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SENSITIVITY ANALYSIS OF AN INTEGRATED NUMERICAL FLOW MODEL OUTPUT TO KEY MODEL PARAMETERS USED IN COMMON QUALITATIVE VULNERABILITY ASSESSMENT METHODS

by
ASSAAD HASSAN HASSAN KASSEM

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AN ABSTRACT OF THE THESIS OF

Assaad Hassan Hassan Kassem for Master of Science in Environmental Sciences
Major: Environmental Technology

Title: Sensitivity analysis of an integrated numerical flow model output to key model parameters used in common qualitative vulnerability assessment methods

Qualitative vulnerability assessment methods applied in karst aquifers rely on key factors in the hydrological compartments and are usually assigned different weights according to their projected impact on the groundwater vulnerability. Based on an integrated numerical groundwater model on a snow-governed karst catchment area (El Assal Spring- Lebanon), the aim of this work is to quantify the importance of the most influential parameters on recharge and spring discharge and to outline the potential parameters that are often not accounted for in standard calibration methods, when in fact they do play a role in assessing the intrinsic vulnerability of a system. The assessment of the model sensitivity and ranking of parameters are conducted using an automated calibration tool for local sensitivity analysis in addition to a variance based local sensitivity assessment of model output time series (recharge and discharge) for two consecutive years (2016-2017). The impact of each parameter was normalized to estimate standardized weights for each of the process based key-controlling parameters. Parameters to which the model was sensitive were factors related to soil, 2) fast infiltration (bypass function) typical of karst aquifers, 3) climatic parameters (melting temperature and degree day coefficient) and 4) aquifer hydraulic properties that play a major role in groundwater vulnerability inducing a temporal effect and varied recession. Other less important parameters play different roles according to different assigned weights proportional to their ranking. Additionally, the effect of slope/geomorphology (e.g., dolines) was further examined. In general, this study shows that the weighing coefficients assigned to key vulnerability factors in the qualitative assessment methods need to be reevaluated based on a process-based approach.

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CHAPTER I

INTRODUCTION

A. BACKGROUND

Groundwater comprises 30% of the global freshwater (Korzun 1978). This important portion of the world freshwater has been under stress due to increased water demand, urbanization with Land Use Land Cover changes affecting aquifer recharge, and more recently climate change affecting temperature and precipitation patters (Famiglietti, 2014). Due to these natural and anthropogenic stresses, various groundwater management methods have been proposed and developed over (Aral et al 2011) to secure a sustainable management of water resources under varying conditions and future stresses. Groundwater management techniques vary with the objective of the management. As such, objectives can be categorized into either quantity or quality of available groundwater. For example, ASCE (1987) considered groundwater as a resource that should be exploited sustainably following groundwater management planning developed based on the hydrogeological understanding of the system. Others highlighted that groundwater management should account for groundwater protection of quality and quantity through the implementation of laws and policies (Fetter, 2001). Therefore, groundwater management and protection can be achieved with qualitative, quantitative, or semi-qualitative tools based on conceptual or numerical models (Doummar et al., 2012) or hydrogeological or vulnerability mapping (Goldscheider, 2002; Aral et al., 2011).

The term vulnerability was first introduced by Margat (1968) to refer to the extent to which aquifers can be exposed to contamination (Foster, 1987, Vías et al., 2006). The National Research Council (1993) defined groundwater vulnerability to contamination as "the tendency or likelihood for contaminants to reach a specified position in the ground-water system after introduction at some location above the uppermost aquifer." and it refined the definition for specific contamination as "specific vulnerability" and for any contamination as "intrinsic vulnerability". The vulnerability concept is often represented by the simplified origin-pathway-target scheme (Goldscheider, 2002, Neukum et al., 2008) that defines the sensitivity of an environment for contamination. The origin defines the source of the contaminant and the pathway represents the media through which the contaminant is transported from the moment it infiltrates (throughout the unsaturated and saturated zones) to reach the groundwater target.

Vulnerability mapping and qualitative approaches are the most common tool to assess vulnerability (Aller et al., 1987, Civita and De Maio, 1997, Doerfliger et al., 1999, Foster, 1987, Vías et al., 2006, Goldscheider et al., 2000) usually referred to by acronyms such as DRASTIC, SINTACS, PI, EPIK, COP, GOD among others. These methods account for the spatial variability of vulnerability, however they rely on weighted surface and subsurface parameters to define the distributed sensibility of an aquifer system or a specific target to contamination. Therefore, the evaluation of the vulnerability key parameters along with their weighting factor is highly subjective according to each method. Moreover, vulnerability maps based on different methods portray discrepancies between the delineated vulnerability classes (Polemio et al., 2009, Doummar et al., 2012).

Additionally, vulnerability assessment in karst aquifers has to account for both the concentrated and diffuse recharge as well as for the significant heterogeneity of hydraulic properties and geometries prevailing in the subsurface. Besides, the combination of all parameters cannot provide a straight forward assessment of vulnerability in a dynamic karst system (Butscher and Huggenberger, 2009). For instance, a high transit time will enable attenuation processes to be active for a longer time and allow for time to react to pollution at the target (Perrin et al., 2003). However, processes like dispersion and diffusion will enhance contaminant attenuation and their peak concentrations, but will increase the duration of restitution at the target. Spring responses are the output signal of a karst system and are highly variable with time according to the input signal, prevailing transport and flow conditions. Therefore, spring responses and their temporal variability cannot be neglected in vulnerability assessments. Butscher and Huggenberger (2009) proposed a quantitative method to assess vulnerability based on a reservoir modelling approach calibrated on the basis of karst spring discharges. Yet, the existing quantitative intrinsic vulnerability (e.g., reservoir models) model fails to account for the spatial variability and heterogeneity of the karst system. The assessment of vulnerability is closely related to physical processes taking place in all the karst compartments (Doummar et al., 2012). Therefore, processes such as type of recharge and flow, along with the importance of storage, play a major role in shaping the output signal (discharge) at an outlet (Kovács and Perrochet, 2008).

The EPIK vulnerability assessment method was the first developed method to target karst systems (Doerfliger and Zwahlen, 1998). Involving precipitation and other factors, COP method was also further developed to evaluate susceptibility of karst aquifers (Vias et al., 2002).

Exclusively developed for vulnerability mapping in karst systems, the EPIK method employs four attributes for the analysis. The factors are mainly the epikarst (E), protective cover (P), infiltration condition (I), and karst network (K). Accordingly four maps representing the spatial distribution of each of these parameters, frequently produced by interpolation within the catchment area to form raster file of each attribute.

Attributes and parameters involved in the vulnerability assessment for EPIK method are presented and defined in Table 1. Moreover, the preassigned weighted scores of each parameter variation employed in the EPIK method is also presented in Table 1.

Each of the attributes that is addressed in the EPIK method will be categorized and assigned a certain weight according to the scores and categories presented in Table 1. Consequently the four outcome maps will be added together to calculate the Protection Factor (F) according to the following equation:

$$F = 3\boldsymbol{E} + 2\boldsymbol{P} + 1\boldsymbol{I} + 3\boldsymbol{K}$$

Table 1: EPIK method attribute definition and description (modified from Protection of Jeita Spring, 2012 and Doerfliger and Zwahlen, 1998)

Attribute	Definition	Code	Score	Description	
Epikarst	Degree and maturity of morphology karstification	E1	1	Caves, swallow holes, dolines, karren fields, ruine-like relief, cuestas	
		E2	2	Intermediate zones situated along doline alignments, uvalas, dry valleys, canyons, poljes	
		E3	3	The rest of the catchment	
Protective cover	Soil layer thickness and the underlying lithology			**A.** Soil resting directly on limestone formations or on detrital formations with very high hydraulic conductivity*	**B.** Soil resting on > 20 cm of low hydraulic conductivity geological formations**
		P1	1	0 - 20 cm of soil	-
		P2	2	20 – 100 cm of soil	20 – 100 cm of soil and low hydraulic conductivity formations
		P3	3	> 1 m of soil	> 1 m of soil and low hydraulic conductivity formations
		P4	4	-	> 8 m of very low hydraulic conductivity formations or > 6 m of very low hydraulic conductivity formations with > 1 m of soil (point measurements necessary)
Infiltration	Geomorphological and slope factors that control surface water infilitration	I1	1	Perennial or temporary swallow hole – bands and bed of temporary or permanent stream supplying swallow hole, infiltrating surficial flow – areas of the water course catchment containing artificial drainage	
		I2	2	Areas of a water course catchment which are not artificially drained and where the slope is greater than 25 % for meadows and pastures	

Attribute	Definition	Code	Score	Description
		I3	3	Areas of a water course catchment which are not artificially drained and where the slope is less than 10 % for ploughed (cultivated) areas and less than 25 % for meadows and pastures. Outside the catchment of a surface watercourse: bases of slopes and steep slopes (greater than 10 % for ploughed (cultivated) areas and greater than 25 % for meadows and pastures) where runoff water infiltrates
		I4	4	The rest of the catchment
Karst	Maturity of underground karstic network	K1	1	Well-developed karstic network with decimeter to meter sized conduits with little fill and well interconnected
		K2	2	Poorly developed karstic network with poorly interconnected or infilled drains or conduits, or conduits of decimeter or smaller size
		K3	3	Porous media discharge zone with a possible protective influence – fissured non-karstic aquifer

A final vulnerability map can be generated by the aggregation of all individual key parameters raster maps with the math raster calculators (e.g., ARCGIS 10.7). As such, the final scores resulting from raster addition will be reclassified to generate a final summary map indicative of the level of degree of vulnerability of assigned areas (Table 2). The final product will be a map showing the spatial vulnerability within the catchment area according to the F score and will help define protection zone and land use constraints in high vulnerability areas.

Table 2: Protection factor and associated vulnerability evaluation

Protection Factor	**Vulnerability Level**
$9 < F \leq 19$	Very high vulnerability
$20 < F \leq 25$	High vulnerability
$26 < F \leq 34$	Moderate vulnerability
> 25 with the presence of both P4 and I3,4 (Table 1)	Low vulnerability
-	Outside catchment

On the other hand, the COP method (Vias et al., 2006) relies on another set of parameters as input for vulnerability assessment primarily in karst aquifers. The parameters as they appear in the acronyms of the COP method are the C (water flow and infiltration through different geomorphological features), O (soil and the unsaturated zone), and P (precipitation quantities and rate). A detailed methodology of the application of the COP method is summarized in Figure 1. Accordingly, three maps that constitute the three acronyms will be generated according to the preset scores of each sub-compartment presented in the Figure 1. The formulas for maps generation are presented in Table 3. Calculations and interpolations applied for maps are primarily conducted using raster calculators. The product of the three produced maps will conclude the COP index of vulnerability resulting in the spatially distributed vulnerability map of the catchment area classified into five categories as presented in Figure 1.

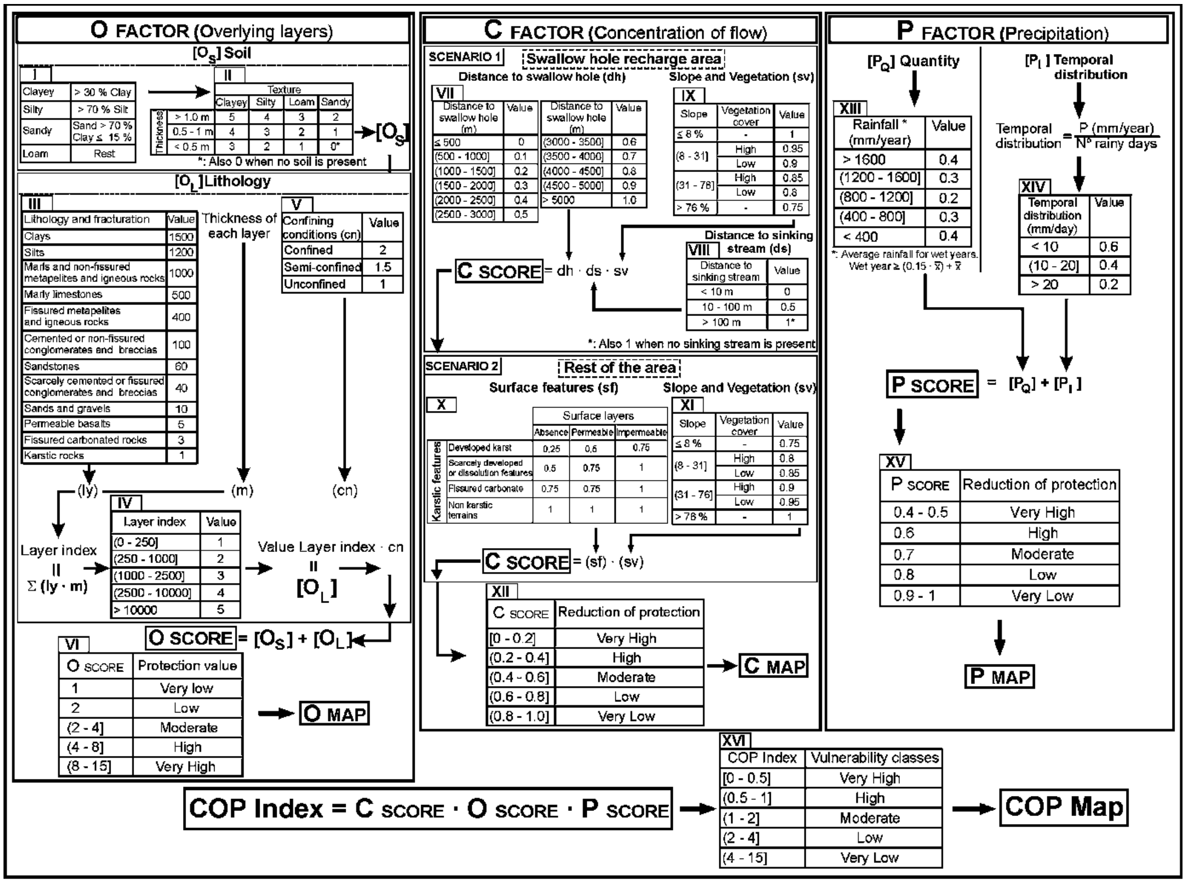

Figure 1: Detailed methodology to apply COP method in vulnerability mapping (Vias et al., 2006)

Table 3: Parameters and equation involved in the generation of maps in COP method

Attribute	Parameters	Description	Involved Calculations
C Factor	dh	distance to swallow hole	Two scenarios: Scenario 1: C Score = dh * sv * ds Scenario 2: C Score= sv * sf
	sv	slope and vegetation	
	ds	distance to sinking stream	
	sf	sf	
O Factor	Os	Soil texture and thickness corresponding score	O Score = Ol + OS
	OL	Lithological and fracturation features and maturity	
P Factor	PQ	Total annual precipitation	P Score = PQ + PL
	PL	Precipitation intensity = total annual precipitation / rainy days	

The complexity of karst aquifers is related to their susceptibility to kinetic dissolution that leads to the formation of various secondary structures that enhance fast infiltration pathways such as dolines, shafts, swallow holes and facilitate turbulent flow subsurface conduits. This duality of infiltration and flow renders karstic aquifers highly heterogeneous and thus vulnerable to groundwater contamination (Polemio et al, 2009). Accordingly, groundwater models that simulate various flow regimes while accounting for the complexity of karst systems are deemed ideal for the vulnerability assessment process in such conditions (Doummar et al., 2012).

Since the 1960s, numerical models have attempted to simulate flow (Sauter et al, 2006) for a better understanding of the physically based processes in a karst system. The complexity of flow (turbulent and laminar) in a highly heterogeneous karst subsurface revealed to be challenging (Scanlon et al. 2003; Worthington et al 2009), especially where

Darcian flow does not apply. A qualitative sensitivity analysis performed on an integrated distributed flow model (MIKE SHE; DHI, 2007) allowed the identification of the parameters that played a major role in karst flow processes in the catchment of the Gallusquelle spring in Southwest Germany (Doummar et al., 2012). The study considered the karst system as an equivalent porous medium and did not account for turbulent flow occurring in conduits and the laminar flow in matrix, which is another approach for modeling flow dynamics in karst. Chang et al (2015) treated turbulent flow in conduit systems as flow in a pipe and used Darcy-Weisbach, Manning Strickler, and Chezy Formula for flow calculations in conduits. Ghasemizadeh et al (2015) and Pardo-Igúzquiza et al (2016) used the equivalent porous media as a solution for turbulent and laminar flow simulation in karst system.

The selection of the type and number of parameters depends on the type of model and the complexity of the governing processes. While a model with a limited number of parameters may oversimplify the complexity of the distribution and the process, a large number of parameters increases the uncertainty of the model and limits the model uniqueness (Doummar et al., 2018). Accordingly, many sensitivity analysis methods have been developed to tackle this problem (Vrugt et al., 2003, 2005; Hill and Tiedeman, 2007; Abebe et al., 2010; Aster et al., 2013; Moreau et al., 2013; Sen and Stoffa, 2013). Sensitivity analysis, besides its role in model calibration, can identify less important parameters that tend to be neglected to simplify additional analysis (Song et al., 2015). Furthermore and in particular for hydrological models, the ranking and weighing of model parameters can identify the main processes or layers that have a major impact on recharge and discharge and thus have a significant impact on the vulnerability.

In this work, an integrated numerical model was constructed for a karst system in a semi-arid region governed by snowmelt (Doummar et al., 2018). Then, the model parameters that play an important role in intrinsic vulnerability according to the most common vulnerability mapping methods were identified and varied within the set of their physical ranges. In order to estimate the impact of these key- vulnerability parameters on the model output, mostly discharge and recharge, a detailed local sensitivity analysis was performed using Autocal (MIKE SHE Analysis Tool). Additionally, the impact of these parameters was highlighted with a variance-based statistical analysis of the model output time series. Based on several statistical analysis methods, the parameters were finally ranked according to their impact on model output. Based on a calibrated numerical model, the results of this study reassess the weights of groundwater vulnerability related parameters using a numerical modeling approach.

B. SCOPE OF WORK

The main objective of this research work was the reassessment of the importance of key parameters in intrinsic vulnerability assessment. The calibrated groundwater model of El Assal spring was used as the main tool for simulations and sensitivity analysis. The updated weights of key factors using the numerical modeling approach will result in the reclassification of key parameters that should be involved in the vulnerability assessment and the recommendations of involving additional factors. The applied methodology and expected results are summarized in Figure 2.

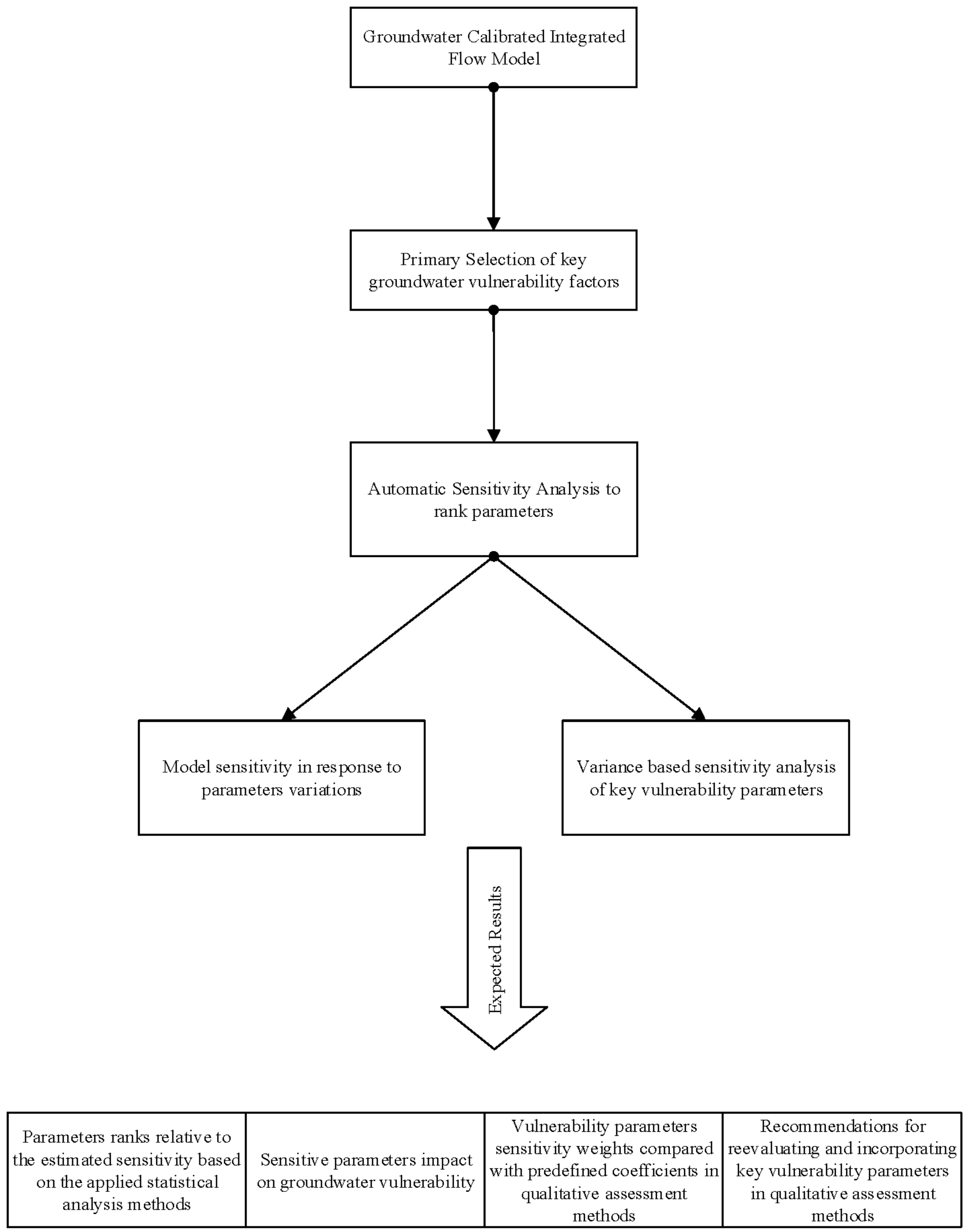

Figure 2**:** Flowchart summarizing the applied methodologies and expected results

C. SIGNIFICANCE OF RESEARCH

Groundwater karst aquifers are characterized by high recharge regimes relative to other aquifer types. Accordingly, this facilitates groundwater pollution from infiltrated contaminants. The heterogeneity of karst aquifers is another challenge that faces catchment areas management and areal vulnerability classification. In the presence of sufficient data, groundwater models are the best representation of the flow processes occurring in the subsurface that influence vulnerability indirectly. Therefore, groundwater modeling approaches to assess vulnerability is deemed quantitative, comprehensive, and more detailed than conventional qualitative assessment methods. For instance, the application of a calibrated model for vulnerability assessment can classify recharge areas at the micro-scale and therefore identify zones of high vulnerability, unlike qualitative methods that may overestimate or underestimate effective recharge zones. Moreover, a detailed sensitivity analysis can narrow down the key factors that impact the vulnerability in a manner that is unique for the evaluated system. The results of this physically based approach could be implemented in the development of a new vulnerability method with updated weighing coefficients attributed to key-vulnerability parameters.

CHAPTER II

STUDY AREA

A. TOPOGRAPHY, SURFACE HYDROLOGY, AND CLIMATE

The catchment area of El Assal spring is located at altitudes varying between 1600 and 2100 m above sea level (asl) in the Kfardebbiane Area of Mount Lebanon around 37 Km northeast of Beirut (Figure 3). The study area lies on a generally moderately sloping (10°) mountainous area towards the west in its southern parts where it becomes gentler towards the north, to the exception of dry steep sloped valleys.

The El Assal Spring sub-watershed falls in the Nahr El Kalb watershed, which includes several seasonal streams. It primarily flows towards the west discharging in Nahr El Kalb River before reaching the Mediterranean Sea.

The study area is located within the climatic zone of central Mount Lebanon. The average yearly precipitation may exceed 1,400 mm, considering the seasonal fluctuations and elevation difference, the average, minimum, and maximum temperatures within the study area are 11.8, -5.8, and 27.7 °C, respectively (Doummar et al., 2018).

B. HYDROSTRATIGRAPHY

Within the catchment area of El Assal Spring, three geological formations and deposits are outcropping. The geological formations that outcrop in the study area range in age from the recent Quaternary to the upper Cretaceous period. These formations are further described below from youngest to oldest and presented in Figure 4.

1. Quaternary Deposits (Q)

The Quaternary Deposits (Q) outcrops in the southwestern parts of the catchment area at the level of El Assal Spring represented by white dotted and grey colors. These deposits are anticipated to be sediments accumulations from the upper outcropping geological formations. As a consequence, these outcrops mainly consist of detrital limestone, conglomerates, marls, and alluvial deposits. Generally, the Quaternary deposits act as a semi-aquifer within Lebanon, but due to the limited thickness and extent within the catchment area it is not expected to act as a water bearing zone within the study area.

2. Sannine Formation (C4)

The Sannine Formation (C4) is usually combined with the Maameltain Formation (C5) because together they form one of the main aquifers in Lebanon. Exceeding 500 m in thickness, this formation combination is of the Upper Cretaceous Period and it covers most parts of El Assal Spring catchment area. The lithology of these formations varies from fractured limestone to marly limestone with some local occurrences of chert nodules. Given its highly karstified nature within the study area, it is the groundwater reservoir that leads to the emergence of El Assal Spring in combination with the underlying impermeable layer (Hammana Formation). In addition to that, dolines presented in Figure 4 facilitate groundwater recharge due to the dissolution features present in their middle parts. The sizes of the mapped dolines within the catchment area is proportional to that of their radius as shown in Figure 4.

The groundwater flow direction is presented in Figure 4. It is mainly controlled by the dip direction of the stratigraphic beds, groundwater conduits system, and topography. The main groundwater flow direction is towards the west.

3. Hammana Formation (C3)

Classified as an aquiclude, the Hammana Formation (C3) is the impermeable layer that prevented further percolation of groundwater from the overlying Sannine-Maameltain Aquifer and allows its emergence as a spring. Mainly, the Hammana Formation is composed of marls outcropping parallel to the Quaternary deposits at the southwestern areas of the catchment area.

C. STRUCTURAL SETTINGS

Faqra and Jabal Hosmaya Northeast-Southwest trending Strike Slip fault systems cross-cuts the El Assal Spring catchment areas (Figure 4).These fault systems have played a role in facilitating groundwater recharge through the conduit systems established along the faults planes upon limestone dilution along these weak planes. In particular, the Faqra fault system has played a major role in the emergence of El Assal spring where the main conduit system within the catchment area is expected to be parallel to groundwater flow direction and passing through the spring's discharge location. As a result, the emergence of El Assal spring was athe result of the stratigraphic (underlying impermeable layer) and structural (Faqra Fault) conditions of the study area.

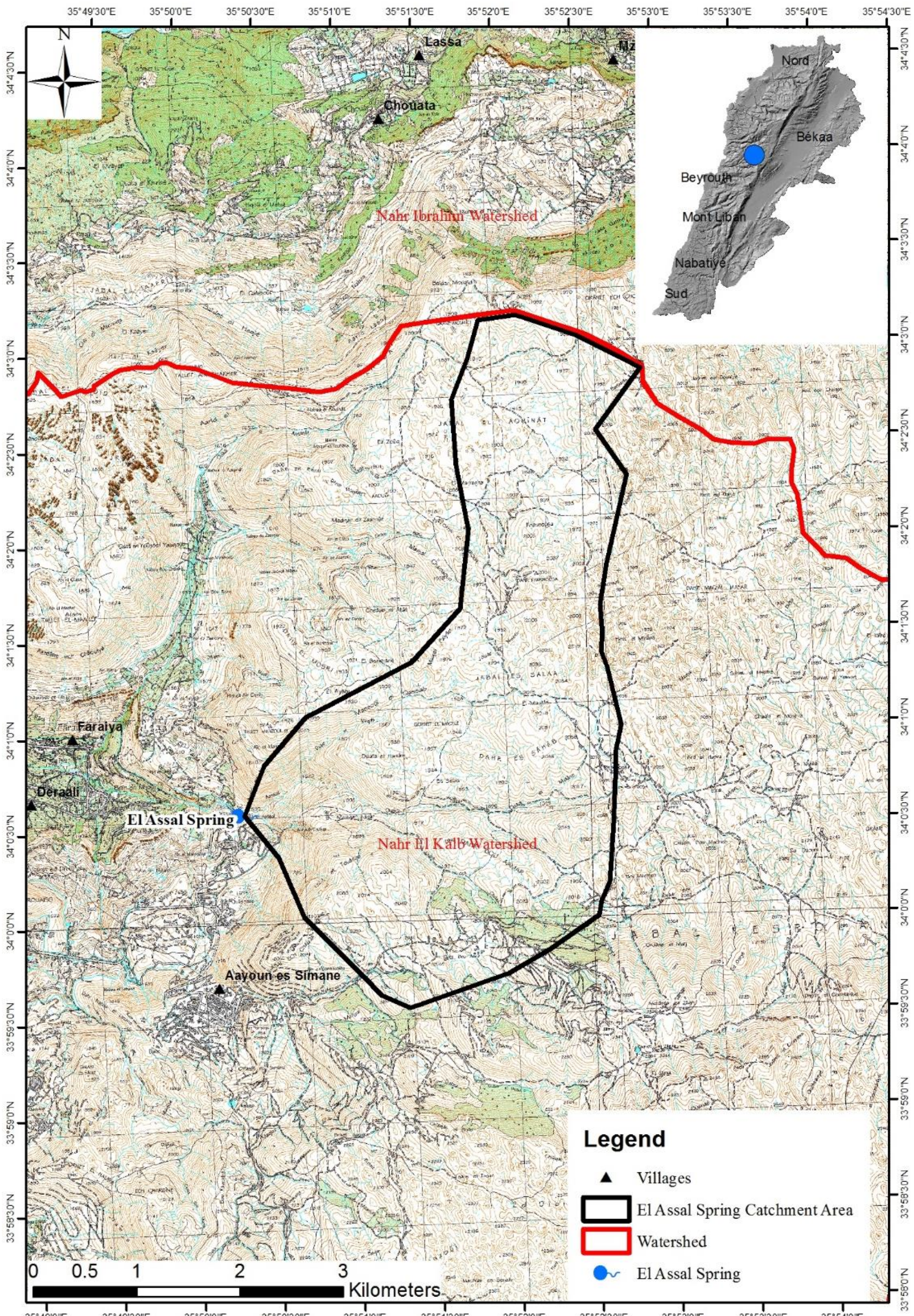

Figure 3: Topographic Map of the Study Area

Topographic maps of Farayya, Biskinta, Afqa, and Sannine: 20,000 Directorate of Geographic affairs (Beirut-Lebanon)

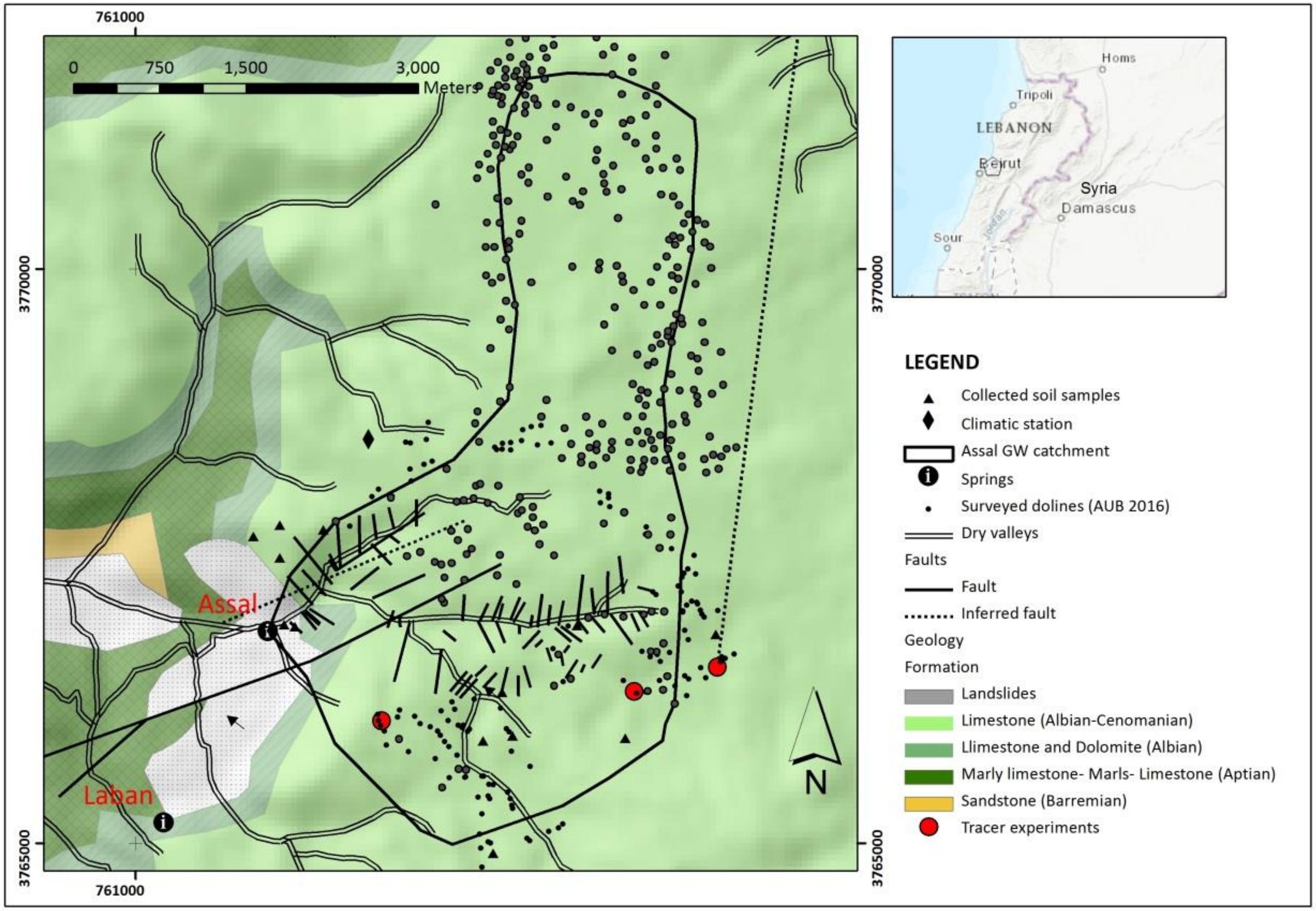

Figure 4: Hydrogeological Map of the catchment area of El Assal Spring

CHAPTER III

TOOLS AND METHODS

A. INTEGRATED FLOW MODEL

A spatially distributed transient integrated groundwater flow model was constructed using MIKE SHE (DHI, 2017, Doummar et al., 2018). The conceptual model was set based on the methodology adopted in (Doummar et al, 2012, Doummar et al., 2018). The model geometry and parameterization was based on surface and subsurface characterization of the catchment area. The model was calibrated and validated based on daily discharge measurements (2015-2018) with a Nash Sutcliffe Coefficient (NSE) and a RMSE of 0.77 and 0.218 m^3/s respectively. In the model geometry and parameterization, bypasses were used to deviate water from the unsaturated zone directly to the saturated zone to simulate fast infiltration pathways below the mapped dolines. The highly conductive layers in the saturated zone were assigned to dry valleys (Doummar et al., 2012, Xanke et al., 2015). Additionally, dissolution and weathering along fault planes, which is the case in the mapped highly conductive lens, is a main reason for a higher flow in a mature karst system (Waltham, 2002). As a result, these locations are expected to have higher conductivities compared to other parts of the aquifer.

Based on the calibrated model (daily time-step) of El Assal spring (Doummar et al., 2018), a sensitivity analysis was performed to quantify the vulnerability of key parameters on the model results. The methodology consists of three main steps that will be discussed later in details:

1) A sensitivity analysis using the sensitivity option in Autocal in MIKE SHE yields a ranking of the model parameters according to their impacts on model results
2) A detailed sensitivity analysis to quantify the impact of parameters on model outputs such as discharge, yearly recharge and infiltration based on Autocal results of most important parameters.
3) A synthesis of sensitivity analysis results to highlight and rank the most important parameters influencing recharge thus vulnerability and their effect on the shape of the spring hydrograph in high and low flow period

B. PARAMETERS SELECTION CRITERIA

Common parameters that are key factors for groundwater vulnerability according to qualitative vulnerability assessment methods are evaluated. Table 4 presents the main vulnerability assessment methods applied for karst aquifers and their corresponding parameters that play a role in each of the hydrological cycle compartments. Each method is characterized by its own prioritization of factors and selectivity. For instance, the COP method solely considers precipitation in the groundwater susceptibility assessment. Moreover, geomorphology and land use are addressed as sensitive factors while applying the EPIK method only. In addition, most of the parameters that are related to the unsaturated and saturated zone are included in the COP and EPIK methods. Accordingly, parameters that will be initially assessed using the Autocal methods that will be introduced in the next section are those include in the COP and EPIK methods. After that further analysis will be conducted for the most important parameters as per the results deduced from Autocal analysis.

Table 4: Key parameters in groundwater qualitative vulnerability assessment methods

	Vulnerability parameters	**Model parameters and data**	**Type of data**	**Parameters representation in vulnerability mapping methods**				
				GOD	DRASTIK	EPIK	PI	COP
Atmosphere	Precipitation	P	time series	No	No	No	No	Yes
	Temperature	T	time series	No	No	No	No	No
	Reference ETP	ETP_{Ref}	time series	No	No	Yes	No	No
	Slope	Topography	spatial	No	No	Yes	No	No
	Land use/cover	C1, C2, C3, and K_{crop}	spatial	No	No	Yes	No	No
Unsaturated zone	Protective cover thickness	Soil thickness	spatial	No	Yes	Yes	Yes	Yes
	Lithology of soil types	Ksat, θsat, FC, and WP	single parameter	Yes	Yes	Yes	Yes	Yes
	Epikarst	λ and ψ	single parameter	No	No	Yes	No	No
	Bypass	% of bypass	single parameter	No	No	Yes	Yes	Yes
	Infiltration	Model output	time series	No	No	Yes	Yes	Yes
Saturated zone	Net Recharge	Model output	time series	No	Yes	No	No	No
	Depth to Groundwater	Model output	spatial time series	Yes	Yes	Yes	No	No
	Aquifer media	K_m (hydraulic conductivity)	single parameter	No	Yes	No	No	No
		Sy_m (Specific Yield)	single parameter	No	Yes	No	No	No
	Karst Network	K_{lens} (hydraulic conductivity)	single parameter	No	No	Yes	No	No
		Sy_{lens} (Specific Yield)	Single parameter	No	No	Yes	No	No
		Lens width	spatial	No	No	Yes	No	No

C. AUTOMATIC SENSITIVITY ANALYSIS (AUTOCAL)

The sensitivity analysis option in Autocal was applied for the initial screening of the local sensitivity of the most important parameters included in the model during the calibration and validation process. Autocal runs with the pre-simulated model run as the basis towards assessing the parameters variations within a provided range. The end result will be the importance or the sensitivity of each selected parameter using the local sensitivity analysis method that works only within the given range and set of parameters. The sensitivity of the model towards key vulnerability parameters is estimated using the difference approximation according to equation (1) (DHI, 2017). Autocal estimates the sensitivity coefficients using the finite difference approximation according to three algorithms depending on the user's preference. Prevailing equations of approximations of sensitivity coefficients are summarized in Table 5. ΔΘi is the perturbation fraction and it is the fraction f_c of the initial parameter or parameter range. The perturbation factor can be calculated using Equations 2 and 3 depending on the choice of parameter perturbation.

$$S_i = \frac{\partial F}{\partial \theta_i} \qquad (1)$$

$$\Delta\theta_i = f_c\theta_i \qquad (2)$$

Fraction of initial parameter value

$$\Delta\theta_i = f_c(\theta_{i,upper} - \theta_{i,lower}) \qquad (3)$$

Where

F is the output measure

θ_i is the model parameter

$\Delta\theta_i =$ Fraction of the parameter interval

$\Theta_{i,upper}$ and $\Theta_{i,lower}$ are the specified limits of the parameter

Table 5: Governing equations for various sensitivity analysis approximation methods by Autocal

Approximation algorithm	**Approximation formula**	**No. of needed evaluations**
Forward difference approximation	$S_i = \frac{F(\theta_1, \theta_2, \ldots, \theta_i + \Delta\theta_i, \ldots, \theta_n) + F(\theta_1, \theta_2, \ldots, \theta_n)}{\Delta\theta_i}$	n+1
Backward difference approximation	$S_i = \frac{F(\theta_1, \theta_2, \ldots, \theta_n) - F(\theta_1, \theta_2, \ldots, \theta_i - \Delta\theta_i, \ldots, \theta_n)}{\Delta\theta_i}$	n+1
Central difference approximation	$S_i = \frac{F(\theta_1, \theta_2, \ldots, \theta_i + \Delta\theta_i, \ldots, \theta_n) - F(\theta_1, \theta_2, \ldots, \theta_i - \Delta\theta_i, \ldots, \theta_n)}{2\Delta\theta_i}$	2n+1

The sensitivity analysis is initially performed by Autocal by comparing the simulated and calibrated time series to calculate the RMSE. Furthermore, the user defined objective function (weighted sum of squares) is then applied to aggregate the error estimated in the initial step and rank different varied parameters after error generalization using the objective function.

Given the complexity of the processes within the different compartments and to avoid computational complexity, the central approximation method was not applied. Moreover, because the forward and backward approximation methods have relatively similar accuracy it was sufficient to apply the analysis employing one method (Ngaradoumbe Nanhorngué et al., 2012). The sensitivity analysis applied within the context of this work is time dependent and uses earlier time-steps outcomes for results improvement which urged the use of backward difference approximation as the ideal method for the available simulations (Momoniat et al., 2013). Concerning the impact of parameters that induces time lag in model outcomes, this was primarily addressed in Doummar et al. 2018 and they were primarily related to climatic factors. As a result, the induced time lag by these parameters will exacerbate the simulated model uncertainty classifying the varied parameter as sensitive according to its impact on recharge/discharge time and rate. The most important parameters involved in the qualitative assessment of intrinsic vulnerability of aquifers (EPIK, COP, etc.) were employed for the sensitivity analysis using Autocal. The analyzed parameters using Autocal are presented Table 6.

Table 6: Parameters involved in the sensitivity analysis applied using Autocal

Component		Parameters	Unit	Type of Data	Calibrated Value	Local Sensitivity Ranges
Atmosphere and surface	**Snow melt**	Melting temperature	°C	Literature	1	0-2
		Degree day coefficient	mm/°C /day		2	1-5
	Vegetation (Kristensen and Jensen)	Leaf Area Index (LAI)	-	Seasonal time series	Seasonal time series specific for crop type from literature	4-10
		Root Depth- (RD)	m			0.1-1.2
		C_1	-	Fitting	0.2	0.2-0.4
		C_2	-		0.2	0.1-0.3
		C_3	mm/day		20	10-30
		A_{root}	-		0.25	0.1-0.35
		C_{int}	mm		0.05	0.01-0.1
Unsaturated Zone	**Soil**	Hydraulic Conductivity at saturation (K_s)	m/s	Measured	1.21E-05	1.0E-05-1.0E-04
		Saturated moisture content (θ_s)	-	Measured	0.39	0.375-0.459
		Residual moisture content (θ_r)	-	Measured	0.176	-
		Alpha (α)	1/m	Measured	0.035	0.1-0.15
		n	-	Measured	1.75	-
	Unsaturated rock matrix	Hydraulic Conductivity at saturation (Kuz_s)	m/s	Measured	10.0E-04	10.0E-05 -10.0E-03
		Saturated moisture content (θuz_s)	-	Measured	0.3	0.09-0.4
		Bubbling pressure (ψ_b)	m	Fitting	0.2	0.15-0.22
		Particle size index (λ)	-	Fitting	0.17	0.15-0.2
	Bypass	Bypass portion of net rainfall (BYP)	-	Fitting	0.25	0.1-0.4
		Moisture content for reduced bypass (BYPθ)	-	Fitting	0.06	0.05-0.2
		Moisture content for no bypass (NOBYP)	-	Fitting	0.05	0-0.1
Saturated Zone	**Low conductive Matrix**	Hydraulic conductivity (vertical and horizontal) (K_{xx}, K_{yy})	m/s	Measured	5.00E-05	10.0E-08-10.0E-03
		Specific yield (S_{ym})	-		0.1	0.02-0.5
		Specific Storage (S_{sm})	1/m		1.0E-04	10.0E-05-2.0E-04

Component	Parameters	Unit	Type of Data	Calibrated Value	Local Sensitivity Ranges
Highly conductive zone	Hydraulic conductivity (vertical and horizontal) (K_x, K_y)	m/s	Fitting	0.3	0.001-0.4
	Specific yield (S_{yc})	-		0.1	0.09-0.5
	Specific Storage (S_{sc})	1/m		10.0E-05	10.0E-06-10.0E-04

D. Manual Statistical Sensitivity Analysis

1. Sensitivity analysis using performance measures

Multiple simulations were performed with subsequent variations of one model parameter at a time selected depending on the sensitivity analysis applied using Autocal. The most important parameters were varied within physical ranges to test their weighted influence on groundwater susceptibility, in other terms to define the degree to which model output are sensitive to the selected parameters. The analysis was done on two hydrological years for model output used previously for validation. Calibrated model time series outputs (infiltration through unsaturated zone; UZ; recharge to saturated zone; SZ, and spring discharge; Q) were used as reference for statistical analysis. The statistical objective functions main aim is to assess the local sensitivity of the model output to certain parameter variations. Qualitatively, the model sensitivity was assessed relative to the objective functions presented in Table 7 along with their impact on groundwater vulnerability and model performance. The statistical objective functions test the model sensitivity to parameters variation. RMSE, R^2, and Nash-Sutcliffe have been widely applied for hydrological models assessment (Legates and McCabe, 1999; Gupta et al., 2009). These parameters evaluate the correlation, variability, and bias of the simulated model outputs versus the observed data. Kling-Gupta Coefficient (KGE), as an additional statistical objective function, helps in understanding the overall model performance by compiling all the objectives that other statistical functions tackle (correlation, variability, and bias) (Gupta et al., 2009). For instance, Kling et al. has applied KGE for hydrological model performance evaluation in the Danube Basin (2012). Results have shown that KGE succeeded in meeting its main objectives (correlation, variability, and bias) with simple assessment representation.

Table 7: Preliminary performance measures of model outputs of varied parameters

Performance measure		**Selection criteria and ranking**	**Impact on vulnerability**
Residual Mean Square Error (RMSE)	$RMSE = \frac{1}{n}\sqrt{\sum_{i=1}^{n}(S_i - C_i)^2}$	RMSE closer to 0	Integrated sensitivity of the calibrated model in response to parameters variations
Nash Sutcliffe coefficient (E)	$E = 1 - \frac{\sum(S_i - C_i)^2}{\sum(S_i - \frac{1}{n}(\sum S_i))}$	Closer to 1	
Coefficient of determination (R^2)	$R^2 = 1 - \frac{\sum(S_i - C_i)^2}{\sum(C_i - C_{ave})^2}$	Closer to 1	
Recession Coefficient (α)	$\alpha = \frac{1}{t}\ln\frac{Q_{max}}{Q}$	Closer to calibrated	Sustainable volume available for dilution and aquifer response to upper hydrological compartments
Maximum ($\boldsymbol{Q_y}$)	Maximum (Q_y)	Closer to calibrated	Sustainable volume available for dilution
Minimum ($\boldsymbol{Q_y}$)	Minimum (Q_y)		
Mean ($\boldsymbol{Q_y}$)	Mean (Q_y)		
Kling-Gupta Coefficient (KGE)	$1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2}$		Model performance and Volume available for dilution

where n is the number of compared outputs, Q is the spring discharge rate at time t, Qmax is the maximum spring discharge rate within a hydrological year Cave is the mean value of the calibrated time series in a certain hydrological year, Si is the simulated value of spring discharge at time i, Ci is the calibrated value spring discharge at time i. Q y is the spring discharge rate in a hydrological year y r: is the linear correlation coefficient between the simulated and observed data, β is the is the ratio between the mean simulated and mean observed data (measures bias), γ is a measure of relative variability in the simulated and observed values, Model output associated with vulnerability consists of spring discharge (maximum, minimum, and mean) and recession coefficient (α). Spring discharge is the resultant force vector of all underground and exposed hydrological processes. The fast and high response of the spring discharge shows rapid contaminants transport due to the high maturity of the karst system that results in a high susceptibility to contamination (Leibungut, 1998). The mean and minimum discharge rate of the spring confirm the sustainable water volumes available throughout the hydrological inducing an impact on the contaminants concentration (Butscher and Huggenberger, 2008). For instance, high recession coefficient implies high sensitivity of the spring to contamination where water discharge from the system will be faster resulting in unsustainable water quantities throughout the hydrological year (Escolero et al., 2002). Lower water quantities leads to lower dilution factor and higher concentrations of transported contaminants.

Moreover, additional sensitivity analysis of the model in relation with hydraulic parameters variations besides the geomorphological effect on groundwater vulnerability will be discussed in the following subsections.

2. Variance-based sensitivity assessment

To assess the local sensitivity towards the key vulnerability parameters tested using Autocal tool, several statistical sensitivity assessment methods were applied. Statistical functions for the sensitivity analysis along with their ranking criteria and relationship to groundwater vulnerability are presented in Table 8. The analysis was performed mainly on the hydraulic parameters of the vadose and phreatic zones.

The ratio of the variance of the parameters variation physical ranges as assigned based on literatures and prior to analysis to that of the variance of several model output data was estimated (Song et al., 2015). Model output time series data were summed or averaged to be represented by one number for calculations. As expected, the model has sensitivity approximation with respect to each of the varied parameters. Accordingly, a score is assigned to each of the explored parameters relative to the maximum and minimum sensitivity values. Three local sensitivity measures related to the variance of model output and parameter variation were adopted to validate the used methodology (Table 8).

Table 8: Local sensitivity of groundwater towards parameters variation

Local Sensitivity Measure	**Ranking Criteria**	**Relationship with groundwater Vulnerability**
Discharged Volume (V) $\frac{\sigma^2(Parameters\ Variation)}{\sigma^2(V)}$	Local sensitivity and values of the measures are inversely proportional to parameter sensitivity	Volume available for dilution
Mean Spring Discharge (Qt) $\frac{\sigma^2(Parameters\ Variation)}{\sigma^2(Mean\ (Qt))}$		Sustainable volume available throughout the hydrological year
Sum of Residuals (R) $\frac{\sigma^2(Parameters\ Variation)}{\sigma^2(R)}$		Spring discharge variations that can show groundwater quantities deviations

The ranking of model parameters according to the model's local sensitivity in accordance with their variations can produce the basis of the newly developed vulnerability method with weights that are unique for each evaluated system. With respect to the three evaluation measures are presented in Table 8, these objective functions allow the assessment of model variations effects on groundwater vulnerability. For instance, measures related to total discharged volume from the system and mean spring discharge are interconnected with the available volume in the system for contaminants dilution and sustainable availability of groundwater flow throughout the hydrological year respectively as mentioned earlier. The function related to the sum of the residual error of spring discharge, besides its evaluation of the model performance to variation of the parameters (Loague and Corwin, 1998), estimates the spring discharge variations with respect to a mean value, as a response to parameter variation. So the residual error was calculated for each time step between the simulated and calibrated model where the sum residual error per hydrological year was estimated. Furthermore, all the sums of residual error per simulation will be aggregated in the variance calculations.

3. Geomorphology and Groundwater Vulnerability

The general assessment of the groundwater recharge corresponding to the different slopes and geomorphological features spatially distributed within the catchment area was done. The categories considered for model outputs extraction are dolines and rocks outcrops. Exposed rocks and slope steepness can affect surface water infiltration into the groundwater thus affecting the rate of contaminants transport to groundwater (Abdullah et al., 2015; Ghazavi and Ebrahimi, 2015). The sensitivity analysis was performed on the extreme levels of slope steepness and exposed lithology, very gentle to very steep and soil to bare-rock respectively. All assessed scenarios of slopes and exposed surface material combinations are presented in Table 9. Consequently groundwater recharge within areas of the presented the two slope steepness categories combined with either Bare-rock or dolines is assessed and estimated to understand how morphology impact groundwater total recharge and fast infiltration trends.

Table 9: Slope and exposed material combinations for sensitivity analysis

Slope Steepness	Surface Exposed Material
Very Steep (> 35°)	Bare-Rock (Fractured Limestone)
	Doline (Clayey Soil)
Very Gentle (0°-5°)	Bare-Rock (Fractured Limestone)
	Doline (Clayey Soil)

CHAPTER IV

RESULTS AND DISCUSSION

Sensitivity analysis results based on the Autocal and additional statistical tools are the basis for the weighing of the tested parameters. The applied analysis methods results are matched to conclude a composite ranking of the assessed parameters. In addition, each tested parameter, depending on its impact weight, will be assessed for its influence on groundwater vulnerability. Moreover, the impact of climatic parameters on vulnerability was presented from a previous study (Doummar et al., 2018). Finally, the impacts of spatial variability of geomorphology (such as exposed rocks/soil and slopes) on groundwater vulnerability are further discussed.

A. AUTOCAL RESULTS AND ANALYSIS

The Sensitivity analysis of parameters (Table 6) reflective of processes in the major compartments of the hydrologic cycle yielded a ranking of parameters according to their influence on model output. Table 10 summarizes Autocal sensitivity analysis results and parameter ranking. Aggregated sensitivity coefficients were normalized (with respect to the maximum coefficient) to obtain a value between 0 and 1 for comparison purposes. Additionally, the sensitivity coefficient is proportional to the impact of each parameter.

Table 10: Sensitivity Analysis Results of Autocal on Selected Parameters

Parameter	**Hydrological Compartment**	**Sensitivity Coefficient**	**Sensitivity Normalized Coefficient**	**Ranking**	**Sensitivity Categories**
Saturated moisture content (θ_s)	Uz (Soil)	8.32E-03	1.00	1	Most Sensitive
Alpha (α) soil	Uz (Soil)	7.55E-03	0.91	2	
n soil	Uz (Soil)	6.88E-03	0.83	3	
Bypass portion of net rainfall (BYP)	Uz (Epikarst)	5.00E-03	0.60	4	
Degree day coefficient (D)	Atmosphere	2.25E-03	0.27	5	Moderately Sensitive
Melting temperature	Atmosphere	2.19E-03	0.26	6	
Hydraulic conductivity (horizontal) (K_{xx}) aquifer	Sz (aquifer)	1.81E-03	0.22	7	
Saturated moisture content (θuz_s)	Uz (Epikarst)	1.00E-03	0.12	8	
C_{int}	Surface (Vegetation)	8.58E-04	0.10	9	
Hydraulic conductivity (horizontal) (K_x) lens	Sz (lens)	7.13E-04	0.09	10	
Hydraulic Conductivity at saturation (K_s)	Uz (Soil)	3.18E-04	0.04	11	Least to not Sensitive
Bubbling pressure (ψ_b)	Uz (Epikarst)	2.76E-04	0.03	12	
Particle size index (λ)	Uz (Epikarst)	9.41E-05	0.01	13	
C2	Surface (Vegetation)	7.19E-05	0.01	14	
C3	Surface (Vegetation)	2.85E-05	0.00	15	
LAI	Surface (Vegetation)	1.84E-05	0.00	16	
Hydraulic Conductivity at saturation (Kuz_s)	Uz (Epikarst)	1.14E-06	0.00	17	
Hydraulic conductivity (vertical) (K_{yy})	Sz (aquifer)	0.00	0.00	18	
Aroot	Surface (Vegetation)	0.00	0.00	19	
C1	Surface (Vegetation)	0.00	0.00	20	
Moisture content for no bypass (NOBYP)	Uz (Epikarst)	0.00	0.00	21	

Parameter	Hydrological Compartment	Sensitivity Coefficient	Sensitivity Normalized Coefficient	Ranking	Sensitivity Categories
RD	Surface (Vegetation)	0.00	0.00	22	
Moisture content for reduced bypass (BYPθ)	Uz (Epikarst)	0.00	0.00	23	
Specific Storage (S_{sc})	Sz (lens)	0.00	0.00	24	
Specific yield (S_{yc})	Sz (lens)	0.00	0.00	25	
Specific Storage (S_{sm})	Sz (aquifer)	0.00	0.00	26	

Moreover, Figure 5 shows a plot of the parameters versus the sensitivity coefficient, where parameters were divided into four categories. Parameters related to the unsaturated zone soil hydraulics (θ_s soil saturated moisture content, and α and n Van Genuchten water retention curve empirical parameters) and BYP (bypass portion of net rainfall) in the epikarst layer scored the highest sensitivity coefficient. This is consistent with the reality that soil is the first receptor of surface contaminants and soil hydraulics and thickness are the main factors that participate in the infiltration and transportation of contaminants to groundwater (Bazimenyera et al., 2008; Prasad et al., 2010; Muhammad et al., 2015).

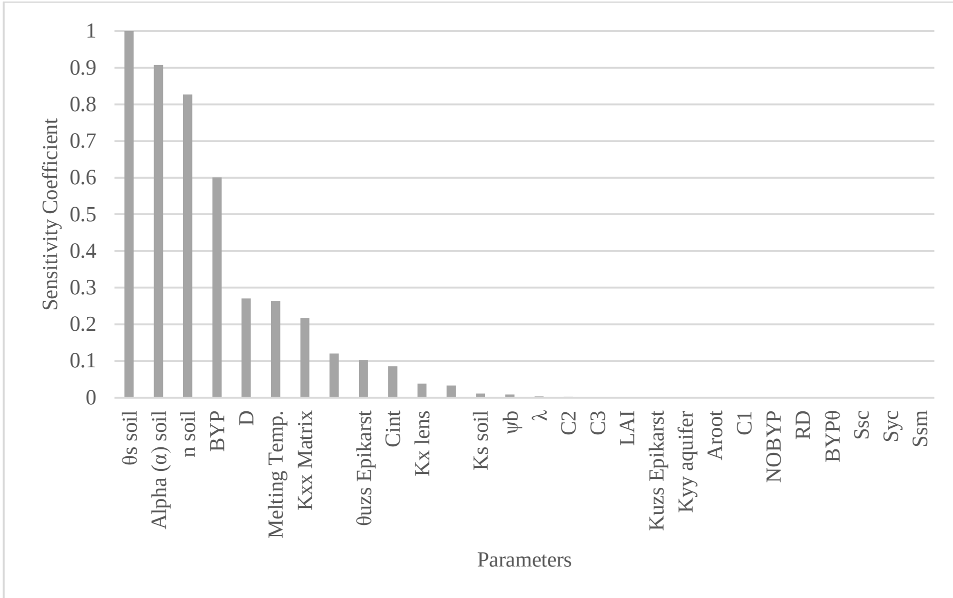

Figure 5: Parameters versus sensitivity coefficient plot

Climatic parameters, specifically temperature and precipitation, affect the storage and levels of groundwater inducing impact on groundwater vulnerability (groundwater volume for contaminants dilution) (Stuart et al., 2011). Accordingly, parameters related to temperature (Degree Day Coefficient (D) and melting temperature) were categorized in the moderately sensitive class. Additionally, because high hydraulic conductivity values can facilitate the movement of contaminants through the aquifer, this parameter also belong to the same category of sensitivity.

Finally, factors related to the vegetation cover and epikarst empirical parameters were the least important or negligible in the model output. For instance, because the modeled aquifer is unconfined and karstic, specific storage of the aquifer is not expected to have any impact on the dynamics in the aquifer which is coherent with their sensitivity coefficients to be classified as non-sensitive. The hydraulic property (Klens) of the highly conductive zone are calibrated values that are already above physical ranges (to simulate fast flow> 0.5 m/s).), thus, the local sensitivity analysis shows a less important effect of this parameter on the model output. With respect to the soil hydraulic properties that play a role in fast infiltration according to soil saturation (NOBYP and BYPθ), the model was not sensitive to variations of these parameters because at saturation the main factors that control water flow through soil is the bypass fraction of the total precipitation (BYP).

Generally, Autocal sensitivity outcomes coincided with the results of Doummar et al. (2012) that was conducted on the karstic catchment area of Gallusquelle spring in the Swabian Albs (2012). Results concurrence, classifying parameters as per model compartments, have shown that model output were the most sensitive to parameters related to the unsaturated zone followed by those related to the aquifer and then to the highly conductive lens.

B. TIME SERIES STATISTICAL ANALYSIS RESULTS

Based on the outcomes of the Autocal sensitivity analysis, additional manual statistical evaluations were conducted on the most important parameters. Primarily a general screening of the impact of the selected parameters was performed using the different statistical objective functions presented in Table 7. The effects on groundwater vulnerability were inferred upon the extraction of additional preliminary statistical evaluation. Variance based statistical methods to assess and validate the local sensitivity of the model parameters were also applied. Additionally, the impacts of climatic parameters, slope, and geomorphological factors on groundwater vulnerability within the catchment area were assessed as well.

1. Preliminary Statistical Assessment

Table 11 and Table 12 summarize the statistical and model outputs results evaluation for Year 1 and Year 2 respectively (2015-2016 and 2016-2017). The studied objective functions are those presented earlier in Table 7. The parameters selected for individual analysis were dependent mainly on the Autocal results and were selected from the different categories of sensitivity (high to low). These are aquifer specific yield, bypass fraction from unsaturated zone, soil thickness, hydraulic conductivity of the aquifer and the highly conductive zone, as well as the soil saturated moisture content. Soil hydraulic parameters were not varied individually, the effect of soil was tested by applying multi-parameters variations (θ_s, α, n…etc.) reflective of the soil type (sandy, loamy sand, etc.) to maintain an actual physical-based approach. The calibrated model results were used as a benchmark for the statistical analysis, to determine the impact of parameter variation on model output i.e., recharge and discharge and indirectly on groundwater vulnerability.

The model was sensitive to variations in all parameters except for the aquifer specific yield. The RMSE based on specific yield variations amounted to around 0.11 m^3/s while the average RMSE of all other model parameters variation was 0.7 m^3/s. Moreover, KGE that takes into considerations correlation, bias, and variability indicated that soil thickness, and the hydraulic conductivity of the lens and aquifer are the parameters with the highest impact on model among the rest. Soil thickness and K (lens) changes induced a decrease in KGE in the increasing and decreasing trends of variations from the actual calibrated values. While Autocal sensitivity analysis was performed for the horizontal and vertical compartment of K (lens) separately, the manually applied statistical methods considered variations in both directions all at once. The latter explains the discrepancy in the classification of this parameter. Similar to K (lens) and soil thickness but to an extent, Km (aquifer) alterations have decreased the KGE index value. In particular, decreasing the Km (aquifer) to a threshold value of 10^{-6} m/s showed a reduction in the KGE index. While with a further decrease in Km (aquifer) ($<10^{-6}$ m/s), the KGE value started to converge to a value of 1 consequently having a minimal impact on model results beyond this range. These results apply for Year 1 and Year 2 as seen in Table 11 and Table 12. In addition, the comparison between calibrated model spring discharge signal and spring discharge outcomes upon parameters variations was presented in Figure 6. As shown, parameters with great effect on model sensitivity (Kx lens) induces a great shift of the spring discharge curve from the calibrated curve, whereas parameters (Sym) with less impact on model performance has much smaller influence on the model outcome.

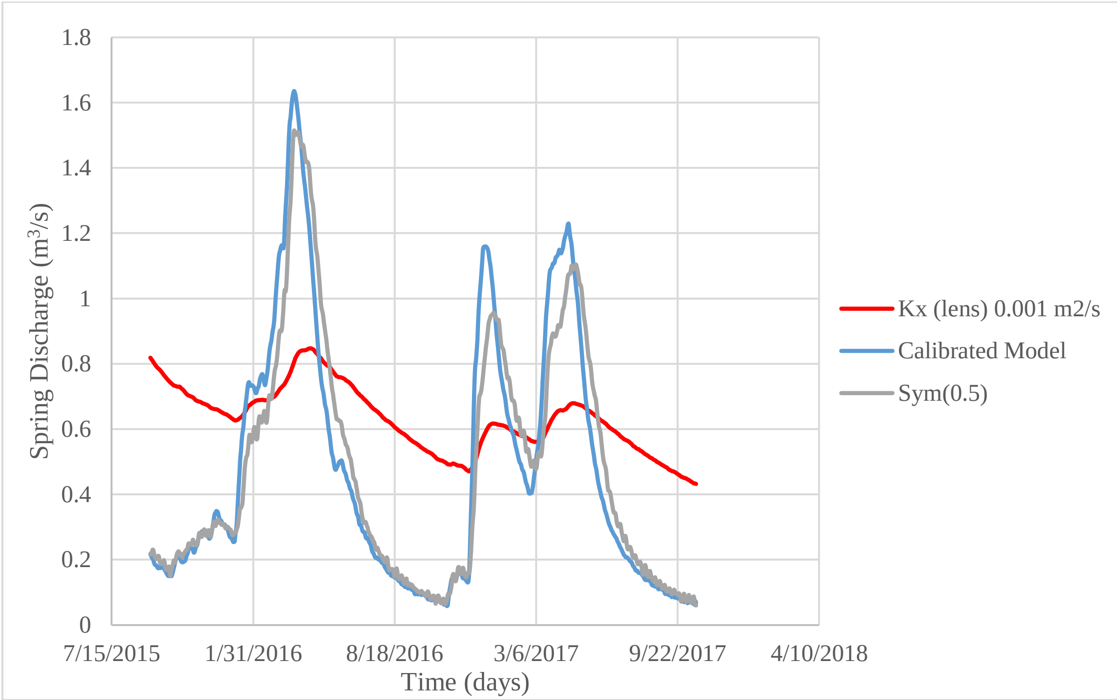

Figure 6: Spring discharge of calibrated model and other simulations with varying parameters

Spring discharge (minimum, mean, and maximum), total discharge volume, and recession coefficients resulting from parameter variations are used to assess the impact of model parameters on groundwater vulnerability. These parameters are all linked to the rate of dewatering of the groundwater system and the sustainable groundwater availability throughout the year as mentioned earlier. Among others, Bypass is the only parameter that had limited effect on annual spring discharge. Table 13 summarizes the relationship between parameters variations and groundwater vulnerability. Based on the results, the following conclusions were made for each of the effective parameters that impact groundwater vulnerability:

- Specific yield and Saturated moisture content (θs) variations from the calibrated parameter value have increased groundwater vulnerability;
- Soil thickness is inversely proportional to groundwater vulnerability; and
- Higher hydraulic conductivity values of the highly conductive zone and the aquifer increase groundwater vulnerability.

Table 11: Year 1 model initial statistical analysis on the varied parameters

Tested Parameters Variations / ***Objective Functions***	**Calibrated Model**	**Specific Yield**					**Bypass**				**Soil Thickness**				**Km (aquifer)**				**Klens**				**Saturated moisture content (θs)**		
		0.02	**0.05**	**0.08**	**0.25**	**0.5**	**0.005**	**0.15**	**0.4**	**0.5**	**1**	**3**	**7**	**10**	**1.00E-07**	**1.00E-06**	**0.0001**	**0.001**	**0.001**	**0.01**	**0.04**	**0.08**	**0.375**	**0.387**	**0.459**
RMSE (m^3/s)	0	0.1191	0.1173	0.1183	0.1175	0.1188	0.7272	0.7264	0.7274	0.7290	0.7577	0.7383	0.7250	0.7210	0.7318	0.7587	0.7104	0.7089	0.8451	0.7557	0.7252	0.7334	0.7266	0.7394	0.7240
KGE	1	0.9312	0.9323	0.9339	0.9311	0.9343	0.9982	0.9991	0.9974	0.9908	0.8918	0.9489	0.8704	0.7558	0.9757	0.6304	0.8221	0.7070	-0.0414	0.6012	0.9391	0.8699	0.9444	0.9337	0.9739
Qmax (m^3/s)	1.6359	1.5067	1.5013	1.5116	1.5134	1.5144	1.6287	1.6371	1.6544	1.6376	1.7722	1.6372	1.4685	1.3653	1.7255	1.3121	1.6634	1.8408	0.8475	1.2325	1.7350	1.9170	1.6668	1.5093	1.6357
Qmin (m^3/s)	0.1216	0.1311	0.1191	0.1401	0.1243	0.1299	0.1251	0.1237	0.1206	0.1158	0.1269	0.1224	0.1301	0.1455	0.1057	0.2617	0.0400	0.0036	0.5852	0.2554	0.1032	0.0894	0.1538	0.1337	0.1234
Qmean (m^3/s)	0.5279	0.5286	0.5291	0.5296	0.5308	0.5292	0.5288	0.5277	0.5292	0.5314	0.5741	0.5450	0.5256	0.5198	0.5355	0.5756	0.5047	0.5025	0.7142	0.5710	0.5259	0.5379	0.5468	0.5242	0.5220
% Volume Change	0	48%	48%	48%	48%	48%	0%	0%	0%	1%	9%	3%	0%	-2%	1%	9%	-4%	-5%	35%	8%	0%	2%	4%	-1%	-1%
alpha	0.0135	0.0170	0.0168	0.0125	0.0141	0.0177	0.0156	0.0141	0.0105	0.0154	0.0124	0.0138	0.0152	0.0162	0.0161	0.0064	0.0208	0.0470	0.0028	0.0093	0.0098	0.0111	0.0130	0.0118	0.0143

Table 12: Year 2 model initial statistical analysis on the varied parameters

Tested Parameters Variations / ***Objective Functions***	**Calibrated Model**	**Specific Yield**					**Bypass**				**Soil Thickness**				**Km (aquifer)**				**Klens**				**Saturated moisture content (θs)**		
		0.02	**0.05**	**0.08**	**0.25**	**0.5**	**0.375**	**0.375**	**0.375**	**0.5**	**1**	**3**	**7**	**10**	**1.00E-07**	**1.00E-06**	**0.0001**	**0.001**	**0.001**	**0.01**	**0.04**	**0.08**	**7.44E-05**	**4.42E-06**	**1.71E-06**
RMSE (m^3/s)	0	0.1257	0.1250	0.1247	0.1254	0.1251	0.6590	0.6583	0.6595	0.6609	0.6757	0.6641	0.6558	0.6518	0.6612	0.6845	0.6513	0.6473	0.7482	0.6712	0.6592	0.6660	0.6597	0.6683	0.6561
KGE	1	0.8799	0.8811	0.8811	0.8803	0.8814	0.9947	0.9959	0.9944	0.9915	0.9410	0.9618	0.8438	0.8062	0.9468	0.6080	0.9230	0.8093	0.0549	0.6378	0.9308	0.8071	0.9352	0.8674	0.9735
Qmax (m^3/s)	1.2295	1.1008	1.1043	1.1003	1.0983	1.1047	1.2367	1.2239	1.2117	1.2268	1.4523	1.2014	1.0990	1.1318	1.1661	0.9729	1.1984	1.2937	0.6791	0.9701	1.2752	1.5602	1.2215	1.0993	1.2085
Qmin (m^3/s)	0.0580	0.0596	0.0636	0.0666	0.0561	0.0602	0.0578	0.0556	0.0657	0.0591	0.0571	0.0603	0.0644	0.0738	0.0535	0.1738	0.0088	-0.0096	0.4317	0.1471	0.0580	0.0422	0.0661	0.0675	0.0655
Qmean (m^3/s)	0.4351	0.4351	0.4352	0.4345	0.4349	0.4346	0.4343	0.4334	0.4350	0.4368	0.4565	0.4410	0.4301	0.4248	0.4372	0.4685	0.4242	0.4190	0.5598	0.4505	0.4346	0.4436	0.4466	0.4304	0.4291
% Volume Change	0	0%	48%	48%	48%	48%	0%	0%	0%	0%	5%	1%	-1%	-2%	0%	8%	-3%	-4%	29%	4%	0%	2%	3%	-1%	-1%
alpha	0.0148	0.0180	0.0157	0.0163	0.0141	0.0115	0.0153	0.0147	0.0176	0.0144	0.0145	0.0144	0.0173	0.0195	0.0164	0.0083	0.0233	0.0360	0.0028	0.0100	0.0152	0.0136	0.0170	0.0169	0.0154

Table 13: Qualitative assessment of the Impact of parameter variation on Groundwater Vulnerability

Objective Functions	**Qmin**	**Qmean**	**Qmax**	**Volume Change**	**Remarks on Groundwater Vulnerability**
Varied Parameters					
Specific yield	Non-linear effect		Decrease when varying factor from the calibrated value	Increases when varying factor from the calibrated value	Any variation from calibrated value has decreased groundwater vulnerability
Soil Thickness	Proportional to soil thickness		Inversely proportional to soil thickness		Soil thickness is reversely proportional to groundwater vulnerability
K Aquifer	Inversely Proportional to increasing parameter trend and to decreasing trend but to a threshold limit (10^{-6}) that it will start decreasing again		Proportional to increasing parameter trend and to decreasing trend but to a threshold limit (10^{-6}) that it will start increasing again	Inversely proportional to aquifer K	Higher hydraulic conductivity increases groundwater vulnerability
K Lens	Inversely proportional to aquifer K Lens		Proportional to lens K	Increases with parameter increasing or decreasing from calibrated value	
Saturated moisture content (θs)	Inversely proportional to θs Soil		Increases with parameter increasing or decreasing from calibrated value	Proportional to θs Soil	Any variation from calibrated value has increased groundwater vulnerability

2. Variance Based Methods Assessment

This method was based on the variance of the parameters variations and the model outcomes (spring discharged volume, sum of residuals, and mean spring discharge rate). The analysis was performed for Year 1 and Year 2 for result validation. Table 14 and Table 15 present the variance methods indices for the eight varied parameters along with ranking for Year 1 and Year 2 respectively. The estimated variance-based sensitivity coefficients are inversely proportional to the model sensitivity of the varied parameters. The ranking was based on the average sensitivity index calculated from the three variance based objective functions.

Most of the sensitivity results coincide with Autocal outcomes. The only discrepancy with the Autocal analysis is the hydraulic conductivity of the aquifer and the highly conductive lens outweigh the model sensitivity towards Bypass, unlike the results of Autocal that classified Bypass as a more impactful factor than the aquifer and lens conductivity. This inconsistency was mainly due to the fact that variations for the analysis using the variance based methods was done for the horizontal and vertical compartments of the hydraulic conductivity together due to their hydraulic correlation, whereas, Autocal variations were applied solely for each conductivity compartment.

In conclusion, soil saturated moisture content and precipitation have the highest impact on model performance according to Autocal and variance analysis. Besides, applied variation of lens and aquifer hydraulic conductivities resulted in ranking these parameters as the second most important parameters. Additionally, temperature and other soil-hydraulics related parameters (Bypass and soil thickness) were ranked as from the third most sensitive parameters. However, specific yield of the aquifer scored the lowest ranking among the other assessed parameters according to the variance analysis with relatively low sensitivity. Finally, climatic conditions impact on vulnerability will be discussed further in the next section given the significant sensitivity of the model towards these factors inferred from the variance based analysis methods.

Table 14: Year 1 Variance based methods local sensitivity Results

Objective Function	**σ^2(parameter)/ σ^2 (Yearly Discharged Volume)**	**σ^2 (parameter)/ σ^2 ($\sum$r)**	**σ^2 (parameter)/ σ^2 (Q mean)**	**Rank**
Varied Parameters				
K lens (m/s)	1.86E-05	1.09E-03	2.40E+00	1
Precipitation	2.97E-05	3.00E-05	2.91E+00	2
Saturated moisture content (θs)	8.80E-05	2.11E-07	1.13E+01	3
Log(K aquifer (m/s))	2.30E-02	2.30E-02	2.13E-04	4
Temperature	9.20E-02	8.72E-02	9.02E+03	5
Bypass	1.36E-01	1.36E-01	1.75E+04	6
Soil thickness(m)	1.95E-01	1.95E-01	2.52E+04	7
Specific Yield	2.73E-01	2.73E-01	3.52E+04	8

Table 15: Year 2 Variance based methods local sensitivity Results

Objective Function	**σ^2 (par)/ σ^2 (Yearly Discharged Volume)**	**σ^2 (parameter)/ σ^2 ($\sum$r)**	**σ^2 (parameter)/ σ^2 (Q mean)**	**Rank**
Varied Parameters				
Precipitation	2.97E-05	3.00E-05	2.91E+00	1
Saturated moisture content (θs)	1.34E-04	1.96E-07	2.28E+01	2
K lens (m/s)	3.12E-05	5.31E+00	5.31E+00	3
Log(K aquifer (m/s))	4.11E-02	5.05E-04	5.05E-04	4
Temperature	9.20E-02	8.72E-02	9.02E+03	5
Bypass	1.50E-01	2.56E+04	2.56E+04	6
Soil thickness(m)	4.81E-01	8.20E+04	8.20E+04	7
Specific Yield	2.30E+00	3.93E+05	3.93E+05	8

3. Climatic Impact on Groundwater Vulnerability

Sensitivity analysis for different climatic parameters was accomplished for the same calibrated model in Doummar et al. 2018. The study's results have coincided with the sensitivity ranking presented in Table 14 and Table 15 and have shown that precipitation and temperature are essential parameters to address during the vulnerability assessment due to their effect induced on the spring discharge and response along with the total recharged volume. For instance, a decreasing or increasing precipitation can affect the maximum and minimum spring discharge inducing impact on groundwater vulnerability by altering the volume available for dilution. Additionally, temperature can incur a lag time for the hydrograph recession by varying the snow storage volume and delaying snow melt. As a result, the yearly climatic fluctuation suggests the introduction of a new concept of yearly temporal vulnerability that should be assessed yearly as per the dominant seasonal climatic parameters.

4. Geomorphology and Slope Impact on Groundwater Vulnerability

Based on the output of the calibrated model, the results were compliant with the theoretical approach to parameters related to slope and geomorphology of the catchment area. Figure 7 presents the groundwater recharge trend versus the slopes and geomorphology variations. In conclusion, steep slopes were characterized by less groundwater infiltration recharge than gentle slopes, and exposed rocks facilitate groundwater infiltration recharge. Dolines are characterized by the presence of a soil layer that delays and decreases groundwater recharge by diffuse infiltration in comparison with exposed bedrocks that has direct hydraulic connection with the aquifer. On the contrary, the well-established karstic system beneath dolines results in rapid bypass recharge as presented in Figure 8. The bypass percentage of groundwater recharge was the highest for the two tested years within flat doline areas amounting for around 26 % greater than all the other geomorphologic features. Steep dolines were characterized by low bypass infiltration flow due to the effect of high inclination that induces surface water flow.

As a result, geomorphology and slope are essential factors to consider for vulnerability assessment. Initial infiltration of precipitation from the surface groundwater recharge is determined by the topographic slope and geomorphological exposed features. Gentle slopes result in higher groundwater recharges reducing surface runoffs to down gradient areas. Eventually the aquifer is more prone to surface contamination below gentle slopes (Ghazivi and Ebrahimi, 2015). In addition, surface exposed media also contributes to the rate and amount of groundwater recharge. Moreover, the presence of surface karstic features, specifically dolines, allowed the differentiation between the bypass flow infiltration within the dolines and unsaturated diffuse flow within the soil matrix (Somaratne, 2014).

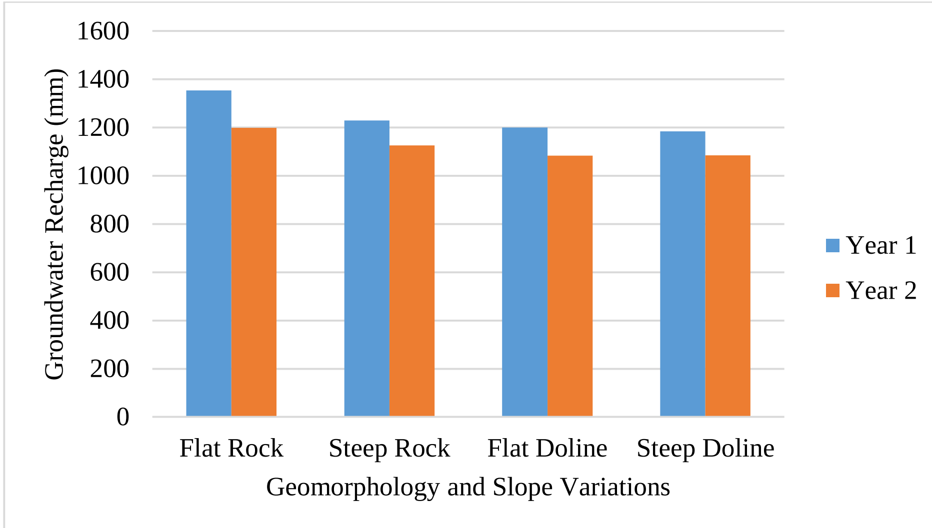

Figure 7**:** Groundwater Recharge from different slope and geomorphology variations for Year 1 and Year 2

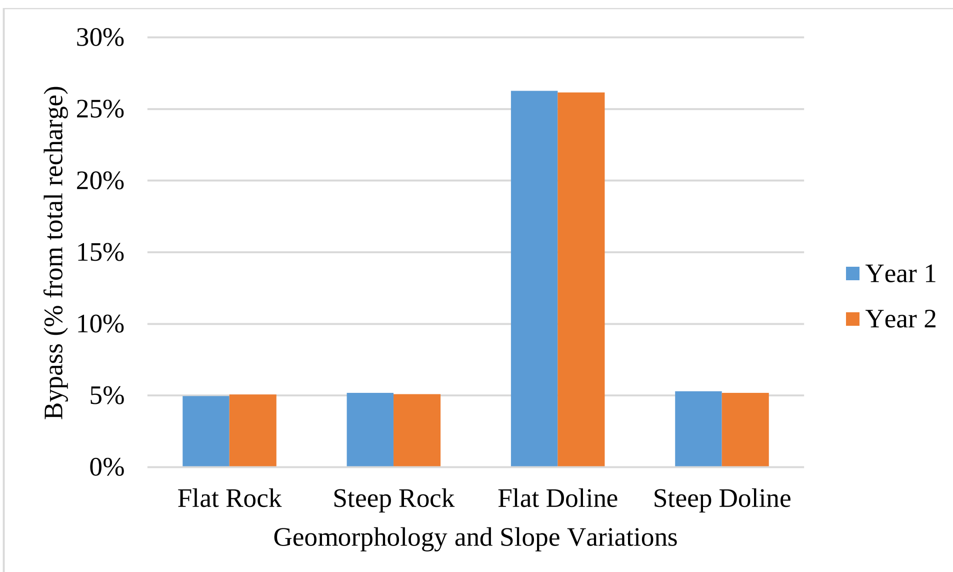

Figure 8: Bypass flow recharge from different slope and geomorphology variations for Year 1 and Year 2

5. Modeling-based parameters ranking compared to Qualitative Methods Coefficients

The ranking of the parameters resulting from the sensitivity analysis using the Automatic sensitivity tool (Autocal) and other statistical methods was compared to the weights attributed to these parameters in the most common qualitative assessment methods. Discrepancies were indicated between the compared methods suggesting the need for a reevaluation of the weighing coefficient in qualitative methods based on a physical-based approach.

The COP method weighing of factors that affect vulnerability was consistent with the results of the variance based methods ranking the soil hydraulics mainly as the most impactful parameters on model functioning followed by the phreatic zone factors. Whereas, the EPIK method have weighed the karstic features and their underground maturation as the most important parameters with coefficient of (3) followed by the soil layer then finally the geomorphological features with coefficients of 2 and 1.

Additionally, climatic conditions, in particular temperature and precipitation, have an important impact on recharge quantities and rate as reflected in the variance based sensitivity analysis. The COP method exclusively included precipitation quantities and intensity as an additional factor related to climate. Besides that, any development or update of a vulnerability assessment method must include temperature as a supplementary climatic factor due to its impact on recharge trends (Doummar et al., 2018).

Furthermore, El Assal Spring catchment area was included in the vulnerability study (Doummar et al, 2012) to assess the vulnerability of the Jeita Spring catchment area. The study yielded vulnerability maps of the catchment area applying the COP and EPIK methods as presented in Figure 9 and Figure 10 respectively. The two methods have resulted in the classification of the catchment area of El Assal Spring as "very high vulnerability". Considering the results, the catchment area of El Assal spring is to be fully protected and restricted from urban land use development including urban settlements to protect groundwater. However, this conservative approach may have economic implications on such protected areas especially from the aspect of the land values. Accordingly, the groundwater modeling approach for vulnerability assessment and its capability of evaluation at a microscale may secure the availability of less vulnerable areas within the investigated zone.

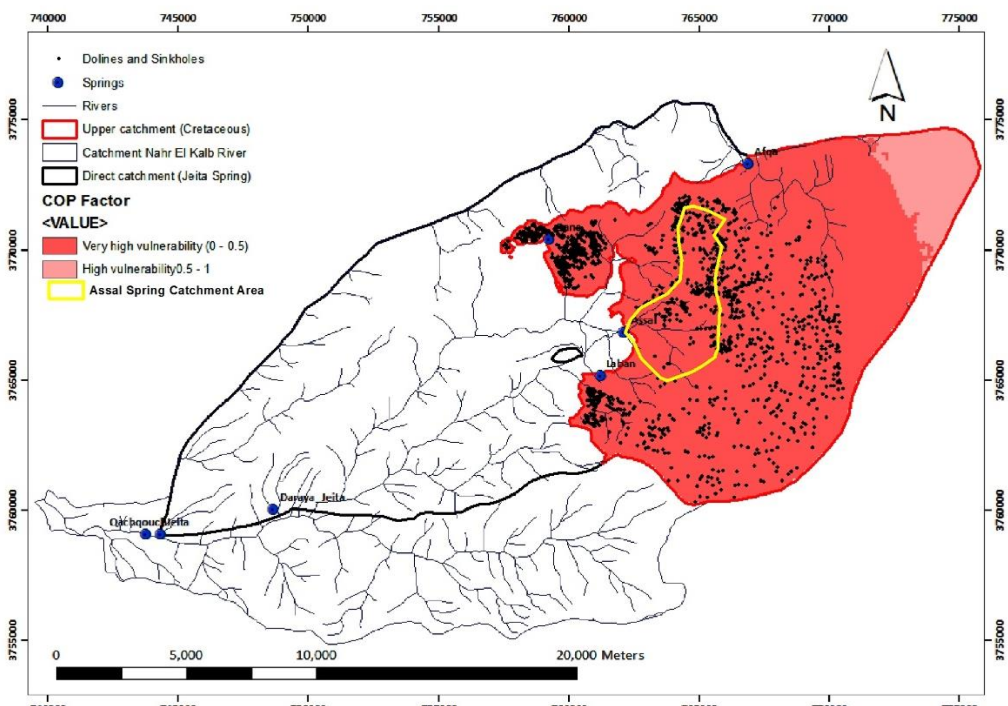

Figure 9: Jeita Upper Catchment Vulnerability Assessment (COP Method), and showing El Assal Spring Catchment Area (modified from Doummar et al, 2012)

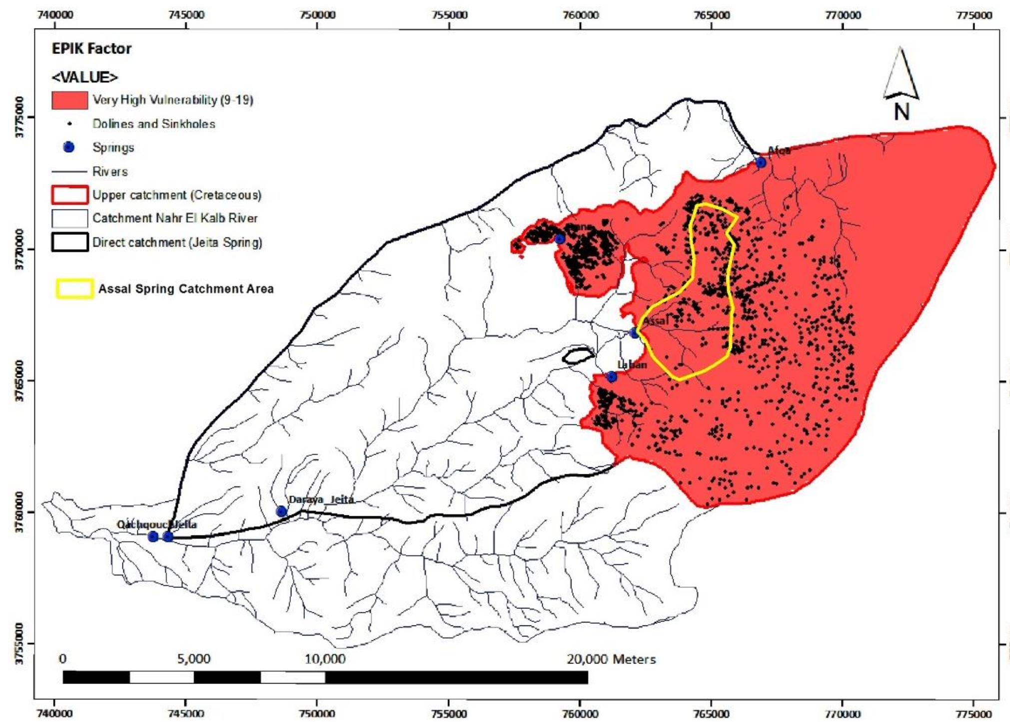

Figure 10: Jeita Upper Catchment Vulnerability Assessment (EPIK Method), and showing El Assal Spring Catchment Area (modified from Doummar et al, 2012)

CHAPTER V

CONCLUSION AND RECOMMENDATIONS

The sensitivity analysis applied to key vulnerability parameters have resulted in ranking these factors according to the model sensitivity to their variations. Generally, the ranking of parameters as per hydrological compartment from the most impactful to the least is as follows: soil hydraulics factors, climatic factors, and aquifer along with highly conductive lens hydraulic factors. Geomorphological and topographical features also have exhibited a significant impact on groundwater vulnerability by influencing the total groundwater recharge quantities. The vegetation cover has induced a negligible impact on the model performance resulting in insignificant sensitivity.

Furthermore, groundwater modeling reveals to be a useful tool for groundwater vulnerability assessment if enough data is available to conduct flow simulations. Given the quantitative and comprehensive approach in modeling catchment areas, the modeling methodology in assessing groundwater susceptibility is deemed more efficient than the conventional qualitative methods (EPIK, COP etc.). Applying the groundwater modeling approach for the El Assal Spring catchment area has classified the parameters that shall be considered while assessing vulnerability. In addition, the groundwater modeling approach, given its numerical estimations of flow rates and volumes of water at each discretized cell within the catchment area, is perceived optimal for groundwater susceptibility evaluation.

The results have shown that parameters that mostly affected model performance were those related to the soil cover and their hydraulics besides the aquifer and karst conduits conductivities. Moreover, geomorphological features and slopes are also important factors that shall be included in the assessment controlling infiltration processes.

For instance, precipitation and temperature were depicted to be essential factors to consider for groundwater vulnerability assessment. Where climatic conditions, because of their seasonal variations, urge the implementation of temporal vulnerability of an aquifer that can only be attained by simulating a groundwater model.

Finally, the groundwater modeling approach for vulnerability assessment can avoid the overestimation of the vulnerability class that may lead to land worth reduction. Thus, the groundwater modeling approach allows an optimal classification of protected areas and reduces areas for expropriation or restricted land use.

While the results were validated using three different statistical methods for two hydrological years, many restrictions are acknowledged. The most important limitation in the analysis is the evaluation of the global sensitivity of the groundwater model to the parameters. This can be attained by varying the key vulnerability factors all at once and assess the model performance under combinations of parameters variations. Additionally, the conclusions from this study are only valid for catchment areas of similar prevailing conditions of the subject watershed. Among others, essential parameters prerequisite conditions to apply concluded results and methods from this study are listed in Table 16. Moreover, the results within the context of snow covered semi-arid karstic system shall be validated by conducting similar studies on other systems of similar environmental conditions.

Table 16: Environmental conditions essential for the application of concluded results and methodologies

Environmental Compartments and parameters	**Conditions for application of concluded results and methodology**
Climatic	- Snow covered area for at least two months per year
Land use/cover	- Lands covered with shrubs or similar vegetation cover in terms of areal coverage and water needs - Uninhabited areas
Area,slope, and topography	- Catchment area with ± 20% of the studied catchment area total area size - Mountaneous area with minimum of 20% slope steepness between the highest and lowest elevation
Unsaturated Zone	- Well exposed karstic features with hydraulic connections with the underlying aquifer
Saturated Zone	- Mature karstic aquifer with highly conductive zones

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