from shore	Topographic map of Akkar plain	Measuring distance using topographic map
Impact of current SWI	TDS= 1.8066 [Cl-] (Johnson et al., 2017) SWI Classified map showing the variation in salinity under normal conditions: Digitized map "Chimie des eaux souterraines" (FAO, 1970) Salinity (TDS) measurements in 2013 (UNDP,2014)	TDS measurements on well samples
Aquifer thickness	Map of interval thicknesses: paper map "Epaisseur de la nappe" (FAO,1970)	Well measurements+ cross section showing the dip of the strata to be able to interpolate

Data for Ghadir

The major part of the data needed is retrieved from a previous study done in 2015 (Doummar et. al, 2015).

The maps and cross sections delivered with the report give information about *G*roundwater occurrence, *D*istance from shore and aquifer *T*hickness. Only one transmissivity (*T*) of 6x10^{-4} m^2/s is reported for Sannine Formation based on the analysis of pumping tests conducted on 12 wells tapping in the Sannine Aquifer in the vicinity of the study area (UNDP, 1970).

The number of wells used to study the chemistry of the groundwater in 2013 is not enough to interpolate for the entire study area. Therefore, a field survey was conducted within 1 km from the shoreline to collect more water samples in order to evaluate the current *I*mpact of SWI. 6 water samples were collected and their ECs were measured. [Cl$^-$] is then deduced according to equations 2 and 3. Groundwater *L*evel is derived from Ukaily (1971) water contour map for Ghadir, assuming that water level does not change significantly (UNDP, 2014).

5.2.2 Spatial distribution layers

The data collected in numerical or nominal values is spatially distributed using GIS in this step. Each dataset is a criterion that quantifies a certain parameter of GALDIT VI in space. The spatial distribution of these datasets will be visualized through the generation of thematic layers.

- **Processing of Akkar aquifer data**

The data available (Table 1), which are mainly scanned paper maps have to be georeferenced and digitized to be able to manipulate and perform spatial analysis. These maps are then rasterized in order to use the raster calculator tool. Kriging interpolation is used to rasterize salinity values obtained from well observations. Kriging is chosen since it depends not only on the distance between known and unknown sampling points, but also on the degree of variation between known points used for interpolation. Practically, the degree of variation is small with sample values close to each other and becomes larger the farther the sample values are. Therefore, Kriging is most suitable for spatially correlated distances or biased data in a certain direction, as it is the case here (Ratan, 2015). The required steps explained above, needed to generate the thematic maps, are summarized in Appendix 3 (a) workflow.

It should be noted that transmissivity map and salinity map need to be converted into hydraulic conductivity map and chloride map respectively for later use. This is done by performing raster calculations (division): “Rasterized Transmissivity map” is divided by “Rasterized Aquifer Thickness map” to get the hydraulic conductivity map, and “Rasterized Salinity map” is divided by 1.8066 according to Equation 3.

- **Processing of Ghadir aquifer data**

The processing of data in this case is a combination of digitizing previous data, interpolating and integrating field data. The workflow followed is described in Appendix 3 (b). As a first step, the boundary of the aquifer is delineated from the map of Ghadir formations (Doummar et. al, 2015). Then, 6 layers are created respectively for the 6 parameters of GALDIT VI. The data collected from Doummar et al. (2015) allowed the generation of ***G*** vector map, ***T*** vector map, and transmissivity vector map. The overlay and interpolation of the water level contours from Ukaily (1971) over the study area, lead to the generation of ***L*** vector map, by dividing the aquifer polygon into water levels. The ***D*** vector map was generated by measuring distances from the shoreline and dividing the aquifer polygon according to the ranges defined by GALDIT VI in

Greece. Finally, the chloride vector map is generated by integrating point measurements of chloride concentration from field survey (Appendix 8) along with previous measurements from Doummar et. al (2015). All the vector maps are then rasterized to be able to use raster calculations at a later stage.

The same procedure applied for Akkar is followed to obtain hydraulic conductivity map from Rasterized Transmissivity map.

5.2.3 Layers rating

Each raster layer is classified into a rating system between 2.5 and 10 according to GALDIT VI rating methodology (Appendix 2), (Chachadi & Lobo Ferreira, 2005). However, a change to the theoretical numbers (Appendix 2) defined for GALDIT VI in 2005 has been made for the Greek coast, when rating *I* and *D* parameters. These modifications will be mentioned in sections discussing *I* and *D*.

- **Groundwater occurrence (*G*)**

Akkar porous aquifer and Ghadir C4c aquifer are both unconfined, therefore according to Chachadi & Lobo Ferreira (2005), this parameter is given a rate of 7.5.

- **Aquifer hydraulic conductivity (*A*)**

After using transmissivity and aquifer *T*hickness maps to get the spatial distribution of the *A*quifer hydraulic conductivity, rates between 2.5 and 10 are assigned for Akkar. Whereas, for Ghadir C4c aquifer, using the theoretical transmissivity value $6x10^{-4}$ m^2/s for Sannine formation (Doummar et. al, 2015), all the hydraulic conductivity values are below 5 m/day. The entire area is then rated 2.5.

- **Groundwater level a.m.s.l (*L*)**

In Akkar, *L* varies progressively from 0 to 10 m a.m.s.l going inland. The area where the water level is smaller than 1m scores 10 on GALDIT VI rating scale. In Ghadir, water level varies from 5 up to 200 m which give a unique rate of 2.5 for the entire aquifer.

➢ **Distance from shore (*D*)**

Theoretical distance ranges are changed in the case study of Greece. In fact, the ranges used by Chachadi & Lobo Ferreira (2005) are insignificant when applied to study areas having a width larger than 3km. The new distance ranges are determined based on a regression relationship with chloride concentration (Recinos et al., 2013), which is an indicator of SWI as explained in Section 2.4.2. The new ranges with their respective ratings are shown in Table 2. For example, when *D* < 2.5 km the area scores 10.

Table 2: Ranges and Rating modified for D parameter (adapted from Recinos et al., 2013).

Range	Rating
<2,500	10
2,500-5,000	7.5
5,000-10,000	5
>10,000	2.5

➢ **Impact of existing SWI (*I*)**

Instead of using Revelle coefficient to valorize the *I* parameter, only chloride concentration is used with ratings defined by Recinos et al. (2013). Chloride can be used on its own since it does not interact with its surrounding and acts as a conservative ion (Pedreira et al., 2014). Chloride ranges and their proper ratings are found in Table 3.

Table 6: Ranges and ratings for chloride concentration as defined by Recinos et al. (2013).

Range	Rating
>500	10
250-500	7.5
100-250	5
<100	2.5

➢ **Thickness of aquifer (*T*)**

Almost the entire aquifer of Akkar has a thickness larger than 10m, which gives it a rate of 10 on the GALDIT VI rating system, except for the Eastern periphery of the study area that has an average thickness of 5m. The Ghadir C4c has a minimum thickness 10 folds larger than the maximum thickness after which the aquifer would score 10 on the GALDIT scale.

It should be noted that the scanned maps available for Akkar (FAO, 1970) are labeled using interval data. The ranges defined by GALDIT VI for each parameter might intersect with one or more interval data when assigning a rate. To avoid this problem, averages were allocated to each interval of values where it was needed.

5.2.4 GALDIT VI computation

The formula to calculate GALDIT VI (Equation 4.2) is used. This formula gives the highest weight (4) to *L* and *T* parameters and the lowest (1) for *G* and *I*. A final vulnerability index map is generated for each pilot area by calculating the weighted average using the raster calculator tool. The general procedure of GALDIT VI generation is described in Figure 8.

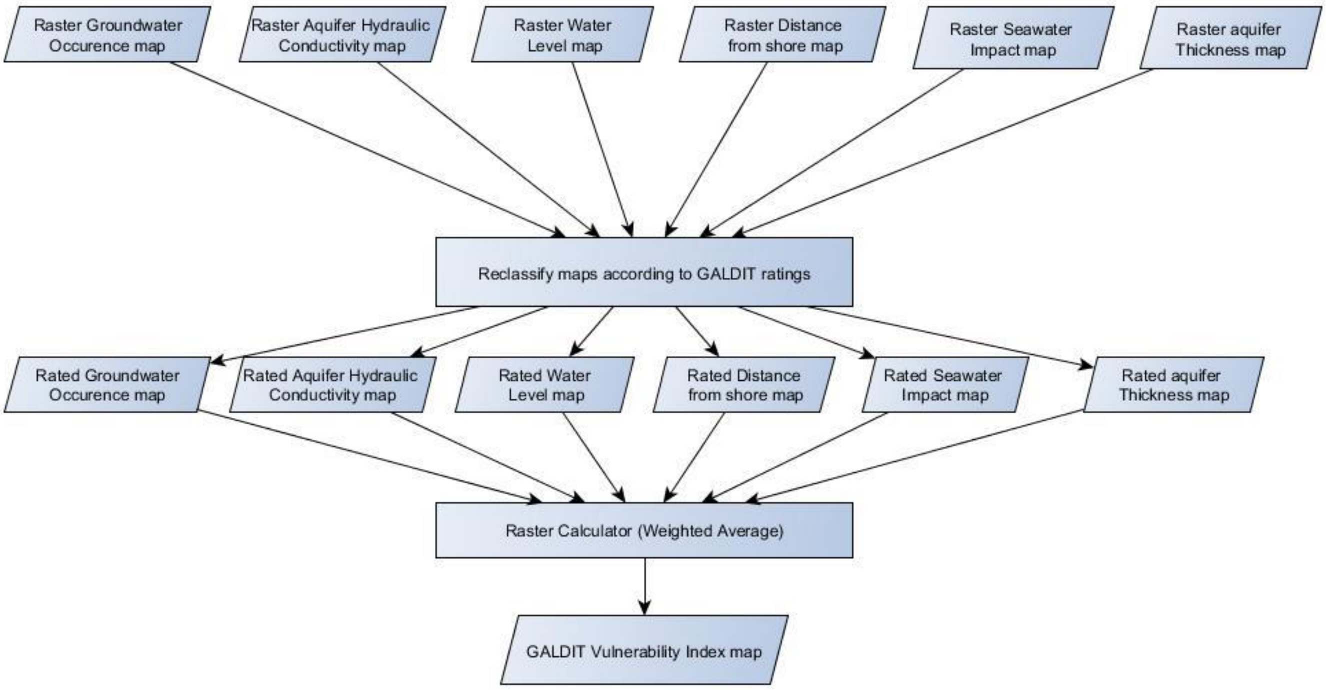

Figure 8: General workflow of GALDIT VI explaining the steps leading to the generation of GALDIT VI map, using the spatial distribution maps of the parameters as input.

The workflow shows the rasterized map produced in Section (5.2.2) as input data. These maps are reclassified by assigning ratings as explained in Section 5.2.3. The last step is the generation of GALDIT VI map through a weighted average calculation, yielding values between 2.5 and 10.

Once GALDIT VI has been derived for Akkar alluvial aquifer for the years 1969 and 2013, it is then possible to assess the change in vulnerability and its relation with the dynamic parameter *I*. To make sense out of the results obtained, a comparison can be made with the results of the alluvial aquifer, Northern-East Greece for the 1992-2004 period (Recinos et al., 2013).

6 Results

6.1 Akkar porous aquifer

6.1.1 Spatial distribution layers

After processing the scanned maps of 1969, spatial distribution maps of each parameter are obtained. The different colors in Figures 9, 10, 11 and 12 indicate different range of values given to each parameter of GALDIT VI. The most predominant variation in zonation is observed for transmissivity (Figure 9), thickness (Figure 10) and chloride concentration (Figures 11 and 12), with yellow being the lowest value and blue the highest. The closer to the shore, the higher the values, in general, for transmissivity and chloride. The dynamicity of the *I* parameter (existing *I*mpact status of SWI) can be observed by comparing Figure 11 to Figure 12. SWI can be well delineated at chloride concentration higher than 250 mg/l. The area representing values higher than 250 mg/l was in 1969 around 53.35 km^2, whereas in 2013 it expanded to 68.64 km^2. It should be noted that the effect of seasonal change is not taken into consideration. In fact, the focus is not on the change in natural SWI, but on the effect of over abstraction that increased over the years and can be shown over the period of 44 years. Appendix 7 shows the minor change in chloride concentration values between February and August 2013, which is explained by seasonal change. The variation in thickness (Figure 10) does not follow a specific trend, however, the aquifer becomes much thinner at its Eastern boundary reaching 5 m.

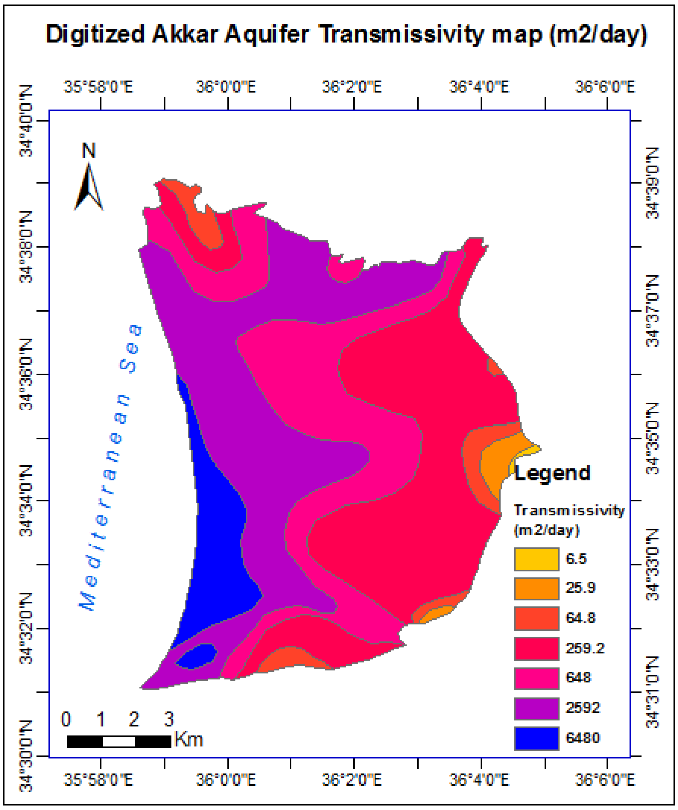

Figure 9: Transmissivity variation in Akkar aquifer. Digitized from FAO (1970).

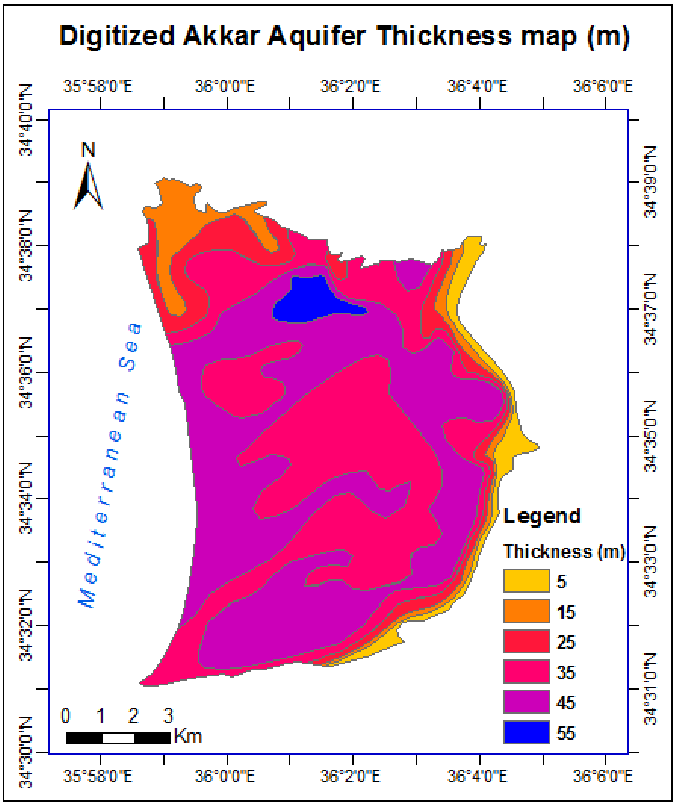

Figure 10: Aquifer Thickness variation of Akkar. Digitized from FAO (1970).

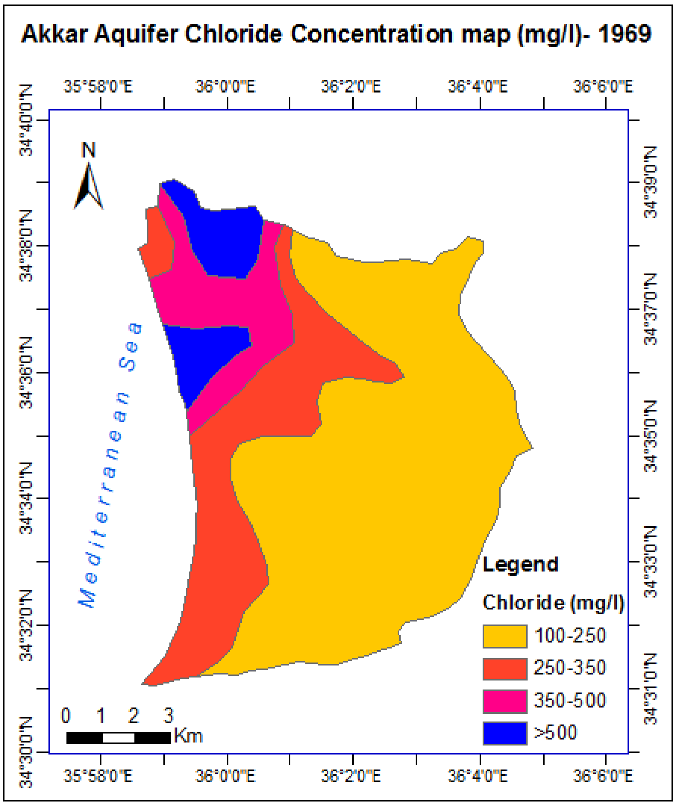

Figure 11: Variation of chloride concentration in Akkar aquifer for 1969. The highest values are found close to the shore (Digitized from FAO, 1970).

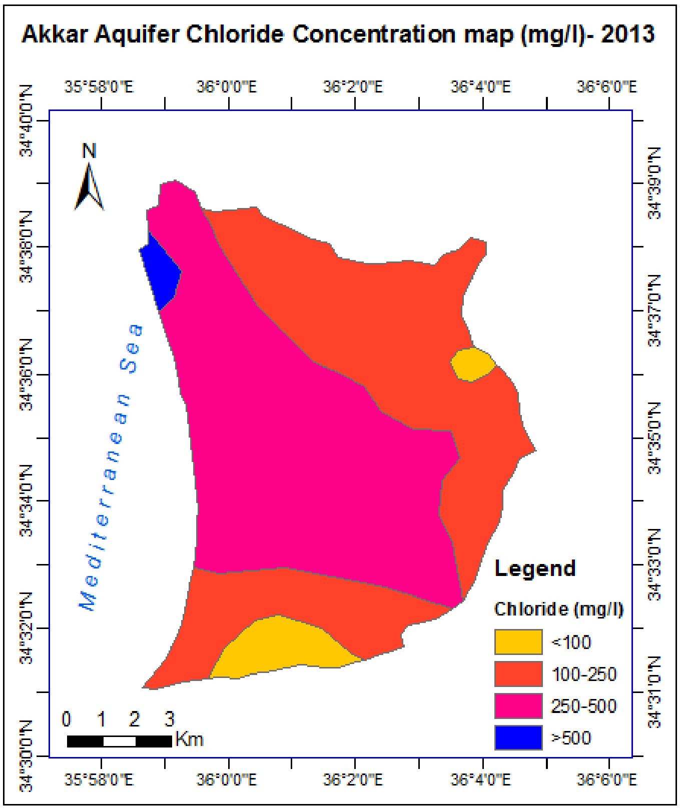

Figure 12: Variation of chloride concentration in Akkar aquifer for 2013. The highest values are found close to the shore (Digitized from UNDP,2014).

6.1.2 Rated layers

In this section the results are shown after classification of the ranges into ratings. Figures 13, 14, 15, 16, 17 and 18 show the highly vulnerable areas (rated 10) in red, and the least vulnerable (rated 2.5) in dark green.

Figure 13 representing the rated map of the hydraulic conductivity is derived from Figures 9 and 10 (as explained in Section 5.2.2). According to this map, *A* (*A*quifer hydraulic conductivity) scores the lowest near the shore and increases when going inland. Figure 14 shows that *L* (groundwater *L*evel a.m.s.l) has a low rating for most of the aquifer. Only a small part along the coastal stretch scores 10. Figure 15 is obtained after dividing ranges of distances and creating parallel contours to the shoreline. The closer the range of distance is to the shore the higher the rating for *D* (*D*istance from shore) is. Figure 16 and 17 representing *I* rated maps for 1969 and 2013 respectively show a major contrast between the area rating 7.5 and the one rating 5. From 1969 to 2013 the area rating 7.5 became larger (expanding inland), whereas the area rating 5 became smaller. The other minor changes are out of the scope of this study and can be due to seasonal change or local external impact. Figure 18 shows that T (aquifer *T*hickness) scores 10 for the entire aquifer except for the thinnest part scoring 5.

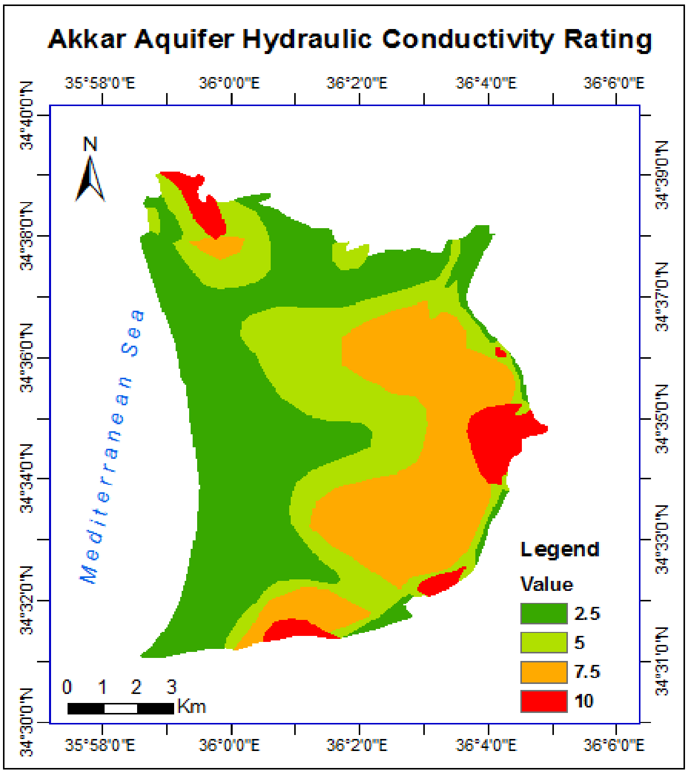

Figure 13: *A* parameter map of Akkar aquifer. This map is produced after the division of Transmissivity values (Figure 9) by the Thickness of the aquifer (Figure 10) and then classifying the map according to GALDT VI.

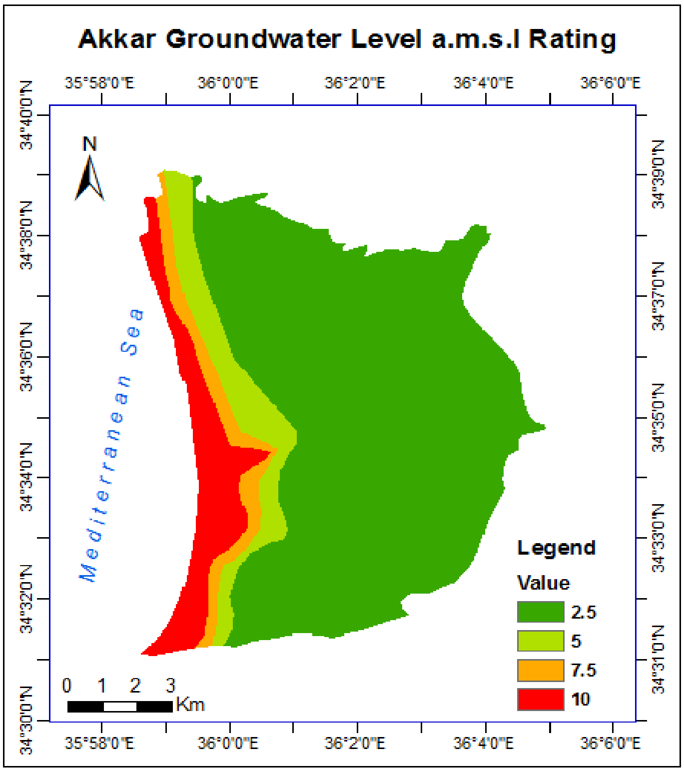

Figure 14: *L* parameter map of Akkar aquifer. This map is classified according to GALDIT VI rating system after digitizing the water level contours from FAO (1970).

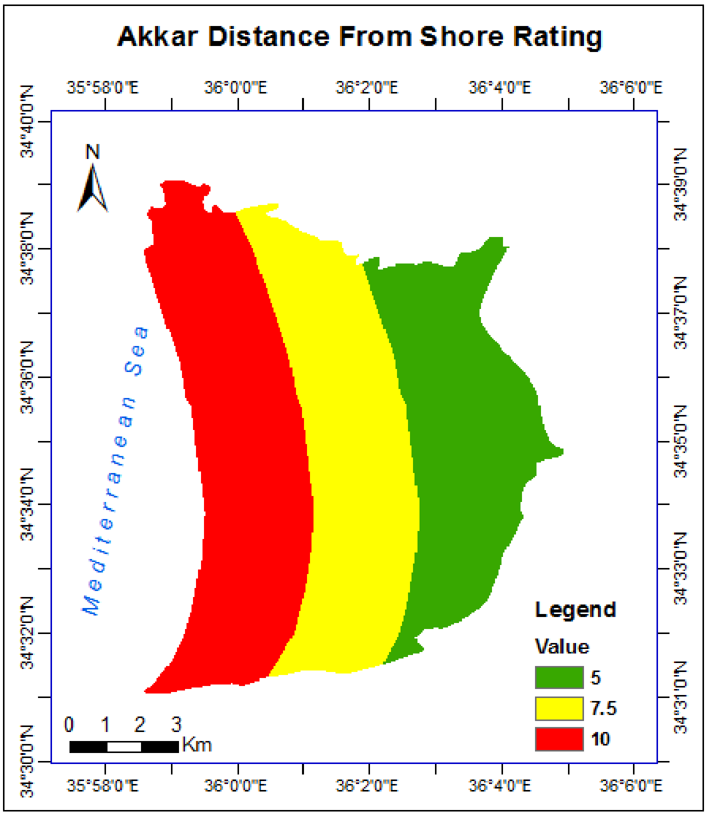

Figure 15: D parameter map of Akkar aquifer. This map is generated after defining the ranges of distances measured from shoreline. The classification is according to GALDIT VI rating system.

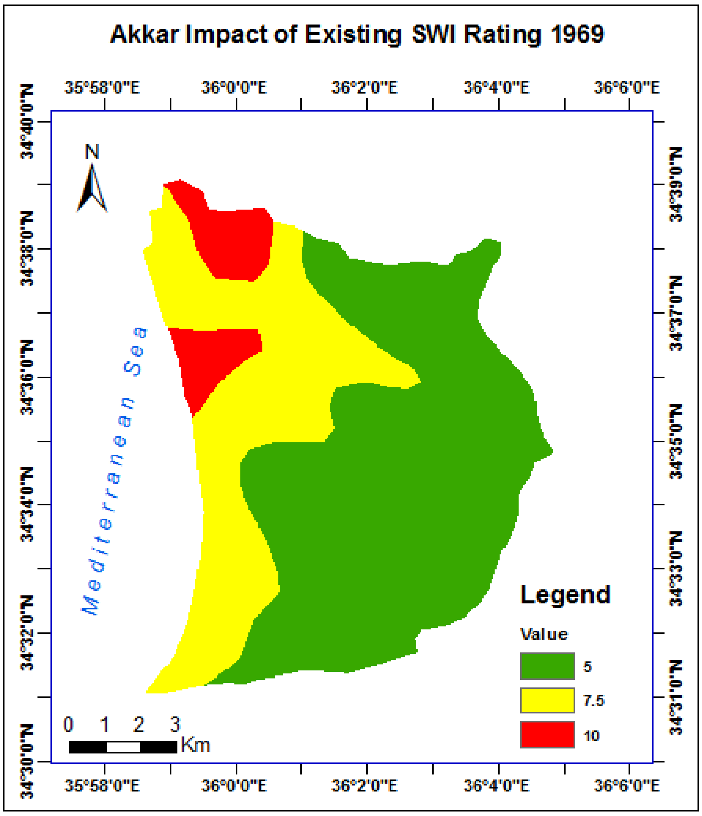

Figure 16: I parameter map of Akkar aquifer for 1969. The map is produced by classifying Figure 11 according to GALDIT VI rating system.

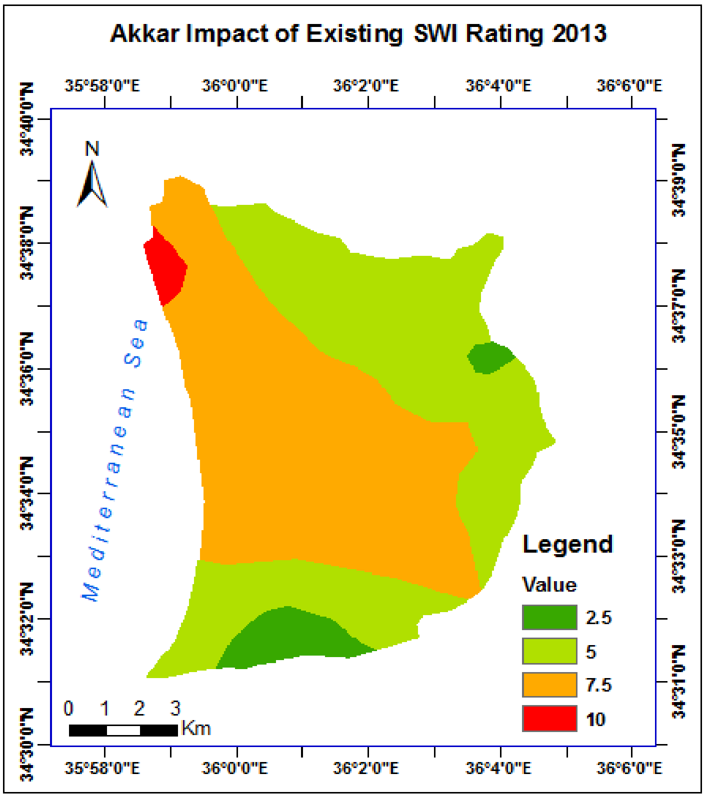

Figure 17: I parameter map for Akkar aquifer of 2013. The map is produced by classifying Figure 12 according to GALDIT VI rating system.

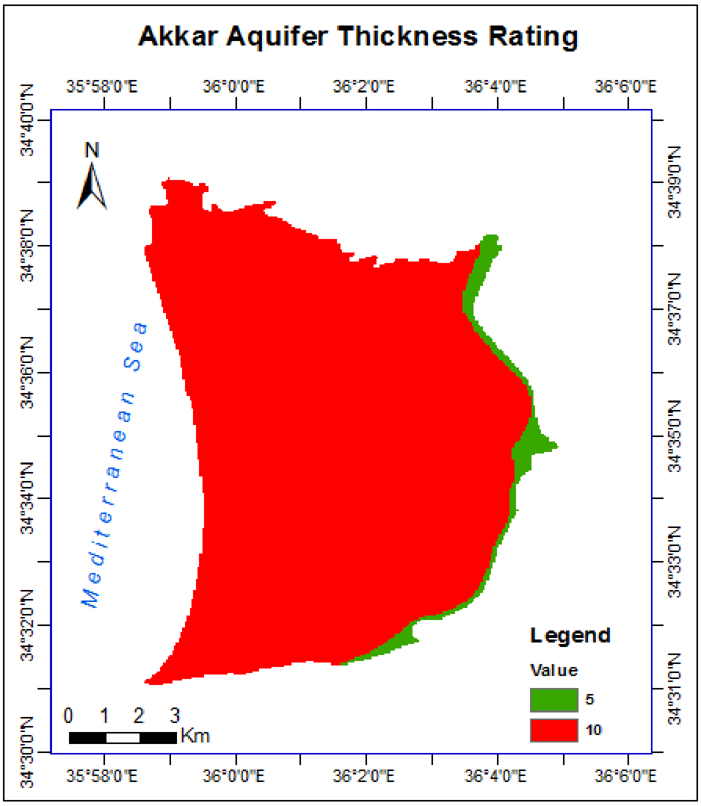

Figure 18: T parameter map for Akkar aquifer. The map is produced by classifying Figure 10 according to GALDIT VI rating system.

6.1.3 GALDIT VI map

Computing GALDIT VI for 1969 and 2013 periods was realized by only updating the *I* parameter.

The results obtained for GALDIT VI 1969 and 2013 are almost identical. The maps are shown in Figure 19 and Figure 20 respectively. The spatial variation of vulnerability can be observed in these latter. In fact, for 1969, the values vary from 3.3 to 9.2 from East to West. For 2013, the values vary from 3.1 to 9. The highly vulnerable area is within 2 km from the shoreline.

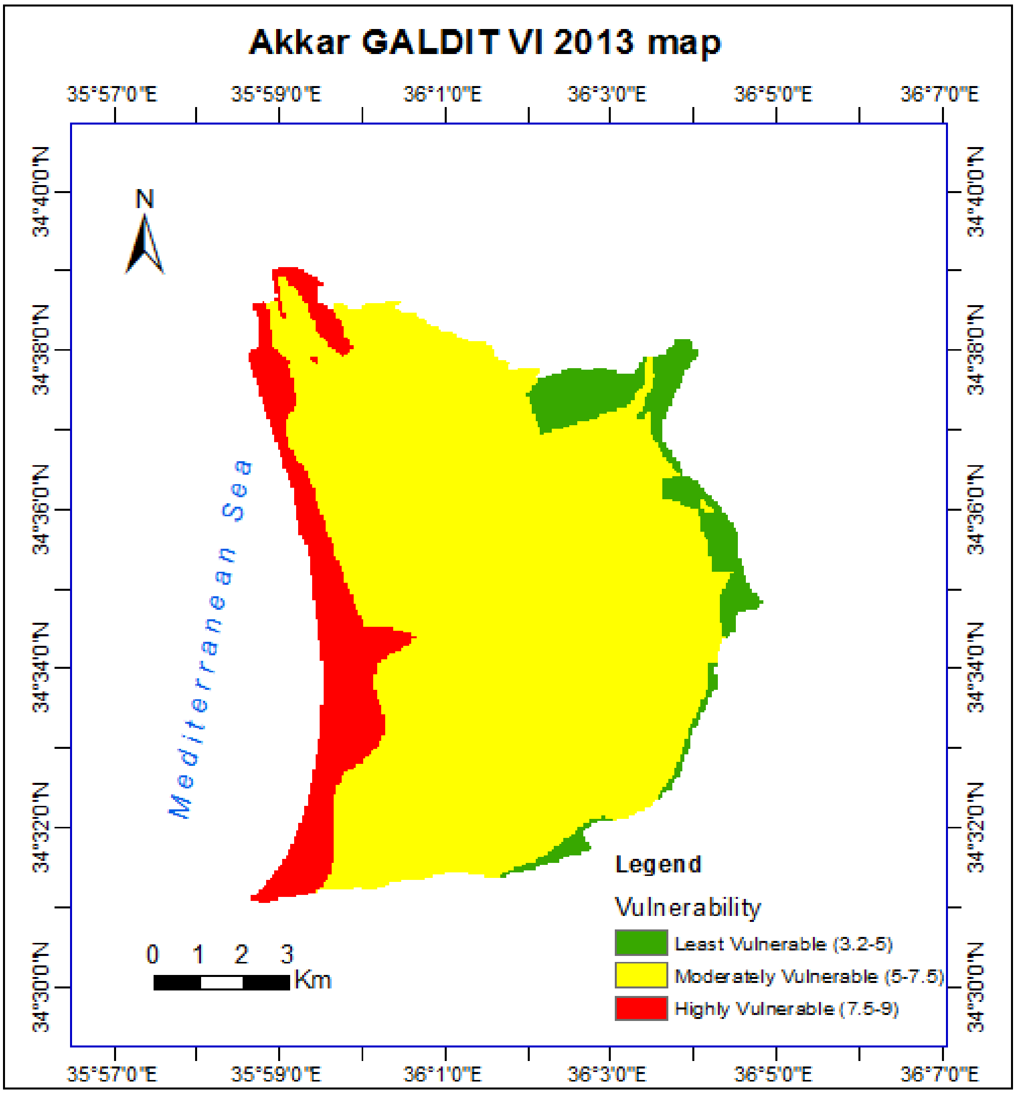

Figure 20: GALDIT VI map for Akkar porous aquifer-2013. This map is produced by using the previous rated maps that apply for the year 2013 and implementing Equation 4.2. Least vulnerable areas are shown in green, moderately vulnerable in yellow and highly vulnerable in red.

6.2 Ghadir C4c karstic aquifer

6.2.1 Fieldwork results

The 6 samples collected from wells tapping the C4c aquifer of Ghadir, within 1 km from the shoreline, have high chloride concentrations (Appendix 8). These values contribute to a better interpolation (using kriging) of the ***I*** parameter by integrating them with the values collected from Doummar et al., 2015.

6.2.2 GALDIT VI results

After gathering all the data needed, digitizing spatial distribution layers and rating them, the final vulnerability map was generated for Ghadir C4c aquifer. However, most of the values found for each parameter of GALDIT VI are out of range (either too high or too low). For instance, the thickness of C4c aquifer varies from 100 to 250 m (In Doummar et al., 2015). Comparing this range of values to the range of thickness values proposed by GALDIT VI (Appendix 2), the entire aquifer is then classified as ”> 10 m”. Therefore, the variation from 100 to 250 m (10 folds larger than the range defined by GALDIT VI) can not be perceived when the map is rated. Actually, the entire aquifer scores 10 according to the rating system defined (Appendix 2).

This being said, most of the rated maps do not show a significant spatial variation when classified (Appendix 5). An exception is observed for <u>D</u> (<u>D</u>istance from shore), where variation can be perceived due to the modified ranges used from Pedreira et al. (2014) (Appendix 5 c). The methodology followed lead to the below VI map (Figure 21). According to Figure 21, the entire study area is classified as moderately vulnerable, having a varying score between 5.5 and 6.3.

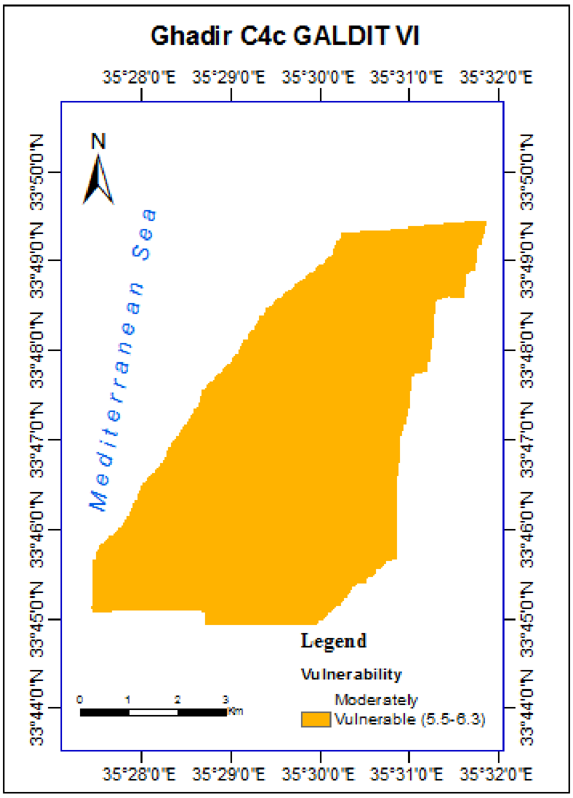

Figure 21: GALDIT VI map for Ghadir C4c aquifer that shows the entire aquifer classified as Moderately Vulnerable.

7 Discussion

In this section, the limitations of the data will be stated and the results will be interpreted relative to each study area. The advantages and limitations of GALDIT VI will be discussed as well.

7.1 Data quality

Quality issues found are related to accuracy, accessibility, completeness and validity. All data used for this study have some degree of inaccuracy mainly due to instrumental noise of field measurements, theoretical equation applied on raw data (Equation 2 and 3) and limitation in digitizing. However, when dealing with qualitative, low resolution methodologies such as GALDIT VI, these inaccuracies are expected to have a low impact on the outcome. In fact, GALDIT VI uses theoretical interval values to classify the observed values into ratings, which gives a certain margin for measurement errors. Therefore, most of the inaccuracies will be damped when the classification is done.

Accessibility, completeness and validity are mainly an issue when applying GALDIT VI to Ghadir C4c aquifer. For example, the transmissivity values needed to compute the <u>*A*</u> parameter are not accessible, thus a theoretical value was used for the entire aquifer. Moreover, water level contours from Ukayli, 1971, used to classify the <u>*L*</u> parameter, do not cover the entire study area. Therefore, interpolation of the contours was needed which also affects the accuracy of the results. Finally, some of the data used for Ghadir C4c appeared to be out of range when compared to the ranges specified by GALDIT VI (data validity problem). For example, the thickness of C4c is more than 100m which is far beyond the few meters considered by GALDIT VI. These data quality issues found for Ghadir C4c aquifer have resulted in an inconclusive final VI map. The quality of the result will be explored in Section 7.3.2.

7.2 General evaluation of GALDIT VI

The vulnerability of an area is not dependent on one parameter only. In fact, in the below matrix (Table 4) the ratings of the first 3 parameters, having different weights(between 1 and 4), were changed separately while fixing all other parameters at 2.5. This sensitivity analysis has revealed a low vulnerability for the final result when only one parameter is varying. Therefore, in order to detect vulnerable areas using GALDIT VI, two or more parameters should be varied simultaneously. The variation of <u>*L*</u>, <u>*D*</u> and <u>*T*</u> is the most important, due to their high weight. It should be noted that the variation of these parameters should be high enough to lead to a variation in their ratings.

Weights							
1	3	4	4	1	2	/15	
Parameters							
G	A	L	D	I	T	GALDIT VI	
2.5	2.5	2.5	2.5	2.5	2.5	2.5	Low Vulnerability
5	2.5	2.5	2.5	2.5	2.5	2.7	
7.5	2.5	2.5	2.5	2.5	2.5	2.8	
10	2.5	2.5	2.5	2.5	2.5	3	
2.5	5	2.5	2.5	2.5	2.5	3	
2.5	7.5	2.5	2.5	2.5	2.5	3.5	
2.5	10	2.5	2.5	2.5	2.5	4	
2.5	2.5	5	2.5	2.5	2.5	3.2	
2.5	2.5	7.5	2.5	2.5	2.5	3.8	
2.5	2.5	10	2.5	2.5	2.5	4.5	

Figure 22: Sensitivity analysis matrix for GALDIT VI parameters, showing a low vulnerability when one parameter is only changed (in yellow).

Figure 22 shows the importance of using a multi-criteria approach to assess vulnerability. However, GALDIT VI remains preliminary and broad when assigning ratings and weights to parameters. For instance, the *G* parameter would score 10 for a confined aquifer and 7.5 for an unconfined one. The justification given by Chachadi & Lobo Ferreira, (2005), is related to the larger cone of depression formed around the well when pumping from a confined aquifer. This is not always the case. In fact, the size of the cone of depression is dependent primarily on the pumping rate and the capability of the aquifer to store and transmit water (National Groundwater Association, 2010). These properties can be very different in two aquifers having the same confinement type.

Furthermore, giving too much weight to the *D* parameter is based on the assumption that the most affected area by SWI is the closest to the shore. However, looking at the maps of chloride distribution for Akkar porous aquifer (1969-2013), it is very obvious that the southern part, in contact with the sea, is less affected by SWI than more distant areas of the aquifer. Therefore, assigning ranges to *D* based on the correlation built with chloride concentration (Pedreira et al., 2014) can be argued.

7.3 Interpretation of results

7.3.1 Akkar porous aquifer

The comparison between the *I* rated maps of 1969 and 2013 reveals a clear shift from low chloride values (<250 mg/l) in 1969, to higher values (>250 mg/l) in 2013. This change can also be detected in the rated maps. In fact, the sum of the areas rated 7.5 and 10, which correpond to chloride values above 250 mg/l, became 29% larger in 2013. However, the water is still usable for most of the aquifer (chloride level < 500 mg/L) (Figure 12).

In the case of the Greek aquifer, a chloride value of 500 mg/l sets the limit between the more affected areas by SWI (>500 mg/l) and the less affected areas (<500 mg/l). In fact, in 1992 chloride values above 500 mg/l can already be observed in the Southern-West part of the aquifer. However, in 2014 all the Southern part of the area becomes highly affected by SWI (>500 mg/l of chloride). A spatial increase of 25% is found only for the area rated 10 (Recinos et al., 2013). Appendix 6 shows this variation in chloride concentration in Northern-East Greece from 1992 to 2004.

Looking at GALDIT VI results for Akkar, no significant difference is observed between 1969 and 2013. Most of the study area is moderately vulnerable except for the Western and Eastern boundaries classified as highly vulnerable and least vulnerable respectively. Therefore, in the case of Akkar, the vulnerability map according to GALDIT VI is considered as an almost static intrinsic map on a short time scale, when the other parameters are unchangeable. This interpretation is only valid for this specific study area. In fact, in the case of the alluvial aquifer, Northern-East Greece, the vulnerability study done on two different periods (1992 and 2004), has revealed different results. With only a gap of 12 years, the area classified as highly vulnerable became 15% larger in 2004 (Recinos et al., 2013). This change is attributed to a significant drop in water level which is not observed for the Akkar aquifer.

When comparing the rated maps to the final vulnerability map it is clear that the highly vulnerable area inherited its shape and position from the *L* parameter. This finding is no surprise when looking at the weights assigned to each parameter. Assigning the lowest weight to the dynamic parameter *I*, and the highest weight to *L* which is in this case considered unchangeable, made the vulnerability map a less dynamic one, almost static. Such a map is used to describe the intrinsic vulnerability of the Akkar porous aquifer since it will not respond to any external disturbance affecting SWI.

Nevertheless, the final intrinsic vulnerability map does not explain the advancement of SWI front inland observed in the *I* parameter maps between 1969 and 2013.

Actually, using the GALDIT VI map of 1969, one can predict that the highly vulnerable area will be mostly prone to SWI. However, looking at the ”existing *I*mpact status of SWI” map in 2013, it is clear that SWI goes beyond the highly vulnerable area. Therefore, if groundwater *L*evel explains the intrinsic vulnerability of the aquifer, anthroprogenic parameters explain the specific vulnerability of the aquifer contributing in the advancement of SWI.

7.3.2 Ghadir C4c karstic aquifer

From the direct application of GALDIT VI, the entire study area is classified as moderately vulnerable. However, keeping in mind the high heterogeneity, complex hydrogeology and high chloride values (Appendix 8) characterizing this aquifer, the result obtained is not satisfying in terms of decision tool. The reason behind this result is the data collected for each parameter that mostly was inapplicable for karst aquifers or out of the GALDIT VI ranges. Due to these data limitations, the rated maps were poorly generated. The parameters that are primarily responsible for the inappropriate results are *A*quifer hydraulic conductivity, groundwater *L*evel a.m.s.l and aquifer *T*hickness. A detailed investigation should be conducted to find suitable solutions or alternatives for these three parameters that can contribute to significant results.

As explained earlier, hydraulic conductivity was obtained by using the theoretical value of transmissivity assigned for C4 formation. Due to the heterogeneity of the aquifer under study, the *A* parameter will change with distance and direction, thus cannot be easily characterized by field measurement. Groundwater *L*evel a.m.s.l and aquifer *T*hickness are considered important parameters for GALDIT VI. Actually, the saltwater-freshwater interface can be determined based on Equation 1.2 and other equations relating *L* to *T*. However, the theoretical Ghyben-Herzberg model is not enough in the presence of double porosity. Therefore, more significant parameters characterizing heterogeneous karst systems and contributing in the prediction of the saltwater-freshwater interface should be integrated.

7.4 Proposed modifications for GALDIT VI

Although GALDIT VI is a low resolution method, some modification can still enhance its adaptation when it comes to a specific study area.
In general, a reclassification is needed for the ranges defined theoretically by Chachadi & Lobo Ferreira (2005), in order to fit the scale of the values obtained in each study area, as it was done for the *D* parameter (Pedreira et al., 2014). More specifically, some modifications will be suggested in the sections below, to suit each of the Lebanese aquifers.

7.4.1 Akkar porous aquifer

As explained earlier, SWI variation is taken into consideration when specific vulnerability is assessed. Therefore, anthropogenic activities should be included as a parameter. To do so, a simple mixing model can be used to derive the abstraction rate effect on chloride concentration.
The simple mixing model is a conceptual approach derived from the mass balance. The following equation summarizes the model:

Equation 5.1 $$\mathbf{C_{sea}Q_{sea} + C_{fw}Q_{fw} = C_aQ_a}$$ (UNDP,2013)

This equation can be written as:

Equation 5.2 $$\mathbf{\frac{Q_{sea}}{Q_a} = \frac{C_a - C_{fw}}{C_{sea} - C_{fw}}}$$

where C_a, C_{fw}, and C_{sea} are salinities (mg/l) of actual water in well, freshwater from the surface (181 mg/l, based on Equation 3 and assuming $[Cl^-]$=100mg/l), and saltwater (35,000 mg/l) respectively. Q_a (Mm^3/l) is the actual flow in the aquifer. Q_{fw} is the discharge of freshwater and Q_{sea} is the flow of sea water inland. Q_a is the sum of Q_{fw} and Q_{sea}. It should also be noted that Q_a is the difference between recharge Q_r and pumping Q_p. Table 5 summarizes the change in the parameters between 1969 and 2013. 1969 values of Q_{sea}, Q_{fw} and Q_a are obtained from FAO (1970) whereas 2013 values are from a project conducted by UNDP (2014). The other values are based on Equation 5.2 and the information provided above.

Table 5: Saltwater and freshwater parameters for 1969 and 2013.

Parameters	1969	2013
C_{fw} (mg/l)	181	181
C_{sea} (mg/l)	35,000	35,000
Q_{sea} (Mm^3/l)	0.05	0.11
Q_{fw} (Mm^3/l)	7.4	5.43
Q_a (Mm^3/l)	7.45	5.54
Q_{sea}/Q_a (%)	0.7	2
C_a (mg/l)	424.7	877.38
$[Cl^-]$(mg/l)	235	486

Assuming Q_r is fixed during the years, the change in Q_a is attributed to the increase of Q_p. It can be deduced from Table 5 that an increase of 26% in Q_p leads to an increase of $[Cl^-]$ by 2.1 times. This interpretation is valid when comparing Figure 11 to Figure 12. In fact, the values raging between 100 and 250 mg/l in 1969 doubled in 2013 with a range of 250 and 500 mg/l. Assuming that the abstraction rate is homogenous over the area, a ranking system can be developed for this parameter to be included in GALDIT VI. In the case of Akkar aquifer it is reported that an abstraction rate of 22Mm^3/y does not threaten sustainability (UNDP, 2014). Taking into account the relationship between the abstraction rate and chloride concentration, the following ratings can be assigned (Table 6):

Table 6: Ratings assigned for abstraction ranges.

Abstraction rate ranges (Mm^3/y)	Rating
<22	2.5
22-28	5
>28	10

A simulation is done to test the effect of adding the <u>A</u>bstraction rate parameter (noted <u>A</u>). According to UNDP (2014), <u>A</u> is assumed to be 22Mm^3/y for the year 1969 and thus scores 2.5, whereas it scores 5 for 2013 (26% increase in Q_p). For the purpose of the simulation, assuming that the total weight should remain constant (total of 15), the <u>L</u> and the new <u>A</u> parameters are given a weight of 2. To account for the abstraction rate parameter, GALDIT VI is modified to GALDIT-A VI, that assesses the specific vulnerability to SWI. The results are shown in Appendix 9. The dynamicity of the GALDIT-A VI map showing an increase in vulnerability from 1969 to 2013 can be observed.

To be able to integrate abstraction as a parameter in the modified GALDIT VI for Akkar aquifer, further investigation, specifically a numerical model, is needed to be able to determine the suitable weight for the new A parameter and to validate the efficiency of this parameter.

7.4.2 Ghadir C4c karstic aquifer

It seems that the movement of fluids in the aquifer is mostly dominated by double porosity (matrix and fractures), especially along the E-NE faults (Doummar, et.al, 2015). Consequently, hydraulic conductivity has much higher values than an EPM. In fact, A becomes at least 10^5 greater with the presence of faults acting as conduits (Ford & Williams, 2007). Therefore, to begin with, at least the area influenced by the presence of these faults should have a rate of 10 instead of 2.5 (referring to Appendix 5 a). Further studies should be conducted to define highly faulted and fractured areas. In Figure 22 the major faults, trending E-NE, delineated by Doummar, et al., 2015 are shown.

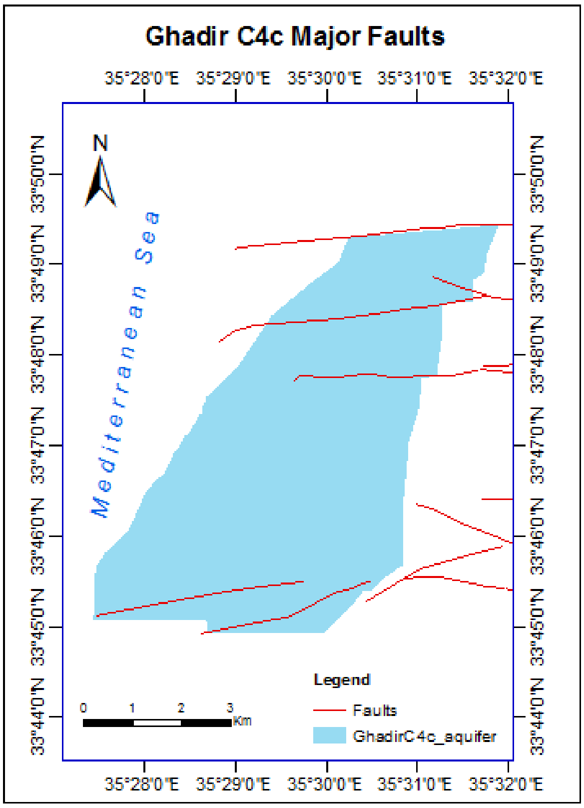

Figure 23: Map showing the major E-NE faults passing through Ghadir C4c (data source from Doummar et al., 2015).

It has been reported that the configuration of the saltwater-freshwater interface is related to the karstic structures found and to the geology of the area (Ford & Williams, 2007). These two properties have been considered in an early study done on a karstic aquifer in Damour, Southern Lebanon (Daher et. al, 2011). This study used a multi-criteria approach, similar to the described EPIK VI, in order to characterize a karst aquifer and assess its recharge potential. The refined EPIK VI, called Aquifer Rechargeability Assessment in Karst (ARAK), uses four criteria: Epikarst, Rock, Infiltration and Karst (Daher et al., 2011). The emphasis will be on Rock and Karst criteria which might bring valuable information to the present study, if added. R and K describe the geology and the karstic structures which would contribute in the prediction of the saltwater-freshwater interface. The R criterion combines lithology, structure and thickness of the aquifer, whereas the K criterion describes the degree of karstification and the growth of fractures (Daher et al., 2011). Appendix 10 gives more detailed information about the classification used in ARAK for each criterion. The above proposed solution offers an introductory approach for better understanding karstic aquifers as well as their vulnerability to SWI. Further investigation and validation are needed to assess the feasibility of the proposed methodology on the Lebanese karstic aquifers.

8 Conclusions

GALDIT VI supports decision making by giving a general insight on vulnerability to SWI. In fact, this low resolution method reveals which indicator/parameter has the highest impact on intrinsic vulnerability. However, some modification can be done to fit this indexing method for the area under study, yielding better results. First, one should secure that all parameters chosen are measurable and possible to map. In the following step, one should verify that the gathered data are within the scale of the ranges defined by GALDIT VI, for each parameter. A reclassification of these ranges might be needed to create more efficient zonation of the data.

More specifically, the results of Akkar study area compared to the results obtained in Northern-East Greece, show that two aquifers of the Mediterranean region with similar geological conditions, have very different vulnerability to SWI, when using GALDIT VI. Water *L*evel a.m.s.l is the parameter responsible for the high intrinsic vulnerability found in both aquifers. However, anthropogenic parameters, in this case abstraction rate, must be considered to explain the specific vulnerability to SWI over the years in Akkar, assuming that groundwater *L*evel is static. The modified GALDIT

VI, named GALDIT-A VI, is dynamic over the years. Therefore it contributes in explaining the specific vulnerability to SWI. However, this method is still of a low resolution and thus must be combined with other, more direct tools (chemical, geophysical, etc.), to evaluate SWI.

It is worth mentioning that the Greek aquifer is more in danger than the Akkar aquifer. In fact, the salinity of Akkar is increasing at a very slow pace over a period of 44 years, especially that a change in water level is not observed in this area. Whereas, in Greece, an alarming increase of 29% is observed over a period of only 12 years. In addition, Akkar groundwater is still mostly usable with most of the chloride values below 500mg/L, whereas the water of Northern-East Greece aquifer is becoming highly unusable.

The results of Ghadir study area, reveal the limitations of GALDIT VI to assess vulnerability to SWI of a karstic aquifer assumed equivalent to a porous medium. Data quality is an issue when it comes to the assessment of $\underline{A}$, $\underline{L}$ and $\underline{T}$ parameters. To be able to overcome the data limitations, these parameters need to be modified. A proposed solution is first to take into account the structures affecting $\underline{A}$. Moreover, two parameters are introduced as alternatives to $\underline{L}$ and $\underline{T}$. The new Rock and Karst criteria, used in ARAK methodology, specifically characterize karst aquifers and might contribute to a better vulnerability assessment. However, the suggestions stated above remain a preliminary approach that needs to be tested in karst areas. Further studies, such as developing a flow/transport model for the aquifer, will support the understanding of the aquifer dynamics in all dimensions and will help validate this qualitative approach.

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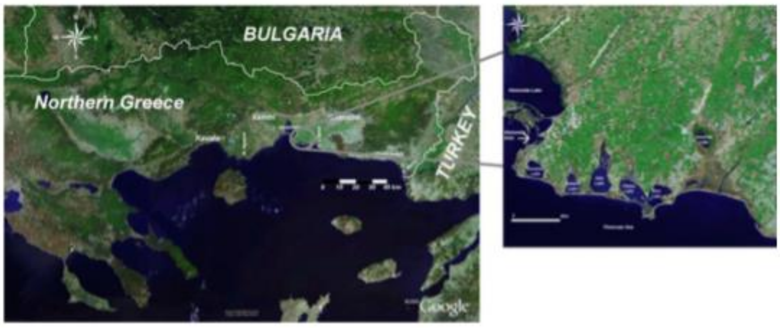
Appendices

The following appendices contain supplementary information that provides support to the reader when needed.

Appendix 1- Geographical location of the porous aquifer, Northern-East Greece (Recinos et al., 2013)



Appendix 2-Ranges, Ratings and Weights of GALDIT VI

The below tables are adapted from (Chachadi & Lobo Ferreira, 2005). Each table corresponds to each indicator of GALDIT respectively. The weight and rating for each indicator are given. Finally, the last table corresponds to the classification of the GALDIT final vulnerability map.

Indicator	Weight	Indicator Variables	Importance Rating
Groundwater occurrence/Aquifer type	**1**	Confined aquifer	10
		Unconfined aquifer	7.5
		Leaky confined aquifer	5
		Bounded aquifer	2.5

Indicator	Weight	Indicator Variables	Importance Rating
Aquifer hydraulic conductivity (m/day)	**3**	>40	10
		10-40	7.5
		5-10	5
		<5	2.5

Indicator	Weight	Indicator Variables	Importance Rating
Height of groundwater level a.m.s.l (m)	**4**	<1.0	10
		1.0-1.5	7.5
		1.5-2.0	5
		>2.0	2.5

Indicator	Weight	Indicator Variables	Importance Rating
Distance from shore (m)	**4**	<500	10
		500-750	7.5
		750-1000	5
		>1000	2.5

Indicator	Weight	Indicator Variables	Importance Rating
Impact status of existing sea water intrusion	**1**	>2	10
		1.5-2.0	7.5
		1-1.5	5
		<1	2.5

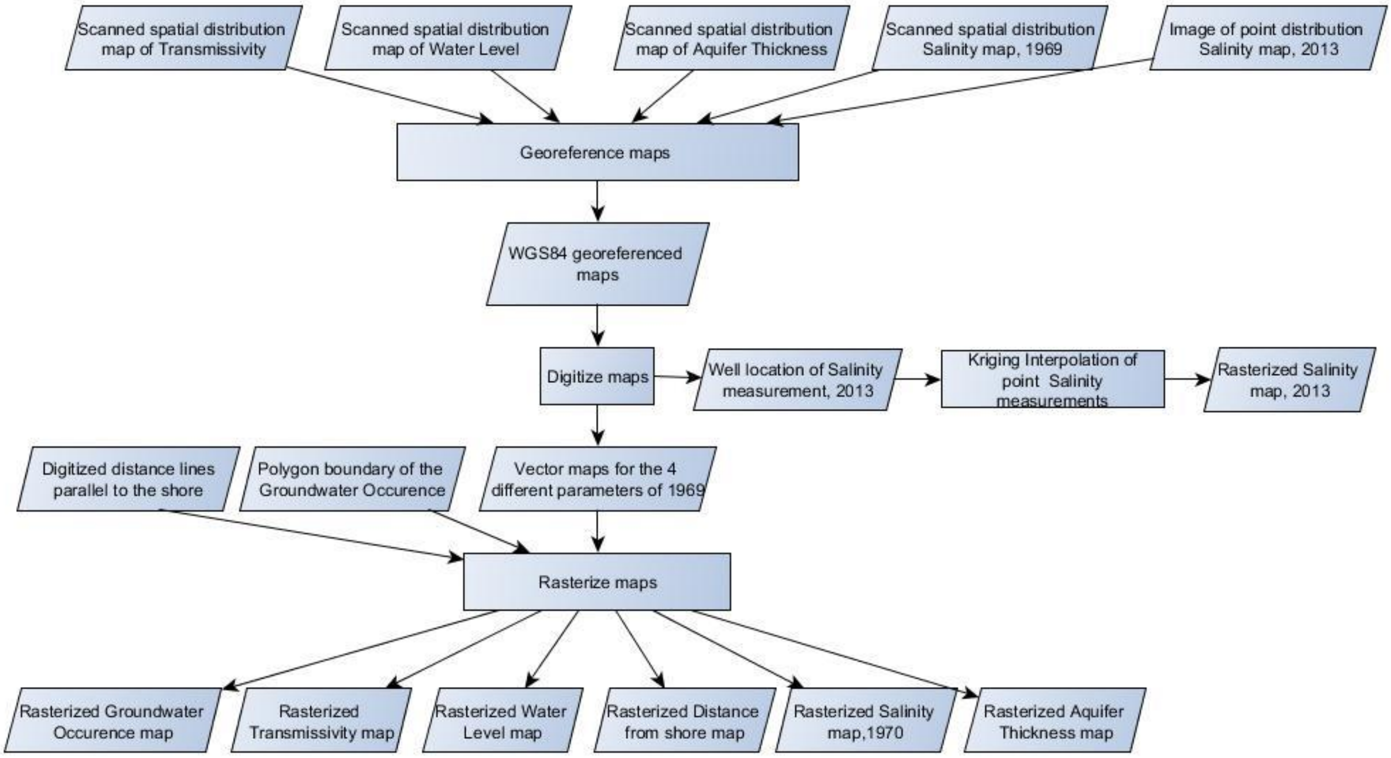
Indicator	Weight	Indicator Variables	Importance Rating
Aquifer thickness (m)	**2**	>10	10
		7.5-10	7.5
		5-7.5	5
		<5	2.5

Sr. no.	GALDIT-Index Range	Vulnerability Classes
1	>=7.5	Highly vulnerable
2	5-7.5	Moderately vulnerable
3	<5	Least vulnerable

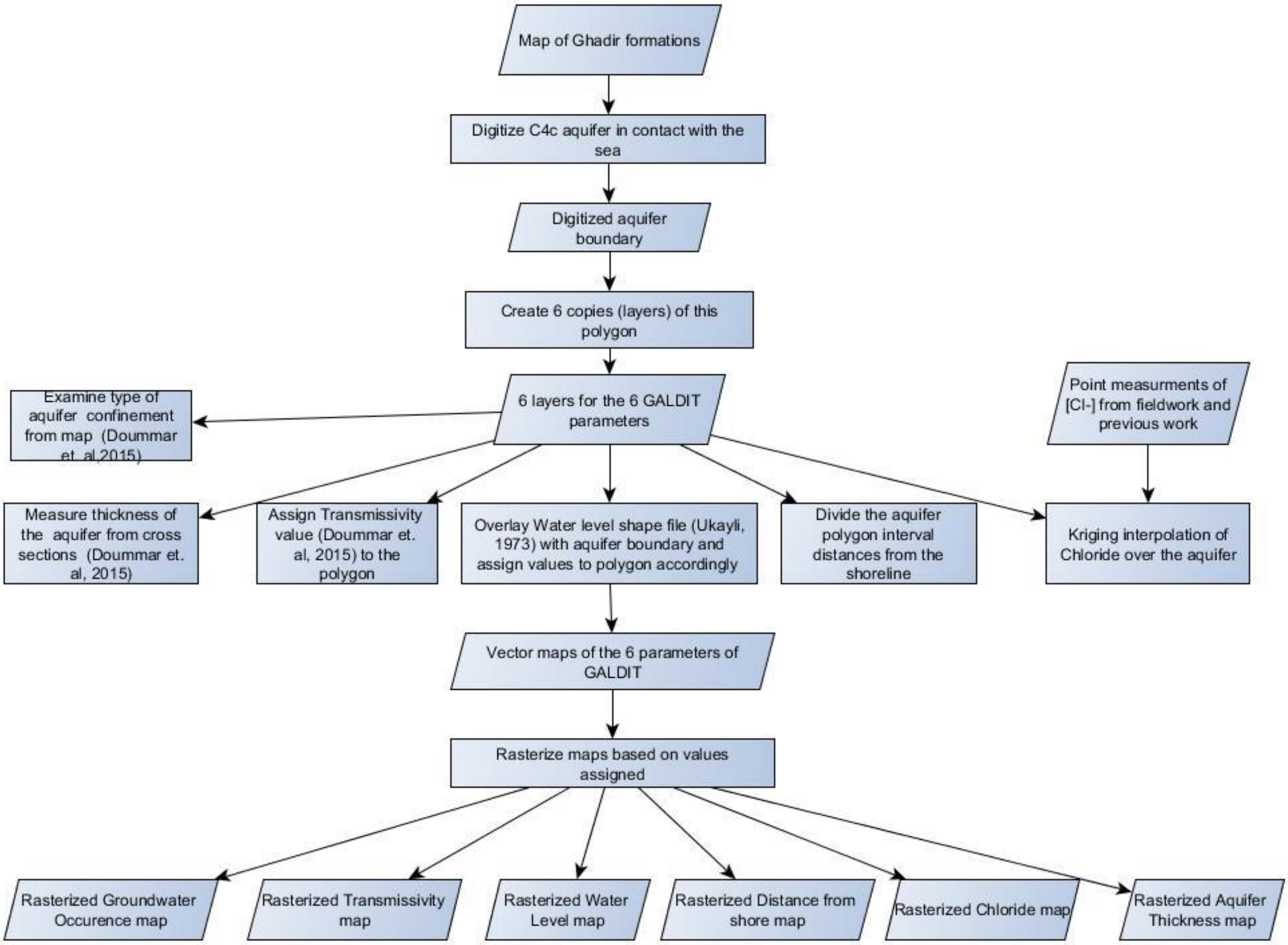
B

Appendix 3-Workflows

a-For digitizing the required maps for Akkar Study area the below workflow is followed starting with raw data collected from previous studies. The processes used are: georeferencing, digitizing, interpolating and rasterizing.

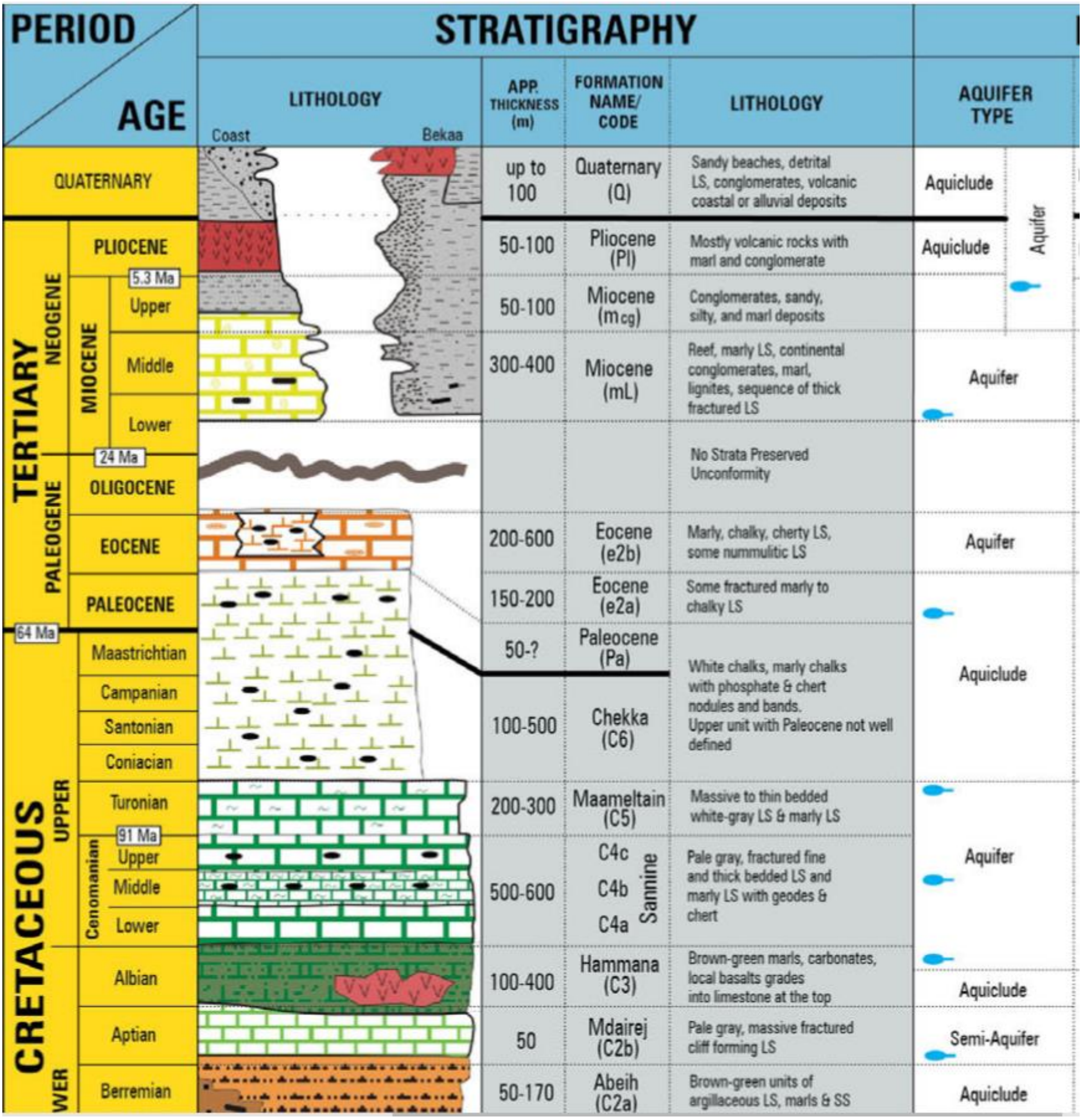


b-For processing Ghadir C4c data the below workflow is followed starting from digitizing the aquifer boundary from Ghadir formation map (Doummar et al., 2015). The processes used are: digitizing, overlaying, interpolating and rasterizing.

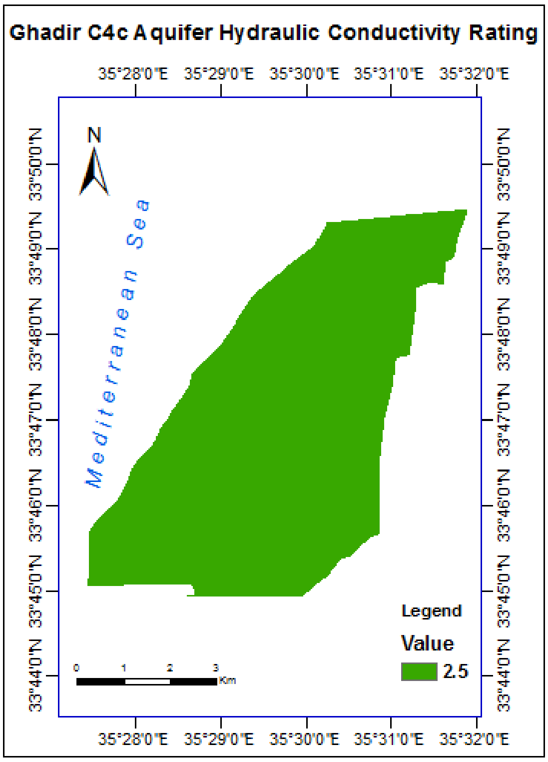


Appendix 4- The lithostratigraphy of the Lebanese coast (UNDP,2014)

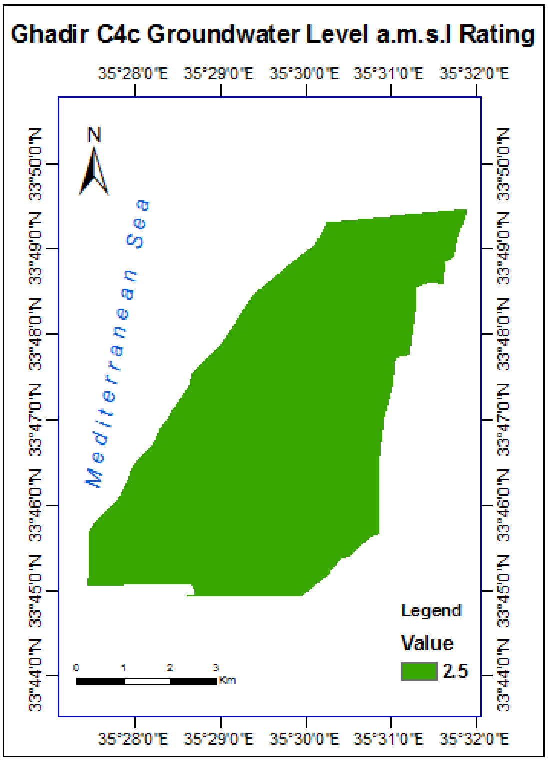
This figure shows the location of the Sannine (C4) aquifer and the Quaternary aquifer in relation to other formation found in Lebanon. Note that C4 is of Cenomanian age whereas the Quaternary formation is the newest.



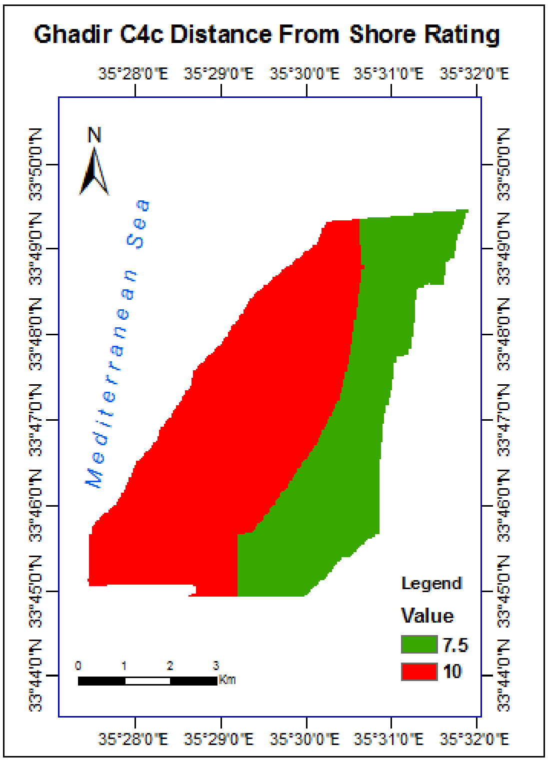
Appendix 5-Rated maps for Ghadir C4c aquifer



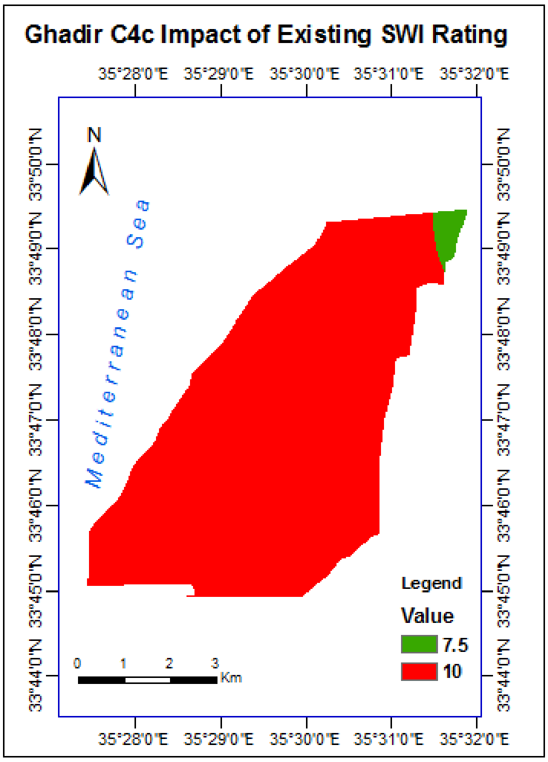
a-The figure shows that Aquifer hydraulic conductivity is very low over the entire aquifer, which explains the low score (2.5).



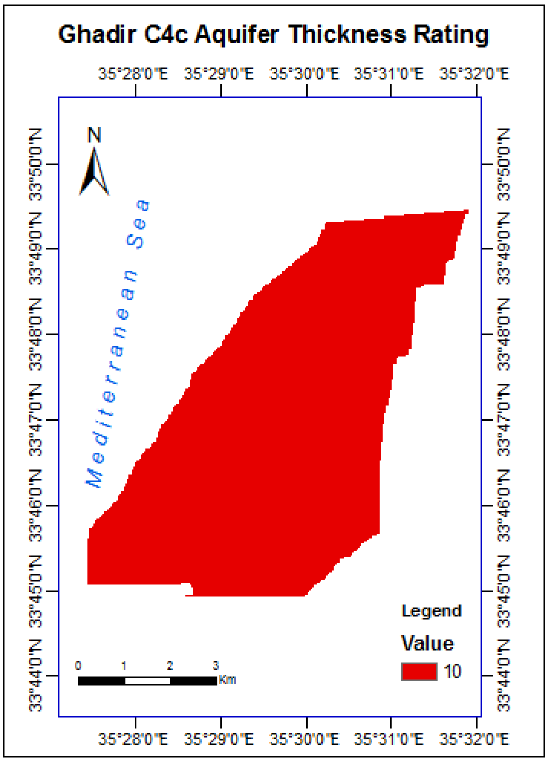
b-The figure shows that water level is higher than 2m, which explains the rating 2.5.



c-The figure shows that using Recinos et. al (2013) rating for distance, a variation in vulnerability is observed.



d-The figure shows that SWI is already too high. Only a negligible part of the aquifer rates less than 10.

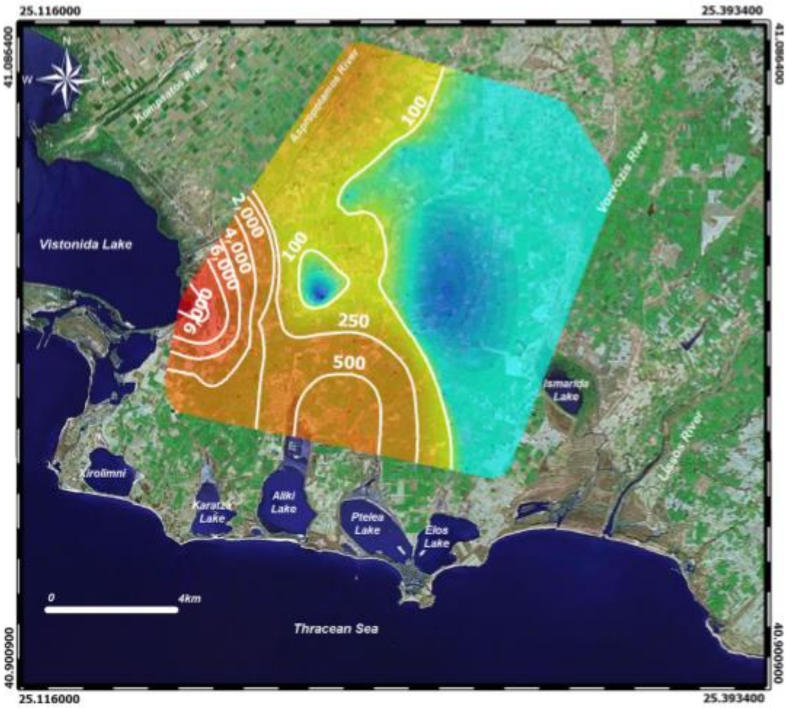


e-The figure shows that the entire aquifer has a thickness larger than 10 m and thus rates 10

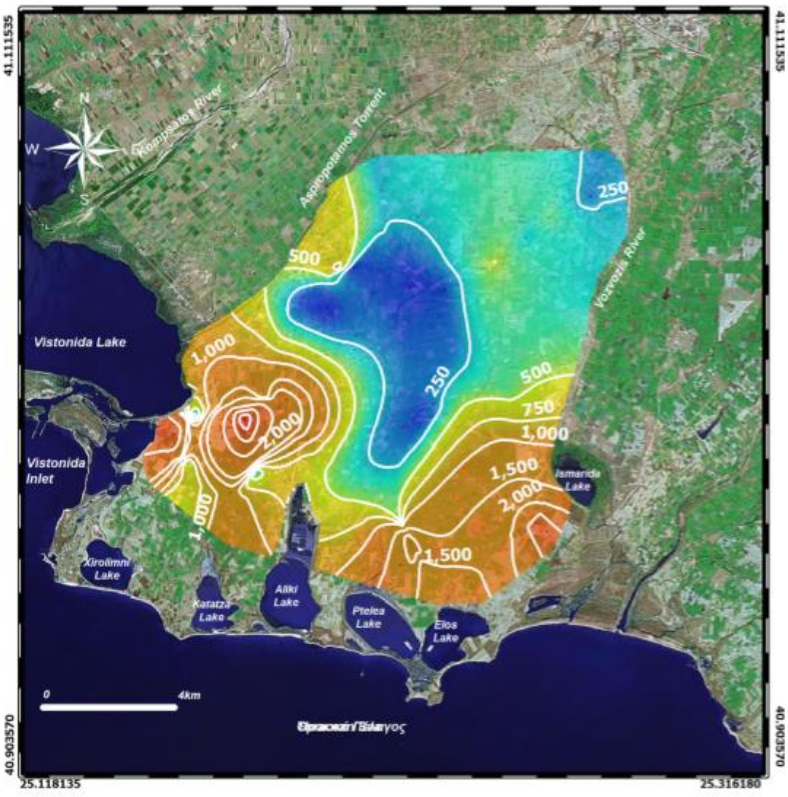
Appendix 6-Chloride distribution in 1992 and 2004, Northern-East Greece (Recinos et al., 2013)

Figure (a) is a chloride distribution map in 1992 (source: Petalas, 1997), whereas Figure (b) is a chloride distribution map of 2004.

a



b



Appendix 7-Chloride concentration (mg/l) Winter-Summer 2013 in Akkar aquifer

The average value derived from Cl-feb compared to the average of Cl-aug reveals the seasonal change effect on chloride concentration

Chloride Concentration Feb-Aug			
X	Y	Cl-feb	Cl-aug
35.98307	34.62667	686.3912	664.2495
36.00522	34.6115	326.5894	280.0919
36.0614	34.62156	332.1248	308.876
36.04268	34.59561	375.301	233.0409
36.06336	34.5923	512.0257	302.7871
36.05467	34.58888	277.3242	266.8069
36.01942	34.58276	356.4806	349.8381
36.05614	34.57823	326.5894	337.6602
36.01587	34.57284	386.3718	362.5695
36.06067	34.55588	282.3061	279.5383
36.03545	34.55551	380.2829	334.3389
36.02676	34.55808	462.207	365.3372
35.99557	34.54911	279.5383	290.0556
36.00838	34.5418	237.4692	218.0953
36.02205	34.52596	0	0
36.05864	34.53881	291.1627	290.0556
	Average	344.5103	305.2088

Appendix 8- Field measurements for Ghadir C4c

The location of the 6 samples collected is shown in figure a (satellite image, Google Earth) and c (Ghadir C4c aquifer map). The results are summarized in table b.

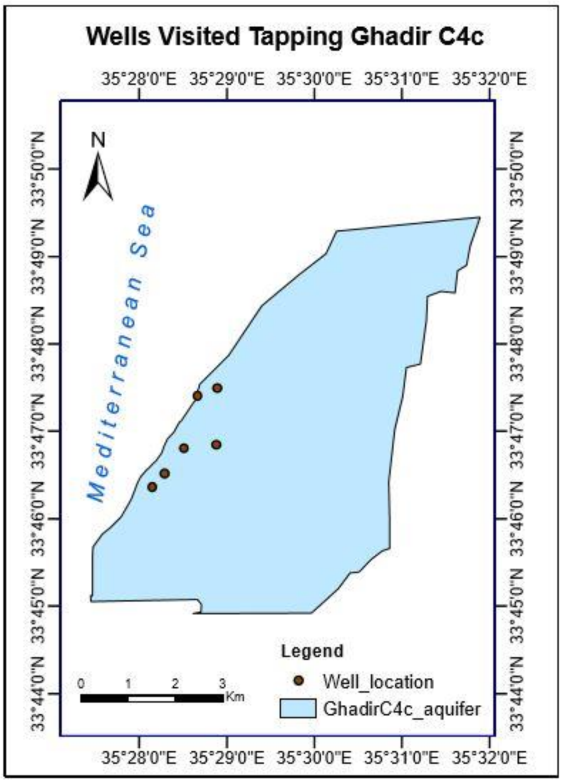
a.

b.

Well measurements in Ghadir area

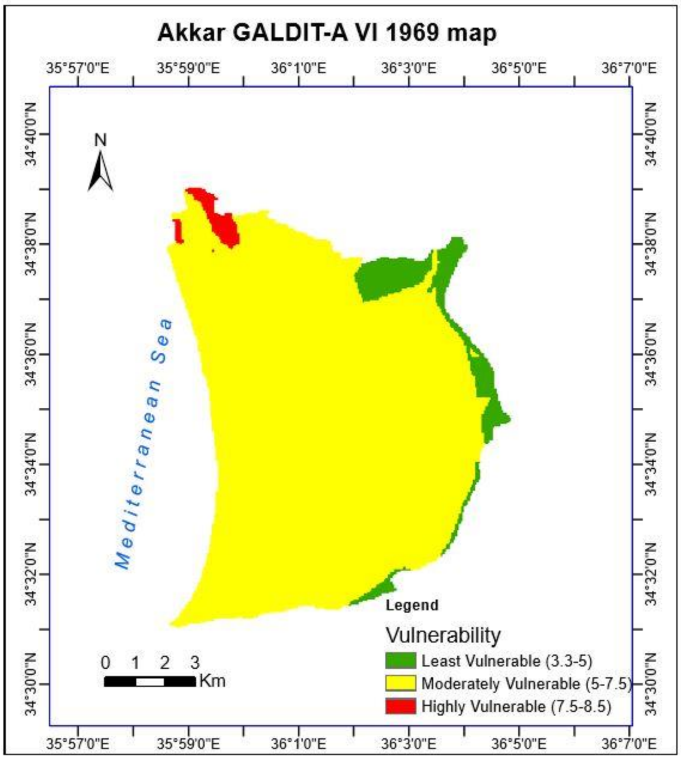
Sample	Y	X	EC(µS/cm)	Cl(mg/l)
1	33.791449	35.481516	3030	1073.398
2	33.780025	35.475202	2330	825.4179
3	33.790074	35.477801	10530	3730.322
4	33.772623	35.46919	3650	1293.037
5	33.775204	35.471541	3010	1066.312
6	33.78071	35.481345	1170	414.4802

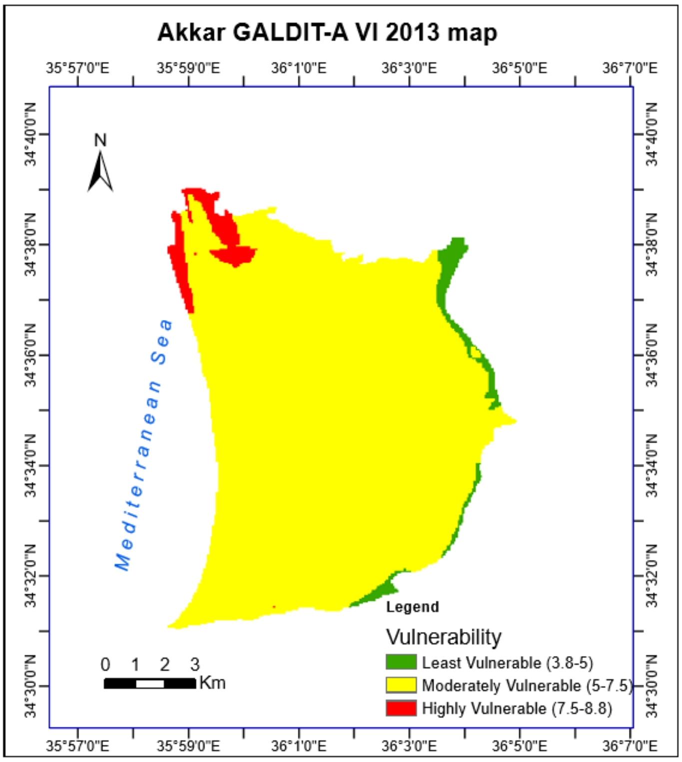
c.



Appendix 9- GALDIT-A VI, a modified version of GALDIT VI that adds abstraction rate into the equation

The change in vulnerability observed in GALDIT-A VI between 1969 and 2013 is due to the change in abstraction rate alone.





Appendix 10- ARAK criteria description (Daher et al., 2011)

Criteria	Class	Description	Index value
E Epikarst	E0	Total absence of epikarst, presence of karst depressions, shafts, swallow holes, etc.	0
	E1	Epikarst: thickness < 1 m, discontinuous and fairly developed; presence of temporary springs with flow rates of l/h; karst depressions (poljes, dolines with flat bottom, dry valleys)	1
	E2	Epikarst: 1 m < thickness < 5 m, developed and laterally discontinuous; presence of temporary springs with flow rates of l/mn; pavement and karren field	2
	E3	Epikarst: thickness >5 m, developed and laterally continuous; presence of temporary springs with flow rates of l/s; thin, discontinuous soil cover	3
	E4	Epikarst: thickness >5 m, developed and laterally continuous; presence of temporary springs; presence of continuous soil and/or sediment cover	4
R Rock	R0	Marly formations (35–65% of clay)	0
	R1	Marl containing limestone (25–35% of clay)	1
	R2	Marly limestone (10–25% of clay)	2
	R3	Thick bedded, highly fractured limestone and dolomite	3
	R4	Thin bedded, moderately fractured limestone and dolomite, with eventual thin marly interbeds	4
I Infiltration	I0	Slope > 50%	0
	I1	30% < Slope < 50%	1
	I2	15% < Slope < 30%	2
	I3	5% < Slope < 15%	3
	I4	0% < Slope < 5%	4
K Karstification	K0	Very developed and functional binary karst; high velocities in tracing tests (>100 m/h)	0
	K1	Low functional binary/high functional unary karsts; high velocities in tracing tests (50 < V < 100 m/h)	1
	K2	Low functional unary karsts; velocities in tracing tests (V < 50 m/h); variable chemical composition and flow rates	2
	K3	Very low functional karst; absence of variability in chemical and physical compositions and flow rates; absence of witness of quick water circulation	3
	K4	Karst system compared to fractured systems or non functional system	4

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