Assessment of Groundwater Vulnerability to Contamination using GIS-based DRASTIC Method in Karacabey and Mustafakemalpaşa Plain, Bursa

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ABSTRACT

MS Thesis

ASSESSMENT OF GROUNDWATER VULNERABILITY TO CONTAMINATION USING GIS-BASED DRASTIC METHOD IN MUSTAFAKEMALPAŞA AND KARACABEY PLAIN, BURSA

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Management and protection of groundwater resources have significant importance. In this respect, groundwater vulnerability assessment is essential and considered the first step in groundwater protection strategies. In this research, the groundwater vulnerability of the Mustafakemalpaşa and Karacabey plain is assessed using the GIS-based DRASTIC method. According to the vulnerability assessment, 16.3% of the study area is under low vulnerability, 18.8% under moderate vulnerability to contamination, while 39% under high vulnerability, and around 25.5% can be considered as an area of very high groundwater vulnerability. A sensitivity analysis is applied to calculate the effect of each used parameter on the resulting vulnerability map. Based on the sensitivity analysis, net recharge and hydraulic conductivity tend to be the most effective parameters. In addition, relationships between the resulting DRASTIC vulnerability indices and the nitrate concentration, TDS measures, sulfate concentration, coliform bacteria measures, and other water quality parameters are investigated. Simple linear regression analysis showed a linear relationship between DRASTIC vulnerability indices and sulfate concentrations ($R^2 = 0.648$). Whilst, the analysis showed that there is no conclusive relationship between DRASTIC vulnerability indices and nitrate concentrations or TDS measurements. Also, the coliform bacteria measurements at some wells showed the aquifer is not free of coliform bacteria.

Keywords: Groundwater; Vulnerability; Water quality; DRASTIC; GIS; Bursa; Turkey.

ÖZET

Yüksek lisans tezi

DRASTIC YÖNTEM İLE YERALTI SUYUNUN KİRLİLİK HASSASİYETİNİN DEĞERLENDİRİLMESİ: BURSA İLİ KARACABEY VE MUSTAFAKEMALPAŞA OVASI UYGULAMASI

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Yeraltı suyu kaynaklarının yönetimi ve korunması büyük önem taşımaktadır. Bu bakımdan, yeraltı suyu hassasiyet değerlendirmesi esastır ve yeraltı suyu koruma stratejisinin ilk adımı olarak kabul edilir. Bu tezde, Bursa ili Mustafakemalpaşa ve Karacabey ovasının yeraltı suyu kirlilik hassasiyeti CBS tabanlı DRASTIC yöntemi ile değerlendirilmiştir. Hassasiyet değerlendirmesine göre, çalışma alanının %16,3'ü ve %18,8'i kirliliğe karşı sırasıyla düşük ve orta derecede hassasiyete, %39'u yüksek hassasiyete ve yaklaşık %25,5'i çok yüksek hassasiyete sahip bir alan olarak belirlenmiştir. Kullanılan her bir parametrenin, elde edilen hassasiyet haritası üzerindeki etkisini hesaplamak için bir duyarlılık analizi yapılmıştır. Duyarlılık analizine göre, net beslenme ve hidrolik iletkenlik en etkili parametreler olarak bulunmuştur. Ayrıca, ortaya çıkan hassasiyet indeksleri ile nitrat konsantrasyonu, TDS ölçümleri, koliform bakteri ölçümleri ve diğer su kalitesi parametreleri arasındaki ilişkiler incelenmiştir. Basit doğrusal regresyon analizi, DRASTIC hassasiyet endeksleri ile sülfat konsantrasyonları ($R^2 = 0,648$) arasında doğrudan bir ilişki olduğunu göstermiştir. Ancak, bu analiz, DRASTIC hassasiyet endeksleri ile TDS ölçümleri veya nitrat konsantrasyonu arasında belirli bir ilişki göstermemiştir. Bazı kuyulardan elde edilen koliform bakteri ölçümleri, akiferin koliform bakteri içerdiğini göstermiştir.

Anahtar Kelimeler: Yeraltı suyu; Hassasiyet; Su kalitesi; DRASTIC; CBS; Bursa; Türkiye.

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SYMBOLS AND ABBREVIATIONS

Symbol	Explanation
A	Aquifer media
C	Hydraulic conductivity
D	Depth to water table
I	Impact of the vadose zone
R	Net recharge
S	Soil media
Sv	Variation index
T	Topography
V	DRASTIC index
W	Effective weight

Abbreviation	Explanation
BUSKI	Bursa Su ve Kanalizasyon Idaresi
DEM	Digital Elevation Model
DSI	Devlet Su İşleri
GIS	Geographic Information Systems
TDS	Total Dissolved Solids
US EPA	United States Environmental Protection Agency
NWWA	National Water Well Association

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1. INTRODUCTION

1.1. General Introduction

Groundwater is a primary resource of freshwater for all human beings and meeting water demands such as domestic, agricultural, industrial use, and other sectors. Also, for sustaining and protecting natural ecosystems and implementing climate change mitigation and adaptation strategies. Whilst, the sustainability of this precious water resource is threatened by increasing pollution, overexploitation, mismanagement, and growing development and agricultural activities (Machiwal et al. 2018; UNESCO 2018).

At present, according to UNESCO (2018), UNICEF and WHO (2017), about 3.6 billion people around the world live in regions facing water scarcity for at least one month yearly, and this population could significantly increase to about 4.5-5.7 billion by 2050. Moreover, about 844 million people worldwide have the main problem accessing safe drinking water. Furthermore, half of the people in developing countries face with the problem of polluted water that risks human health.

It is expected that using groundwater as a safe and reliable water resource across the globe will significantly increase in the future, which could make aquifers more vulnerable to contamination because of anthropogenic effects, such as increasing agricultural activities, huge changes in land use and land cover due to urbanization which has been increasingly changing, burgeoning population, increasing water consumption and quickly growing urbanization and industrialization. Climate change and global warming which most countries worldwide face, will have deep repercussions for groundwater demands and supplies (Taylor et al. 2013).

The option of building more reservoirs or dams as a water resource becomes increasingly limited because of many reasons, like decrease in the available runoff and environmental constraints and restrictions. Also, in many developed countries, the most cost-effective and applicable lands have been used. In many cases, recharge of groundwater can be considered as an ecosystem-friendly form of water storage that can be more sustainable and cost-effective than conventional forms (UNESCO 2018).

In the past decades, both quality and quantity stresses on groundwater have increased to a level that threatens water resources and ecosystems. For example, the main source of high concentrations of Nitrate in groundwater is agricultural activities. Therefore, optimum groundwater protection and environmental management using vulnerability maps in aquifers have become a vital tool and a goal in all countries (Cucchi et al. 2007).

The aquifer vulnerability concept is utilized to measure the aquifer's ability to be contaminated from the surface (Foster et al. 2013). The term "Aquifer Vulnerability" was used for the first time in 1968 to find the degree of protection provided by the natural ecosystem against contaminants going into groundwater (Margat 1968). Since 1968, many definitions of groundwater vulnerability have been used. The vulnerability definition basically includes words like risk, contaminants, natural or artificial pollutants, groundwater systems, and groundwater quality.

Groundwater vulnerability comprises two specific concepts: 1) intrinsic vulnerability and 2) specific vulnerability (Kouli et al. 2008). The intrinsic vulnerability is the groundwater vulnerability to pollutants produced by hydrological and anthropogenic activities, considering hydrogeological characteristics, but without considering the nature of pollutants. While specific vulnerability may be defined as the aquifer's vulnerability to a particular type of pollutant or a set of pollutants considering its properties, also how these pollutants can be transferred to the aquifer based on its hydrogeological characteristics (Gogu and Dassargues 2004).

There are many groundwater vulnerability assessment methods and approaches; many criteria should be taken into account to select the appropriate assessment approach, such as the type of aquifer. In general, methods are distinguished into three main categories: 1) Index and overlay methods or qualitative methods, 2) Process-based methods, and 3) Statistical methods (Marin et al. 2015). All approaches are explained later in the literature review chapter (chapter two).

Groundwater vulnerability maps are based on dividing the geographical area into vulnerable zones, of varying degrees namely, very low, low, moderate, high and very high. Finding out the zones vulnerable to contamination and reasons that made these areas under high vulnerability will help water resource protection and consequently, reduce water treatment costs for urban suppliers and contributes to amended access to safe drinking water in all communities (UNESCO 2018).

1.2. Problem Identification

It is essential to prevent and protect the groundwater aquifers from pollution, such as nitrate contamination caused by fertilizers and increasing agricultural activities. This research aims to asses the groundwater vulnerability to contamination in Mustafakemalpaşa and Karacabey plain, Bursa, Turkey. The study area has intensive agricultural activities, that makes it vulnerable to be contaminated by nitrate. And the main problem is the pollutants found in the aquifers that have a negative impact on the adverse health, environmental, and economic. Regarding health, contaminants are associated with cancer, kidney damage and damage to the central nervous system, that can be very dangerous to people live in the study area.

The environmental impacts in the study area include declination of water quality due to interactions between contaminated groundwater and surface water. Also, the economic impacts of groundwater contamination are very high, including the high costs of mitigating contamination, developing another water source and decreasing the industrial and agricultural yields which are very significant sectors in the study area.

The best practice for groundwater sustainability as a water resource is the protection of the aquifer from getting polluted by anthropogenic sources. This process is a crucial issue since remediation of groundwater is expensive and impractical. Therefore, the first step in protecting the groundwater is determining what parts of the aquifer are under high vulnerability to contamination.

In this research project, data analysis and model implementation are carried out using geographic information system (GIS), which has the advantage of both geospatial data gathering and data processing. The DRASTIC method is used for assessing and mapping of intrinsic vulnerability. Seven parameters are considered in this assessment approach: **D**epth to water table, **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of vadose zone, and hydraulic **C**onductivity. Calculating the DRASTIC value, which means the sum of each parameter's weight multiplied by its rating, gives an indication of the vulnerability to contamination (Aller et al. 1987). Also, some filed data like total dissolved solids, arsenic concertation, Nitrate concertation, and coliform bacteria are used to evaluate the results and describe the last state of the aquifer quality.

1.3. Research Objectives

This research project aims to:

1. Conduct a literature review for the current groundwater vulnerability assessment approaches.
2. Assess the vulnerability of the Mustafakemalpaşa and Karacabey plain aquifer to contamination and find out the aquifer zones that are vulnerable to contamination using the GIS-based DRASTIC method.
3. Validate the results using field data and describe the current state of the aquifer quality.

1.4. Research Question

The research question is:

1. Which parts of the aquifer in Karacabey and Mustafakemalpaşa plain are under high vulnerability to contamination?
2. What parts of the aquifer or study area that should be of top priority and what actions should be taken to protect the aquifer as a sustainable groundwater resource?
3. What is the current state of the groundwater quality?

1.5. Methodology

The research methodology is divided into three phases. The first phase starts with identifying research objectives; after that, a literature review on different vulnerability assessment approaches is conducted. The main objective of a literature review is to provide basis of knowledge on the topic and characterize areas of prior studies, the need for additional research, and the assessment methods depending on the types of aquifers. In addition, this phase includes data collection mainly from the Bursa Su ve Kanalizasyon Idaresi – Bursa Water and Sewerage Administration (BUSKI), Devlet Su İşleri – State Hydraulic Works (DSI), and Tarım ve Orman Bakanlığı Metreoloji Genel Müdürlüğü - Metrological Service Turkish State.

The second phase consists of modeling and data processing with the aid of GIS and Excel. The output will be presented as a vulnerability map in raster format.

The third phase consists of analyzing the vulnerability map by determining the percentages of the zones that are under very low, low, moderate, high and very high vulnerability to contamination. The last phase also covers a discussion of the results, conclusions and recommendations that will be shared with water utility in Bursa and environmental decision-makers. These phases are summarized in Figure 1.1 below.

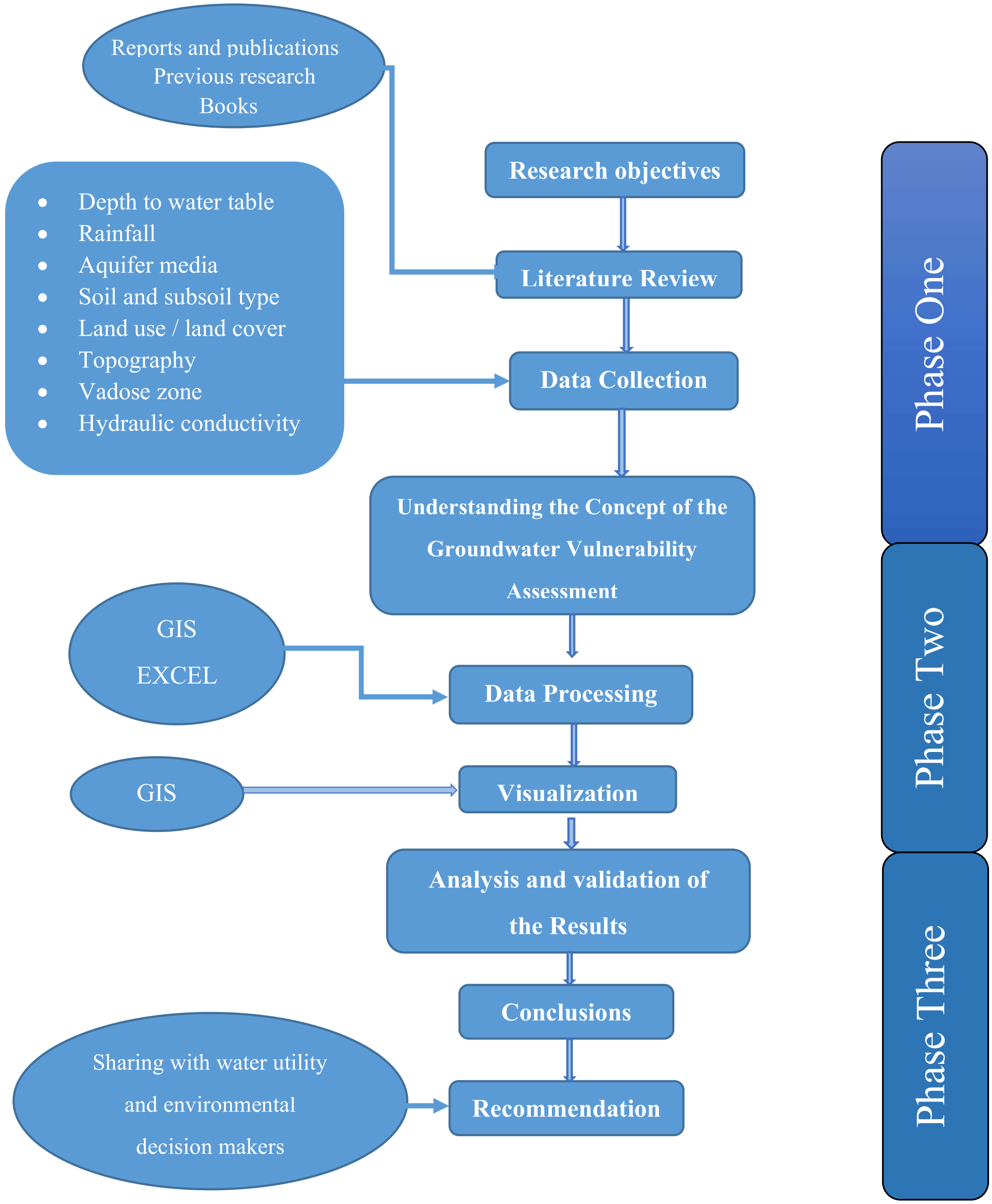

Figure 1.1. A flowchart that depicts the overall methodology in this research.

1.6. Thesis Outline

This thesis consists of five chapters. Chapter one is the introduction. Chapter two encompasses the literature review. Chapter three is material and method which consists of description of the DRASTIC method, sensitivity analysis, field data and a brief description of the study area (Karacabey and Mustafakemalpaşa plain, Bursa). Results, discussion and corresponding vulnerability maps of Karacabey and Mustafakemalpaşa plain's aquifer are presented in chapter four. Also, chapter four includes the analysis and validation of the results. Finally, chapter five contains conclusions and recommendations.

2. LITERATURE REVIEW

2.1. The Concept of Groundwater Vulnerability

The term "vulnerability" was used the first time in 1968 by the French hydrologist Jean Margat. The term 'vulnerability' is not limited to groundwater, it is used in a wide sense to describe the sensitivity of anything to any sort of stress, e.g., the vulnerability of global warming to human impacts. After that, the concept was adopted in hydrology all over the world. He used the term of vulnerability to imply the degree of resistance that the environment shows against contaminants' entrance to aquifer (Albinet and Margat 1970).

Many definitions have been proposed by scientists and hydrologists to realize groundwater vulnerability, and some of them are similar, but there is no common and recognized definition that has been accepted yet.

Groundwater vulnerability comprises two specific concepts or types of vulnerability: the first one is intrinsic vulnerability, which represents the vulnerability of groundwater to pollutants produced by hydrological and anthropogenic activities by considering hydrogeological characteristics, but regardless of the kind of pollutant (Kouli et al. 2008).

Conversly, specific vulnerability term is utilized to represent groundwater vulnerability to a particular type of pollutant or a set of pollutants considering their properties. Ways by which pollutants are transferred are also crucial in this type of vulnerability (Gogu and Dassargues 2004).

2.2. Groundwater Vulnerability Assessment

The assessment of groundwater vulnerability aims to recognize the most vulnerable zones/regions of a selected aquifer at different scales that may cause groundwater pollution and provide scientific knowledge and basis for groundwater protection as well as land use planning, including agricultural activities.

According to US EPA (1993), groundwater vulnerability assessment is an essential and the first step in groundwater protection strategy. Assessment can be used for point inspection, environmental and policy development efforts to zones with high and very high groundwater vulnerability to contamination. Also, it can be used in the distinction between areas in which the polluting activities make insignificant or little threats to groundwater and the areas in which polluting activities make significant threats to groundwater and natural ecosystem. Consequently, these areas need urgent and necessary protection (Lindström 2005).

Depending on the aquifers' hydrological and hydrogeological characteristics and attenuation processes, aquifers show a different level of natural protection against contamination. Thus, some areas have high vulnerability to groundwater pollution more than others (Vrba and Zaporozec 1994).

Transport processes of groundwater pollution play an essential role in the assessment of the groundwater vulnerability. The vulnerability of a selected area can be assessed not only by the vertical transport of contaminants in the vadose zone but also include the horizontal transport in the saturated zone (Goldscheider 2004).

Many factors affect the groundwater vulnerability assessment process, such as the type of pollution, the transport process, the source of contamination (agricultural activities, etc.). Figure 2.1 below shows the "Origin-Pathway-Target" model, which is the basis of the groundwater vulnerability assessment process. "Origin-Pathway-Target" model differentiates between the aquifer as a 'resource' (water storage) and the aquifer as a 'source' (like a spring). Origin in the model means the location where the pollutants are firstly released. The pathway means the path that is taken by the pollutant during its travel from the origin to the target. The target is the last destination of the contaminant that needs to be protected. The main goal of the 'resource protection' is to protect and save the whole aquifer. The 'source protection' aims to save the well or the spring from contamination. (Goldscheider 2004). In 'resource protection', groundwater water table is the target, and the vadose zone is the pathway that transports the contaminant. In the 'source protection', the pathway is the transportation of contaminant within the groundwater. And the well or the spring is the target (Goldscheider 2004).

In this research, the assessment of groundwater vulnerability process deals with the 'resource protection'.

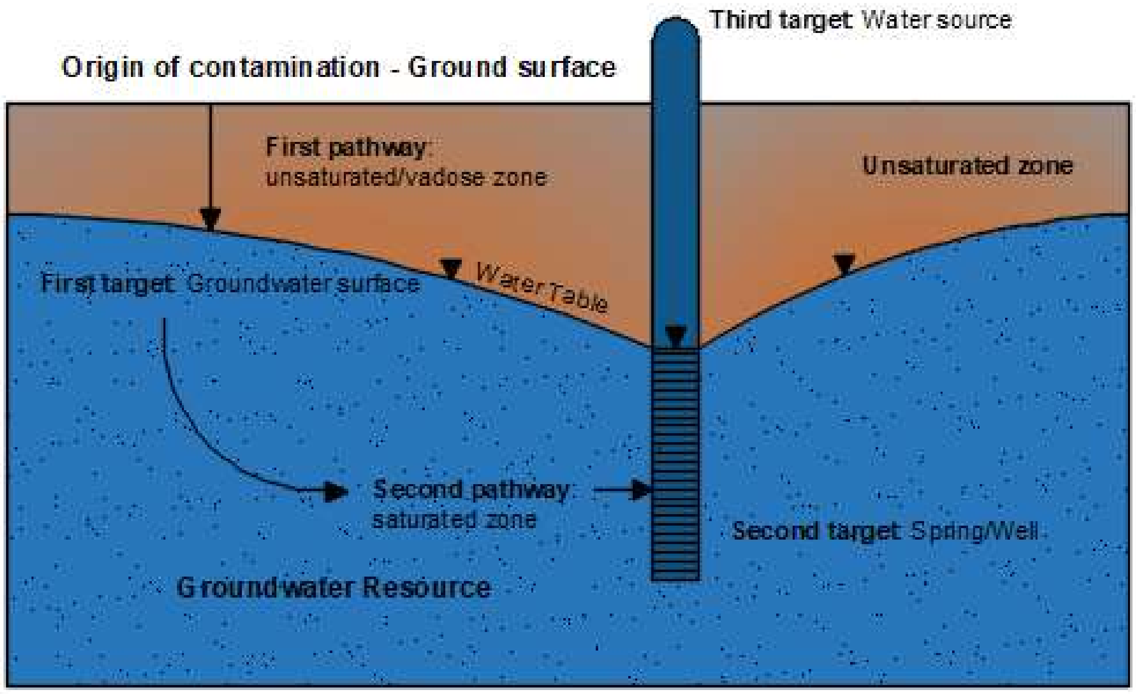

Figure 2.1. Description of 'Origin-Pathway-Target' model including the concept of 'source' and 'resource' protection in the groundwater vulnerability assessment (modified from Goldsheider, 2004).

According to Brouyère (2004), three key aspects should be considered in the groundwater vulnerability assessment: 1) time needed to travel by the pollutant from the origin to the target. 2) Contaminant attenuation within the pathway. 3) period of contamination at the target. Figure 2.2 below depicts the three main aspects mentioned above.

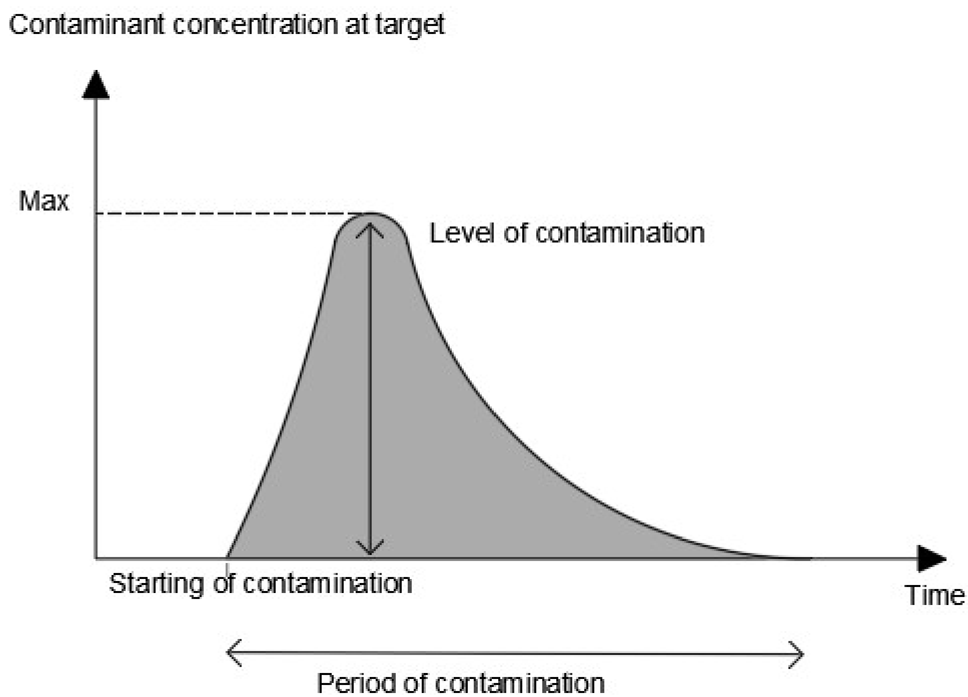

Figure 2.2. The three main quantitative aspects that should be considered in the groundwater vulnerability assessment process. (Modified from Brouyère 2004),

2.3. Methods and Approaches for Groundwater Vulnerability Assessment

There is no common method of aquifer vulnerability assessment. Depending on criteria and aquifer types, methods of aquifer vulnerability assessment can be categorized into three (Lindström 2005):

1- Index and overlay qualitative methods.
2- Process-based quantitative methods, including simulation models.
3- Statistical methods.

Qualitative and statistical methods are used in assessing 'intrinsic vulnerability'; on the other hand, quantitative methods are used in determining the 'specific vulnerability' (Gurdak 2014).

Each of the above-mentioned methods has its advantages and limitations that should be taken into consideration upon selecting the most suitable method for an area.

Depending on the media of aquifers, the qualitative methods can be classified into two: 1) porous-media aquifers and 2) karst aquifers. Also, according to Gurdak (2014), the quantitative methods can be categorized into two: 1) complex simulation models using the advection-dispersion model, and 2) Simplified simulation models.

Figure 2.3 below shows the classification of the methods for assessing groundwater vulnerability into the categories of resource, and source protection together with the main three resource protection types.

2.3.1. Index and overlay qualitative methods

The overlay and index qualitative methods depend on the overlaying of multiple parameters that play an important role in groundwater vulnerability. The main advantage of this approach is that most of the needed data are generally available (Gurdak 2014). The vulnerability result is relative and qualitative. In the qualitative methods, parameters do NOT have the same weight because each parameter has its effect on the groundwater vulnerability. The simplest methods utilize the same weights for all parameters. However, to be more accurate and get more reliable results, different weights for these parameters based on their contribution to groundwater vulnerability must be used (Gurdak 2014).

These methods use spatial data, so there is a significant need for spatial data tools, such as geographic information systems (GIS). It is widely used because GIS can demonstrate the spatial variance that is important for the assessment (Gurdak 2014).

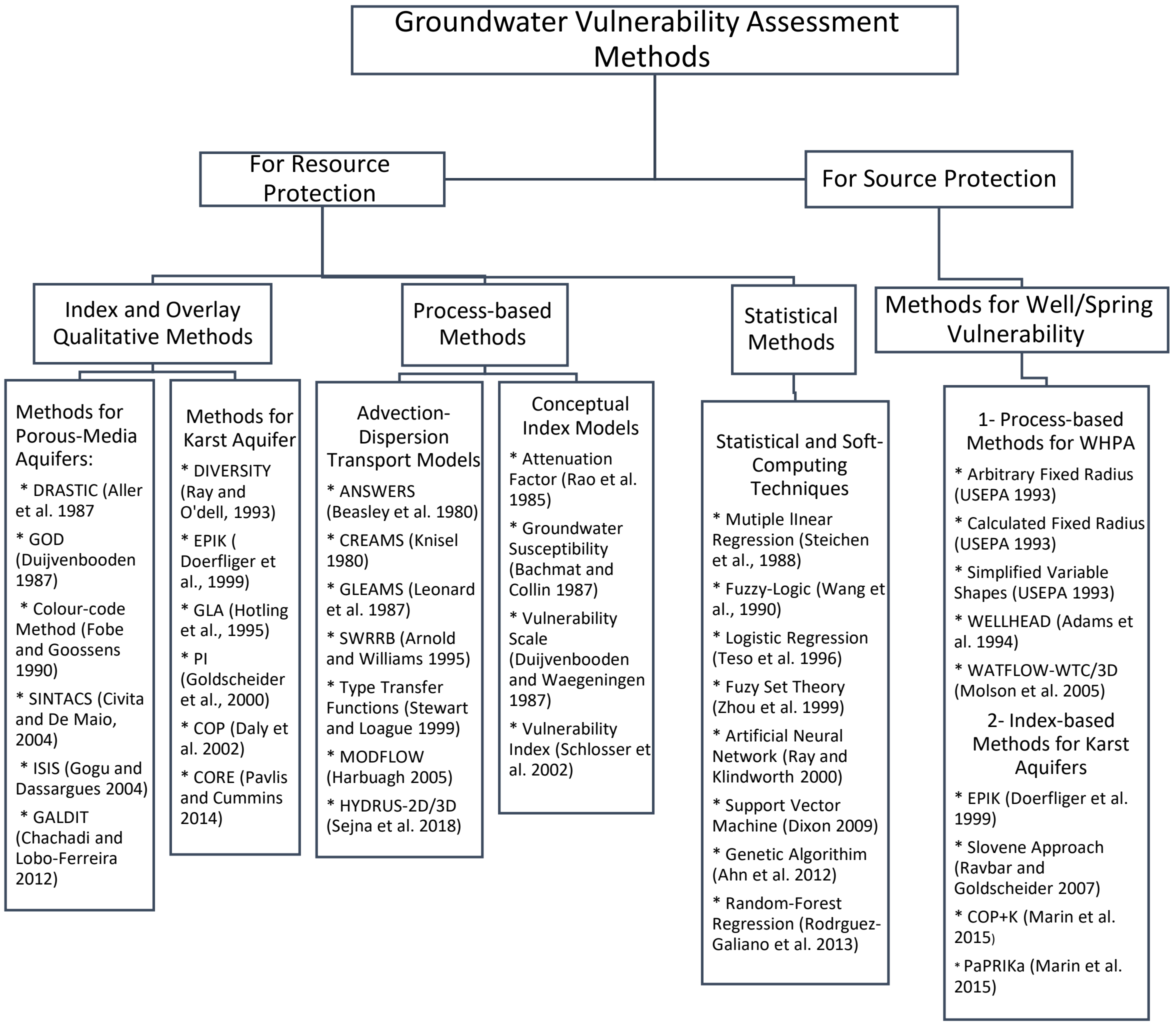

Figure 2.3. Tabulation of methods for groundwater vulnerability assessment (modified from Machiwal et al. 2018).

For example, in order to calculate the groundwater vulnerability using overlay and index method. First, each parameter is spatially mapped using GIS with available data. After that, each intended map is rated based on the contribution of this parameter to the vulnerability, and all parameter maps are integrated to get the final map. Also, the vulnerability map is classified into several categories. It can be classified into three, four, or five categories which are: high, moderately high, moderate, moderately low, and low.

The widely used overlay and index methods including DRASTIC (Aller et al. 1987), GOD (Duijvenbooden and Waegeningen 1987), SINTACS (Civita and de Maio 1997) and other methods are shown in Figure 2.3 above.

- Methods for Porous-media aquifers:

1- DRASTIC method: DRASTIC is one of the most common and widely-used groundwater vulnerability assessment methods worldwide, incubated under the cooperation between the United States Environmental Protection Agency (US EPA) and the National Water Well Association (NWWA) (Aller et al. 1987). It is developed to measure the vulnerability values for the selected area by considering and integrating several parameters, like **D**epth to water table and net **R**echarge. DRASTIC method is explained with details later.

2- GOD Method: GOD method considers the Groundwater occurrence, which includes recharge, Depth to groundwater and Overlying lithology (Duijvenbooden and Waegeningen 1987). In this method, it is assumed that the vulnerability could be assessed empirically. Rating of vulnerability from 0, which is not vulnerable, to 1, which is vulnerable, can be evaluated based on the groundwater system. The groundwater may be categorized by three factors: type of aquifer (unconfined, semi-confined, and confined), overlying lithology and the unsaturated zone for unconfined aquifer. GOD method is not widely-used compared with the DRASTIC method (Machiwal et al. 2018).

3- SINTACS method was developed in Italy in 2004 (Civita and De Maio 2004). It measures the vertical vulnerability value by considering seven parameters (the first words are in Italian language): Soggiacenza (depth to groundwater), Infiltrazione (recharge action), Nonsaturo (attenuation potential of the vadose zone), Tipologia della copertura (attenuation process of the soil), Aquifero (hydrologic characteristics of the aquifer), Conduciblita (hydraulic conductivity), and Superficie topografica (topographic slope). It is quite similar to DRASTIC method (Gogu and Dassargues 2004).

4- SEEPAGE model: it is a numerical model developed in the USA, and it is the "System for Early Evaluation of Pollution potential of Agricultural Groundwater Environments" (Moore and John 1990). Six parameters are considered in this approach, and their weights range from 1 to 50 based on their contribution to groundwater vulnerability (Machiwal et al. 2018).

- Methods for Karst Aquifers:

1- EPIK method: it is developed in Switzerland and it was the first method to calculate the vulnerability of karst aquifers. 4 parameters are considered: **E**pikarst, **P**rotective cover, **I**nfiltration, and **K**arst network development (Doerfliger et al. 1999). These factors represent the protection factor index (Fp), it can be calculated by a rating technique. A lower Fp index value indicates a higher vulnerability of the aquifer (Machiwal et al. 2018).

2- GLA method: (Geologisches Landesamt) method was used for the first time in Germany. It consists of integrating maps, it is quite similar to DRASTIC method. Six parameters are considered in this method: protective effectiveness of the soil and unsaturated zone, weight for effective field capacity, infiltration rate, rock type, and thickness of the soil and rock cover over the aquifer. Regarding the parameters indicated above, the GLA method considers only the effect of unsaturated zone (Machiwal et al. 2018).

3- PI method: It is adopted in the framework of the European COST Action 620 program for the intrinsic groundwater vulnerability. It can be applied to all aquifers regardless of its type, particularly for karst aquifers. The vulnerability can be calculated using two factors: 1) Protective cover (**P**), and 2) Infiltration condition (**I**). Hence the name is PI method. It is also based on the 'Origin-pathway-target' model, which is previously explained (Goldscheider et al. 2000). The P parameter represents the protective of all layers that cover the distance from the ground surface to the water table, such as sub and top-soil. I factor represents the infiltration conditions (Kouli et al. 2008).

2.3.2. Process-based quantitative methods

These methods are physically-based methods used to calculate the aquifer vulnerability by considering natural processes that occur in the aquifer system; for that reason, these methods are also called 'process-based methods'. Besides, they include simulation models that can be categorized, according to Gurdak (2004), into complex models and simple models. To simulate the natural process such as infiltration, recharge, and contaminant attenuation, empirical equations and/or analytical solutions can be used. For example, developed analytical and semi-analytical solutions to the complex advection-dispersion equation are developed. In addition, computer programs such as MODFLOW (Harbuagh 2005) can be used for simulating the fate and transport of groundwater contamination.

2.3.3. Statistical methods

Statistical methods are the third method of groundwater vulnerability assessment, and it is less common than the quantitative and qualitative methods mentioned above because of its difficulty to apply. Statistical methods provide a reliable and feasible approach to assess groundwater vulnerability depending on the groundwater quality data obtained from a spring or well, hydrogeological data, land cover, land use and etc. (Lindström, 2005).

Logistic Regression (LR) is a statistical method for groundwater vulnerability assessment. And the main advantage of this method is its ability to determine weights, avoid anomalies (which are insignificant variables), and specify significant variables. Moreover, weights are calculated based on observed data (Focazio et al. 2002).

Another statistical method is multiple linear regression (MLR), concentration can be predicted by using MLR, and it's very useful in drinking water issues to compare concentration with drinking water standards (Machiwal et al. 2018).

In the last two decades, new technologies and approaches are used in groundwater vulnerability assessment, the most common one is artificial intelligence (AI), such as artificial neural networks (ANW), support vector machine (SVM), and fuzzy logic (Dixon 2005).

Briefly, Statistical and overlay-index qualitative methods are used for assessing intrinsic vulnerability. On the contrary, Process-based/quantitative methods are used for assessing specific vulnerability (Kouli et al. 2008).

2.4. Groundwater Vulnerability Visualization and Mapping

The first published paper that presents methodological groundwater vulnerability assessment and mapping was in the late 1960s (Zektser et al. 1995). The groundwater vulnerability assessment results are presented as a map that illustrates the zones vulnerable to contamination. Therefore, it is a significant process. The final maps could be shared with water utilities and environmental decision-makers. These maps may be utilized in water resources management and land-based projects and planning since agricultural activities are one of the main reasons for groundwater contamination (Zektser et al. 1995).

Table 2.1 below shows some examples of groundwater vulnerability assessment and mapping and also includes the first time that the method is used, type of vulnerability, its scale, and some case studies for each method, and the most important parameter that each method needs. Tick symbol (✔) means that this parameter is required to apply this method. D means depth to water table, R means net recharge, A means aquifer media, S means soil type, T means topography, I means impact of vadose zone, C means hydraulic Conductivity, O means overlaying lithology, other means other characteristics such as permeable pathways, concentration of the flow, infiltration factor, and reservoir factor (Machiwal et al. 2018).

Table 2.1. Some examples of selected methods for groundwater vulnerability assessment and mapping (Machiwal et al., 2018)

Method	Scale	Case study	Parameter								
Overlay Index qualitative method			D	R	A	S	T	I	C	O	Other
DRASTIC	Small to large scale	Zghibi et al. 2016	✓	✓	✓	✓	✓	✓	✓		
GOD	Large scale	Foster 1987	✓	✓						✓	
SINATICS	Medium to large scale	Gogu and Dassargues 2004	✓	✓		✓	✓	✓	✓		✓
EPIK	Large to regional scale	Doerfliger et al. 1999	✓	✓							✓
GLA	-	Höltıng et al. 1995	✓	✓		✓					✓
PI	-	Goldscheider 2000	✓	✓	✓	✓					✓

In general, mapping software can be divided into two types: (GIS) and Computer Aided Cartography (CAC). GIS software provides the ability to store, manage, and analyze spatial data. On the other hand, CAC software is used for high-resolution visualization of spatial data.

Visualization of the results can be presented using GIS. GIS is a fully interactive and has huge functions, and its capabilities make it a powerful tool for spatial analysis and complex analysis. In this research, GIS can be used in multiple ways to prepare data, analyze data, processing, and visualization to produce the vulnerability maps (Gogu and Dassargues 2004).

2.5. Previous Studies on Groundwater Vulnerability in Turkey

This section includes some groundwater vulnerability assessment case studies in Turkey.

- Sener and Davraz (2013) evaluated the vulnerability in the Egirdir lake catchment, which locates in the southwest of Turkey, using the GIS-based modified DRASTIC method in combination with Analytic Hierarchy Process (AHP) to determine precisely the rating coefficient of each parameter. Modified DRASTIC includes the main hydrological factors used in the original DRASTIC method and the effects of lineament and land-use on the vulnerability.
- Soyaslan (2020) assessed the groundwater vulnerability in the Bucak catchment located in Antalya, Turkey. The study was applied by using GIS-based modified DRASTIC- (AHP). The results showed that 10% of the Bucak catchment is at very high risk, 26.3% is at high risk, 60% is at moderate risk, 3.7% is at low risk.
- Güler et al. (2013) carried out the groundwater vulnerability assessment to nonpoint source contaminants in easternmost part of Mersin, which is called Tarsus Coastal Plain, Turkey, using GIS-based DRASTIC method. Both Generic DRASTIC and Pesticide DRASTIC methods were applied.
- Ersoy and Gültekin (2013) evaluated the vulnerability of Merzifon and Gümüşhacıköy basin aquifers using GIS-based DRASTIC method. The selected area was categorized into three: 1) low vulnerability, 2) medium vulnerability, and 3) high vulnerability. Resulting vulnerability maps show that 47% of the groundwater is under low vulnerability, 37% is under medium vulnerability, and 16% is under high vulnerability. Areas with high vulnerability generally contain flat slope areas.

3. MATERIAL AND METHOD

3.1. Description of the Study Area

3.1.1. General Introduction

Bursa province is located in the north-west of Turkey, the fourth-most crowded city in Turkey and the second-most congested city in the Marmara Region. Bursa is an industrial city; many automotive industries locate in Bursa. Also, it was the first capital of the Ottoman Empire in the 13th century. It is called "Green Bursa" due to gardens, parks, and mountains located across it.

The study area is Mustafakemalpaşa and Karacabey plain located in the west of Bursa (Figure 3.1). The study area is located in the Susurluk Basin, in the northwest of the Anatolian peninsula. For many reasons, like intensive agricultural activities, the main water resource is groundwater. The Susurluk basin has, on average, 650 mm of annual rainfall and 1055 mm of annual evaporation (Dorum et al. 2010). Following points summarize the main lake and streams located in the study area. Figure 3.2 shows the boundary conditions.

- Simav (Susurluk) stream: It is the most important stream in the Susurluk basin. It springs from Kütahya and flows out to the Sea of Marmara. Its length is about 175 km. Simav stream also divides the susurluk basin into two areas, the east and the west.
- Mustafakemalpaşa stream: it is located in Bursa province boundaries; its length is 134 km. It is formed by the combination of Orhaneli and Emet streams in Çamandar village, and it flows into Ulubat lake in the east.
- Ulubat lake: it is a shallow lake with a maximum depth of 6 m. It is located in the south of the Marmara Sea. It is mainly fed by Mustafakemalpaşa stream. Also, the amount of water entering the lake varies seasonally and yearly.

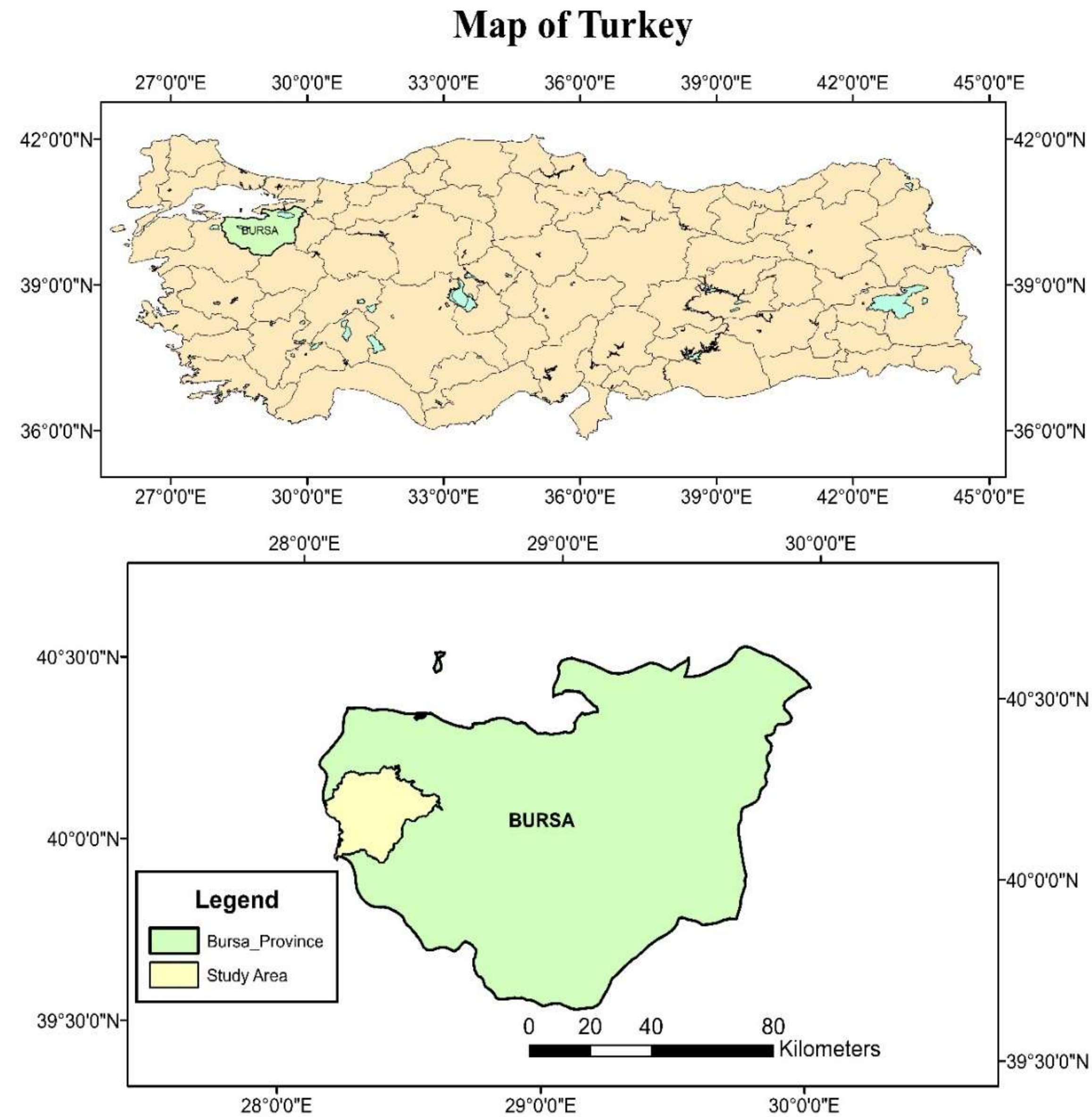

Figure 3.1. Location of the study area and Bursa province.

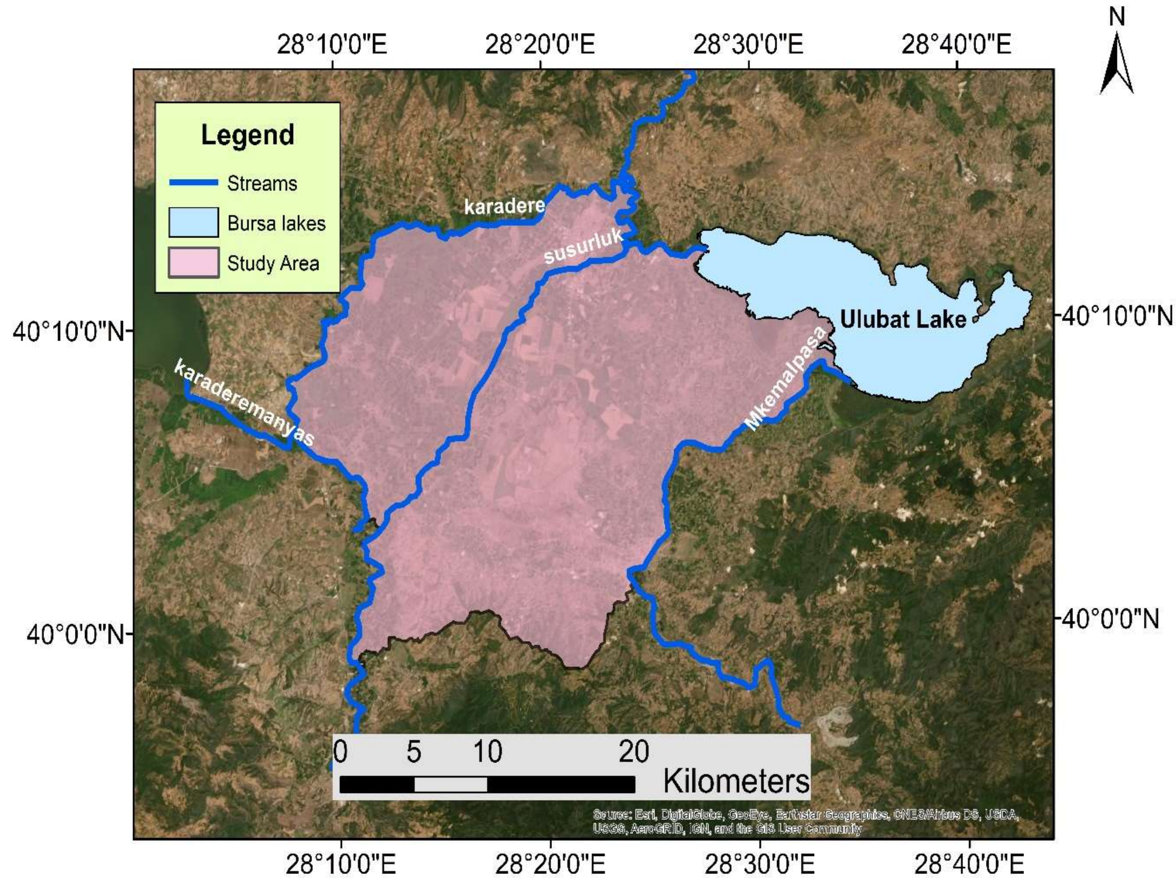

Figure 3.2. The study area: Mustafakemalpaşa and Karacabey plain with Ulubat lake and streams.

3.1.2. Topography

The study area covers an area of 640 km^2 (Figure 3.2). It contains some elevated areas in the south and a plain area in the remaining region. The mountains play an essential role in feeding the aquifers. The highest point in the area is 280 meters above mean sea level (AMSL), whereas the lowest elevation is 5 meters AMSL at the Ulubat lake (Figure 3.3).

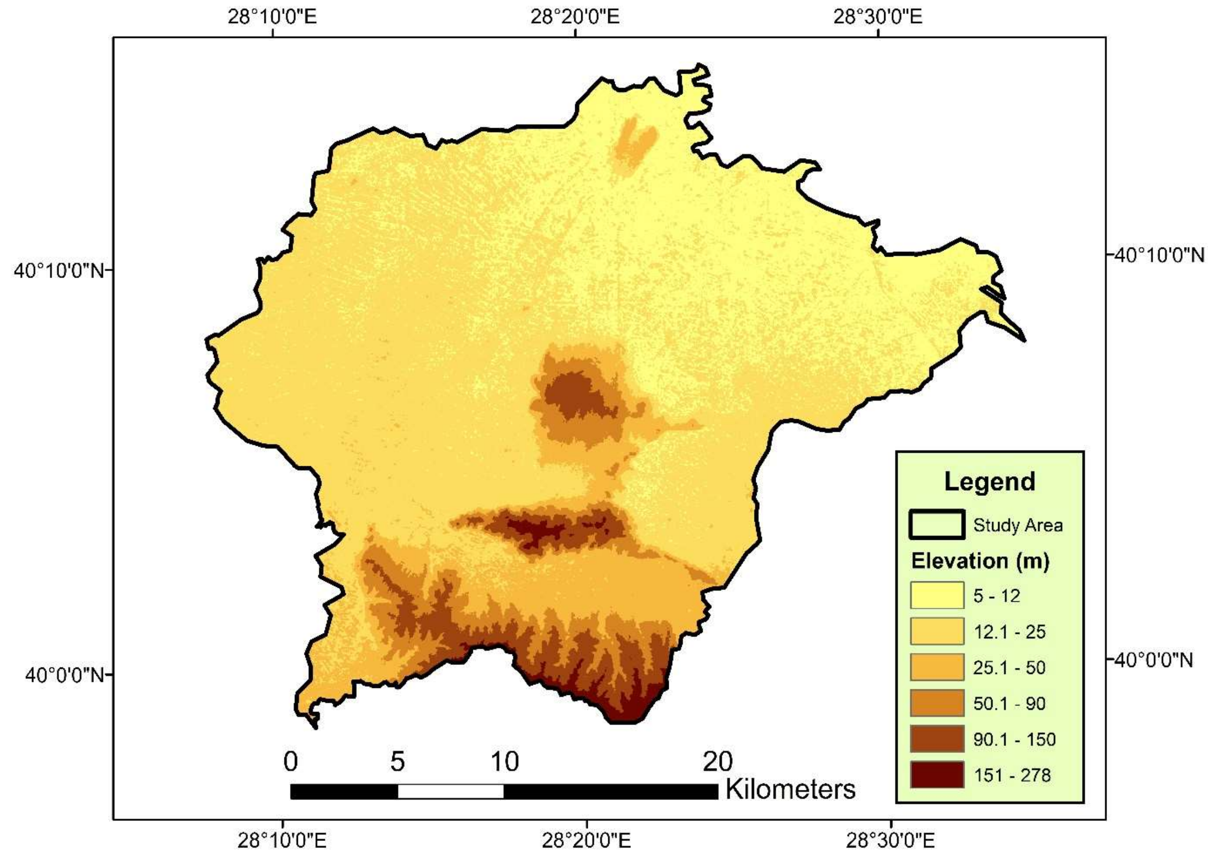

Figure 3.3. Topography of the study area.

3.1.3. Climate

Generally, Bursa is located in Marmara Region and affected by the Mediterranean region climate, hot and dry in summers from June to September, and cold and rainy in winters. Also, there can be snow in winter.

The mean temperature ranges from 13.6°C to 30.9°C in summer and from 1.6°C to 9.4°C in winter. The main component of precipitation is rainfall, the annual precipitation depth is between 600-800 mm, and it can be considered as 700 mm in average, and the average monthly precipitation in Mustafakemalpaşa and Karacabey districts is shown in Figure 3.4 below. The maximum monthly precipitation is in November, December and January which is around 112.5 mm, and the minimum monthly precipitation is in July and August, which is around 12.5 mm (Ministry of Agriculture and Forest 2010). Figure 3.5 below shows the location of the rain gauge stations with their codes.

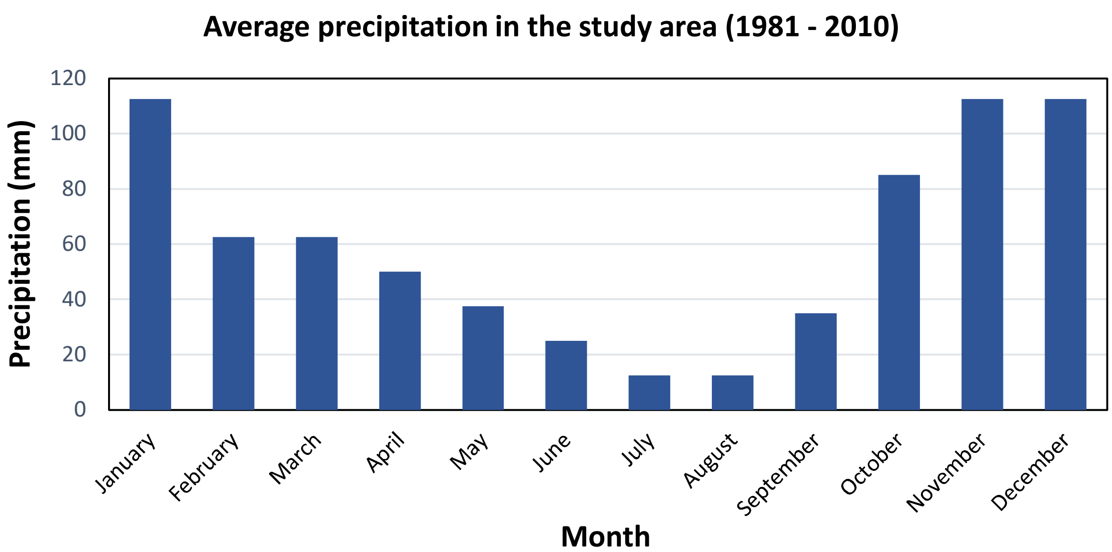

Figure 3.4. Average monthly precipitation in the study area between (1981 – 2010)- (Ministry of Agriculture and Forest, General Directorate of Meteorology website 2010).

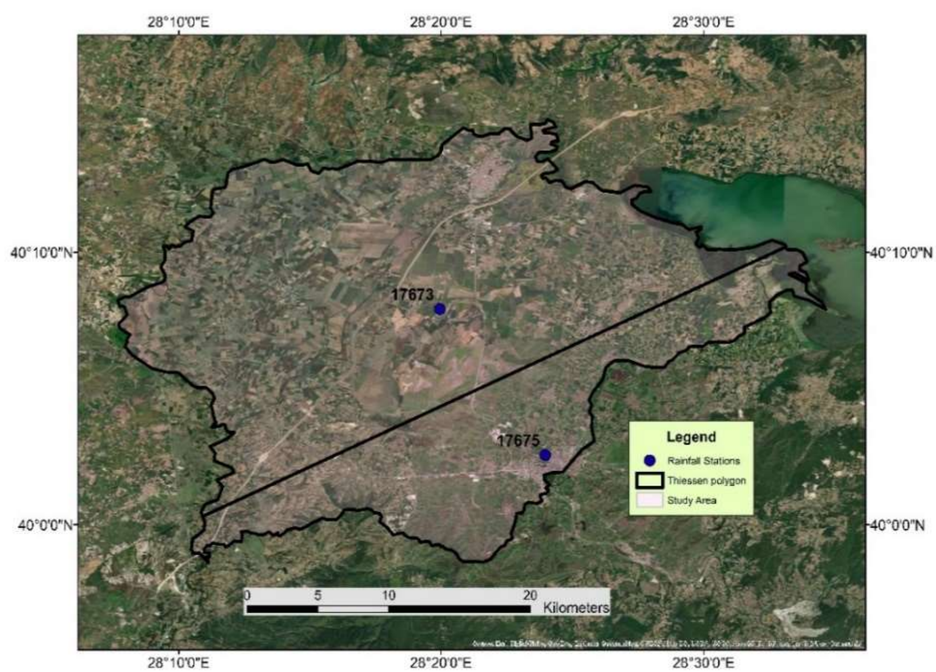

Figure 3.5. Rain gauge stations.

3.1.4. Land Cover

Land cover is the physical cover that can be observed on the surface of the earth. Land use is used to characterize how the land is used, which is affected by activities that people conduct at the land surface to change or maintain it. Both "Land use" and "Land cover" terms are used interchangeably by policymakers, forest and land managers, agricultural sectors, academia, and the like. Still, they are not the same because land cover deals with what covers the earth's surface and land use deals with how the land is used.

Land cover data were obtained from Copernicus Global Land Service, which is a European website (Corine 2018). All data is freely accessible to all users. It uses a minimum mapping unit of 100 m for areal data. In the present study, data from the year 2018, which is the last available data, was utilized. For data in 2018, Sentinal-2 satellite is used.

Figure 3.6 and Table 3.1 shows the land cover in the study area with percentage and area covered by each type of land cover. For example, 66.63% of the study area is covered by permanently irrigated land. Land use decisions have huge effects on the land and people, and they are significant for water resources, the environment and the economy, (UNESCO 2018).

Mustafakemalpaşa district has a population of 101,000 capita, and Karacabey district has a population of 84,000 capita, so the total number of populations in the Mustafakemalpaşa and Karacabey plain is about 185,000 capita. Agriculture activities represent major forms and types of land use. Population and both irrigated and non-irrigated land should be taken into consideration in any possible land use decision, since they are an important part of the ecosystem.

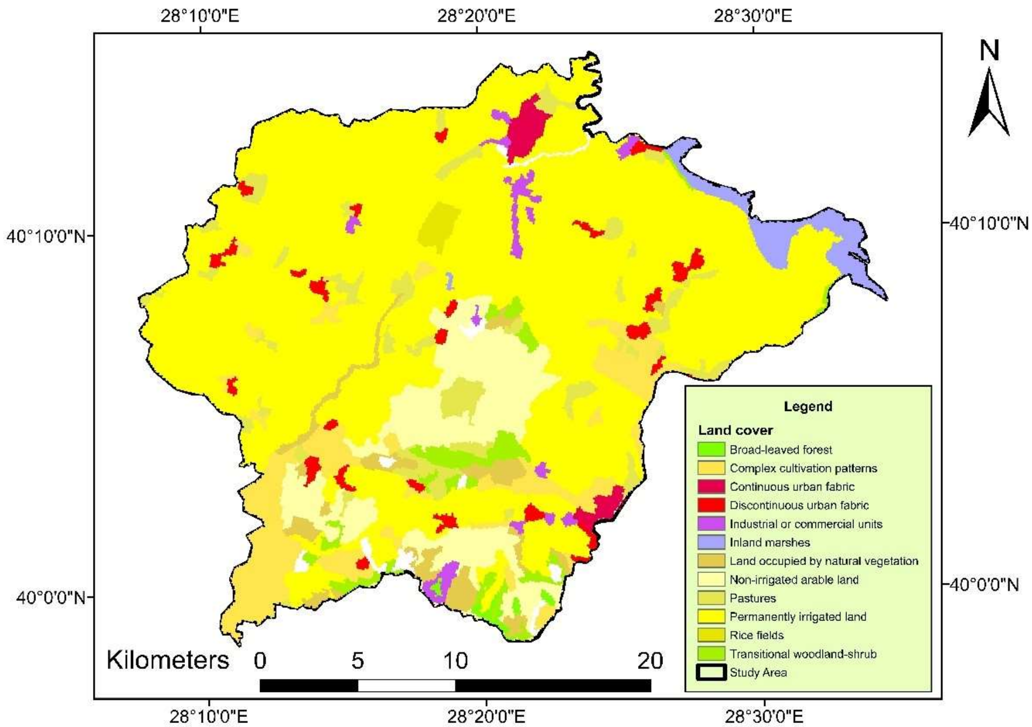

Figure 3.6. Land cover in Mustafakemalpaşa and Karacabey plain (Corine 2018).

Table 3.1. Land cover in the Mustafakemalpaşa and Karacabey plain.

Land Cover	Area covered (km^2)	Area percentage %
Discontinuous urban fabric	12.73	1.99%
Industrial or commercial units	8.43	1.32%
Non-irrigated arable land	61.98	9.71%
Permanently irrigated land	425.09	66.63%
Pastures	31.31	4.91%
Complex cultivation patterns	50.40	7.90%
Land occupied by natural vegetation	18.41	2.89%
Transitional woodland-shrub	15.19	2.38%
Inland marshes	14.48	2.27%

3.1.5. Soil

According to the Atalay (2008), the whole soil clusters in the Mustafakemalpaşa and Karacabey plain are Alluvial. Figure 3.7 below presents the distribution of the soil types in Turkey.

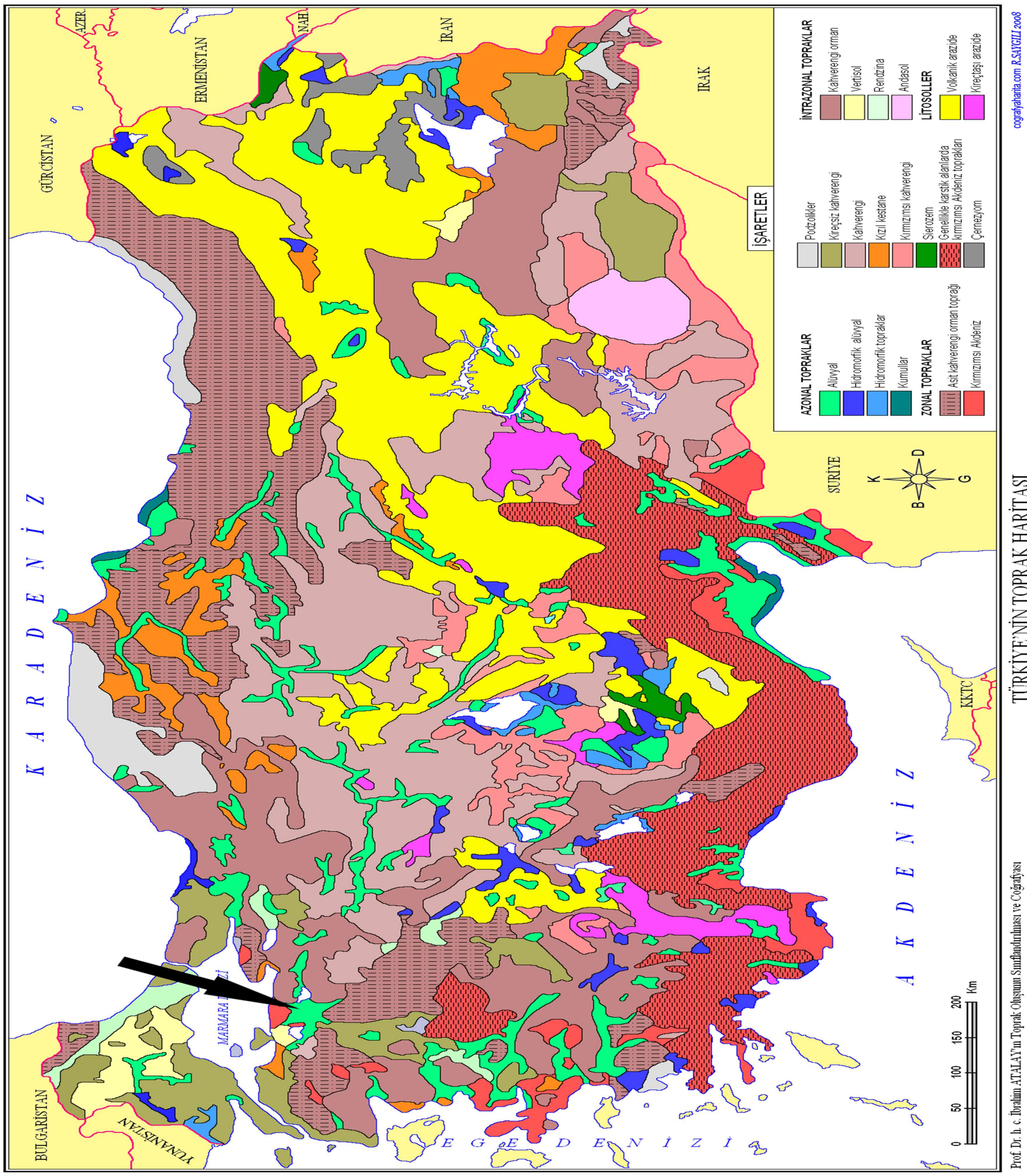

Figure 3.7. Soil types in Turkey (Atalay 2008).

They are called Alluvial soils that are deposited by surface water, they are found along rivers and floodplains, and they are also called alluvial fans. Alluvial fans result from large floods that make the soil to spread out. There are many differences between alluvial soils and other soils in reference to their formation. Alluvial soils are composed through rock transformation processes, which take thousands of years (Ricker 2020).

Many functions can be provided by alluvial soils, and the most important one is to remove sediments flowing in the water. Alluvial soils can also remove pollutants from rivers and improve water quality (Ricker 2020). Soil in aquifers is essential and critical in controlling the movement and storage of water.

3.2. The GIS-based DRASTIC method

Many techniques and methods have been developed to evaluate the effects of human activities and ecosystem on groundwater contamination, and groundwater vulnerability assessment is one of these techniques. The GIS-based DRASTIC method which will be used in this thesis, as mentioned earlier, developed under the cooperation between the (US EPA) and the (NWWA). It is utilized for assessing and mapping intrinsic vulnerability. It was utilized in the US and many others countries in the world (Aller et al. 1987, Zghibi et al. 2016).

3.2.1. Main properties and features of DRASTIC method

In DRASTIC method, the following hypotheses should be considered:

- The source/origin of the contaminants is at the surface of the earth.
- Contaminants are moved and transferred into the aquifer by precipitation and infiltration.
- The movement of contaminants within the aquifer is done by advection, so both the pollutants and the water have the same velocity.

DRASTIC method was developed as an easy-to-use groundwater vulnerability assessment method depending on multiple hydrogeological. Besides, it has good precision and flexibility to include or exclude parameters based on local conditions of the area and which data is available (Gogu and Dassargues 2004). DRASTIC method identifies regions with high vulnerability to pollution. Also, resulted groundwater vulnerability assessment maps may provide an enhanced vision and understanding of the groundwater system in a specific area.

DRASTIC method can be applied in different scales from small to large. In this research, GIS-based DRASTIC method is selected for all the reasons mentioned above to study intrinsic groundwater vulnerability. Also, data availability plays an essential role in choosing this method. Groundwater vulnerability assessment in agricultural regions is an essential and significant issue. The resulting maps can be used in upcoming aquifer monitoring and protection plans.

3.2.2. The Parameters of the DRASTIC Method

In the DRASTIC method, seven parameters are the input parameters to the model; these parameters are:

- *D - Depth to water table.*
- *R - Net Recharge.*
- *A - Aquifer media.*
- *S - Soil media.*
- *T - Topography.*
- *I - Impact of the vadose zone.*
- *C - Hydraulic Conductivity.*

Each of the seven DRASTIC parameters is mapped separately using GIS and categorized into ranges, and these parameters differ in their weight on groundwater contamination. Each parameter is assigned a specific rate (from one to ten). Then, the weight multipliers are used in the model for each of the above parameters to reflect its effect on the vulnerability assessment. The most important parameters have a higher weight, which is five, while the least important parameters have a lesser weight, which is one. So, this is called a parameter weighting and rating approach. The weights are given by US EPA depending on the knowledge and expertise after studying various regions (Aller et al. 1987). Table 3.2 below summarizes the assigned weight for DRASTIC parameters its percentage (each weight over the total weights). Figure 3.8. depicts the methodology of groundwater vulnerability analysis using DRASTIC method.

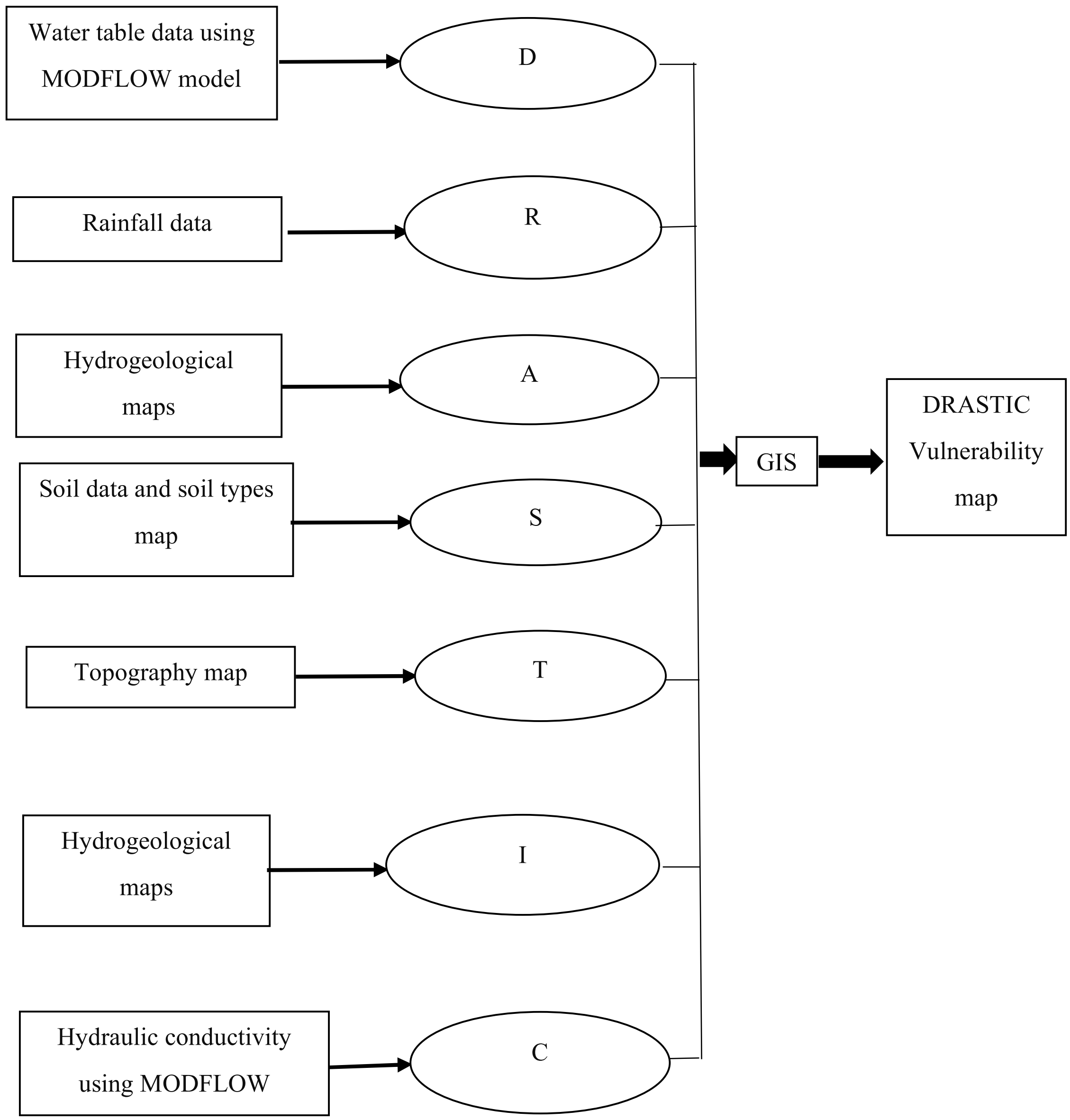

Figure 3.8. Flow chart of the methodology for groundwater vulnerability assessment using GIS-based DRASTIC method.

Table 3.2. Assigned weights for DRASTIC parameters(Aller et al. 1987).

Hydrological factor	Weights
D -- Depth to Water Table	5 - (21.47%)
R -- Net Recharge	4 - (17.39%)
A -- Aquifer Media	3 - (13.04%)
S -- Soil Media	2 - (8.70%)
T -- Topography	1 - (.35%)
I -- Impact of the Vadose Zone Media	5 - (21.74%)
C -- Hydraulic Conductivity	3 - (13.04%)

Then, the DRASTIC index value (V) can be built using the following equation:

$$V = D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W \qquad \text{(Equation 3.1.)}$$

Where the subscript R is the rating and the subscript W is the parameter's weight, and *D, R, A, S, T, I, C* represent the seven hydrogeological parameters given in Table 3.2. The DRASTIC Index value calculated by the above equation provides a proportional measure of groundwater vulnerability to contamination. Higher DRASTIC Index indicates a greater groundwater vulnerability to contamination. An area with low DRASTIC index values does not imply that this area is totally free of contamination. That means it is less sensitive to contamination with respect to other sites with higher DRASTIC indices.

3.2.3. Explanation of DRASTIC Method Parameters

- **Depth to water table:**

It contains the soil media and unsaturated zone representing the effect of pathway through which contaminants travel to reach the water table. The relationship between vulnerability and depth to water table is an inverse relationship. When the aquifer is shallow, it is more sensitive to contamination. The rating values are presented in Table 3.3.

Table 3.3. Rating values for different ranges of depth to water table (Aller et al. 1987)

Depth to water table (m)	Rating
0 - 1.50	10
1.51 - 4.60	9
4.61 - 9.10	7
9.11 - 15.20	5
15.21 - 22.80	3
22.81 - 30.41	2
More than 30.41	1

- **Net Recharge:**

Aquifers are fed by recharge, which is considered the main source of groundwater. Meanwhile, the main source of recharge is precipitation. Net recharge (R) [mm/year] is the annual infiltrated water depth. Recharge is an essential parameter in groundwater vulnerability assessment due to its significant role in transporting the contaminants. The possibility of pollutants and vulnerability increases if recharge increases. Table 3.4 summarizes the rating values for the net recharge.

Table 3.4. Rating values for different ranges of annual net recharge (Aller et al. 1987).

Recharge (cm/year)	Rating
0 – 5.0	1
5.0– 10.2	3
10.2 – 17.8	7
17.8 – 25.4	8
More than 25.4	9

- **Aquifer Media:**

Aquifer media is the unconsolidated soil or consolidated rock that works as a storage of water. It can be referred to the area with a high potentiality for water storage. Groundwater flow, contaminant fate, contaminant transport, and pollutant attenuation processes of an aquifer, which are significant components in aquifer remediation and treatment processes, depend on the type and amount of fine grains. Generally, a larger grain size with more openings in the aquifer provides more permeability, and the attenuation process capacity is lower causing a high potential of pollution and higher groundwater vulnerability (Anwar et al. 2003). Rating values for different aquifer media are summarized in Table 3.5.

Table 3.5. Rating values for different aquifer media (Aller et al. 1987).

Aquifer Media	Rating
Shale	2
Igneous	3
Weathered igneous	4
Large sandstone Thin-bedded limestone and sandstone	6
Gravel and sand Large limestone	8
Basalt	9
Karst limestone	10

- **Soil Media:**

Soil media is the weathered upper section of the ground. In other words, it is the upper section of the vadose zone. Soil characteristics have a significant impact on the movement and transport of contaminants within the soil, amount of recharge infiltrating and percolating into the ground, dispersion, and attenuation processes of contaminants. Soil pollution and the ability of soil to transfer contaminants are affected by the type of clay, its amount in the soil, the size of soil grain as well as shrink potential that controls the macro-pores and permeability. Soil cover with fine substances such as clay and organic materials can protect the groundwater from contaminants by preventing their migration due to low permeability (Zghibi et al. 2016). Table 3.6 below summarizes rating values for different types of soil media.

Table 3.6. Rating values for different types of soil media (Aller et al. 1987).

Soil Medium	Rating
Non-shrinking clay	1
Muck	2
Clay loam	3
Silty loam	4
Mud	5
Sandy loam	6
Shrinking clay	7
Peat	8
Sand	9
Gravel	10

- **Topography:**

In DRASTIC method, topography means the slope of the specific area. Hydrological slope or steepest descent can be calculated using the elevation of the center cell and neighboring cells (8 cells around the center cell). In general, an area with a low or flat slope tends to accumulate more water and prevent it from going downstream for a longer period of time. A lower slope indicates more infiltration of water from the ground surface and, thus, causes a higher potential of pollutant transport into the subsurface. Therefore, in areas with low slopes, groundwater vulnerability to contamination is high. Areas with steep slopes have smaller amount of infiltration and higher amounts of surface runoff. Thus, they have a lower vulnerability to groundwater contamination. To calculate the slopes, Digital Elevation Model (DEM) can be used. Rating values for various ranges of slopes are summarized in Table 3.7 below.

Table 3.7. Rating values for different ranges of slopes (Aller et al. 1987).

Topography - slope %	Rating
0 – 2	10
2 – 6	9
6 – 12	5
12 – 18	3
More than 18 %	1

- **Impact of the Vadose Zone:**

It is the unsaturated section of aquifer located over the groundwater. The influence of soil medium and the vadose zone is similar, both based on the soil medium's permeability features, attenuation and remediation characteristics. However, studying the vadose zone's impact is generally complex. The pathway of contaminants begins at the soil media then goes into the vadose zone. To study and understand pollutant movement in the vadose zone, hydrogeology maps and lithological cross-sections can be used. Table 3.8 summarizes rating values for various types of vadose zone material.

Table 3.8. Rating values for different types of vadose zone material (Aller et al. 1987).

Vadose zone medium	Rating
Silt/clay	1
Shale	3
Metamorphic/igneous	4
Sandstone Sand and gravel with high clay Bedded limestone and sandstone Limestone	6
Gravel and sand	8
Basalt	9
Karst limestone	10

- **Hydraulic Conductivity:**

Hydraulic Conductivity depends on the properties of the medium and the fluid flowing through it. It represents the ability of aquifer medium to transmit water. It is a critical parameter that plays a significant role in contaminant transport within the saturated zone and the concentration of the plume in the aquifer. Therefore, aquifers with high hydraulic conductivity values have higher groundwater vulnerability, and the aquifer vulnerability is lower for aquifers with low hydraulic conductivities. Table 3.9 summarizes the rating values for various ranges of hydraulic conductivity values.

Table 3.9. Rating values for ranges of Hydraulic Conductivity values (Aller et al. 1987).

Hydraulic Conductivity of the Aquifer (m/day)	Rating
0.04 – 4.10	1
4.11 – 12.30	2
12.31 – 28.70	4
28.71 – 41	6
41.1 – 82	8
More than 82.10	10

3.3. Sensitivity Analysis

As mentioned earlier, DRASTIC method has many advantages, and one of these advantages is the vulnerability assessment carried out using multiple parameters. Employing seven parameters as input data limits and decreases the effect of error of each parameter on the final result. At the same time, many scientists said that the groundwater vulnerability might be calculated without utilizing the whole DRASTIC parameters (Rosen 1994). In order to evaluate the effect of each parameter, two sensitivity analyses can be carried out: single parameter and map removal sensitivity analyses.

3.3.1. Single parameter sensitivity analysis

It is utilized to calculate and determine the effect of each parameter on the resulting groundwater vulnerability map. It is carried out for each raster cell. The DRASTIC method is considered sensitive to the parameters' ratings and weights, so the parameters' effective weights will be determined. The "effective weight" is calculated using the following equation (Rosen 1994):

$$W = \frac{P_r P_w}{V} x\ 100 \qquad \text{(Equation 3.2.)}$$

Where:

W: the effective weight of the parameter P.

P_r: *the rating of the parameter P.*

P_w: *the weight of the parameter P.*

V: the DRASTIC index.

3.3.2. Map removal sensitivity analysis

The map removal sensitivity analysis is utilized to determine the sensitivity of the groundwater vulnerability to removing one or more parameter, and is calculated using the following equation (Lodwiek et al 1990):

$$S_V = \frac{|(V/N) - (V'/n)|}{V} \, x\ 100 \qquad \text{(Equation 3.3.)}$$

Where:

S_V: the variation index (%).
V: the DRASTIC vulnerability index.
V′: the vulnerability index without one or more map layers.
N: the number of parameters used for calculating V.
n: the number of parameters used for calculating V'.

3.4. Water Quality Parameters and Validation of the Results

The total number of observation wells located in the study area is 22, and these wells can be used to validate the results and study the quality of the aquifer. Samples collected from the observation wells were tested by BUSKI and DSI laboratories. The main objective of these measures is to validate the results and describe the final state of the aquifer quality. Also, the relation between the resulting vulnerability indices and quality parameters were investigated.

3.4.1. Nitrate concentration

Aquifer can be polluted by nitrate as a result of wide agricultural activities, such as using fertilizers, and from both sewage systems and septic tanks. In addition, some aquifers can be polluted by nitrate as a result of leaching from plant. Nitrate can be the main cause of many diseases (WHO, 2011). Nitrate concentration is considered a dominant factor to study the impact of agricultural activities on the aquifer.

3.4.2. Total Dissolved Solids (TDS)

Total dissolved solids (TDS) is an expression utilized to depict inorganic matters and tiny amounts of organic material present in water. The major constituents of TDS are usually sodium, magnesium, calcium, potassium cations, hydrogen carbonate and carbonate, sulfate, chloride, and nitrate anions. According to WHO (2011), the TDS levels are classified as follows:

Table 3.10. Classification of TDS according to WHO (2011).

TDS (g/L)	Classification
Less than 0.3	Excellent
0.3 – 0.6	Good
0.6 – 0.9	Fair
0.9 – 1.2	Poor
Greater than 1.2	Unacceptable

And there are many methods for measuring TDS value in water, and one of the most common methods is the measurement of electric conductivity using a conductivity probe by detecting the ions in water.

In this research, TDS measurements can be used to validate and describe the last state of the Mustafakemalpaşa and Karacabey aquifer. Groundwater samples are taken from 22 locations and the measurements are done by BUSKI and DSI. The TDS measurements and vulnerability indices are presented in chapter 4.

3.4.3. Sulfate

The existence of sulfate (SO4) in drinking water can make the taste of water noticeable. The main source of sulfate in the water is the industrial wastes as well as atmospheric deposition. Furthermore, mineral dissolution and anthropogenic activities like fertilizers is considered the source of sulfate in aquifers (WHO 2011).

3.4.4. Coliform Bacteria

Continuously monitoring has been necessary for coliform bacteria in groundwater, since the human health can be directly or indirectly affected by these microorganisms. These bacteria can be a reason for sever illnesses, such as gastroenteritis, and the main source of these bacteria is contaminated water from untreated waste water, septic tanks, and the like.

Total coliform, fecal coliform and E coli can be used as an indicator whether water is suitable for drinking purposes. Total coliforms contain whole members of the coliform bacteria so it can be considered as a huge collection of different types of bacteria, which are found in the environment such as vegetation, and water. Fecal coliform is a subtype of total coliform which particularly exists in gut of warm-blooded animals. E coli is a small group from fecal coliform. So, if the coliform bacteria are found in the water sources, the water sources and systems should be inspected to remove any possible sources of coliform contamination.

4. RESULTS AND DISCUSSION

Many distributed and geospatial data were used as input to get the resulting map. As a powerful tool to analyze the geospatial data and visualize the results, GIS was fundamentally used in data preparation, developing the maps, and analyzing the results. Briefly, chapter four describes the preparation of each parameter's necessary data to develop the vulnerability map of Mustafakemalpaşa and Karacabey plain with associated analysis and results.

4.1. Raster Maps for DRASTIC Parameters

There are five observation wells distributed in the Mustafakemalpaşa and Karacabey plain under the State Hydraulic Works (Devlet Su İşleri) supervision. Three of these wells are in the Karacabey district, and two are in the Mustafakemalpaşa district. Groundwater head data obtained from these wells were utilized in this research (Keskin 2019). Figure 4.1 below depicts the location of the observation wells with their codes. The resolution that used in these maps were 150 x 150 m because the available data has this resolution, and it is sufficient to cover all variability in the study area. The following subsections describe the development of each parameter map with the source and methodology used to develop these maps.

4.1.1. Depth to water table

Between 2013 and 2015, daily water levels from five observation wells were collected by Keskin (2019) and State Hydraulic Works (DSI). The obtained data were utilized to prepare and develop the first parameter map. The model done by Keskin (2019) using MODFLOW software (Harbuagh 2005) was utilized to calculate the depth to water table. MODFLOW is a groundwater flow modeling software that can be used to model groundwater flux and groundwater contamination. It is developed by United States Geological Surveys (USGS).

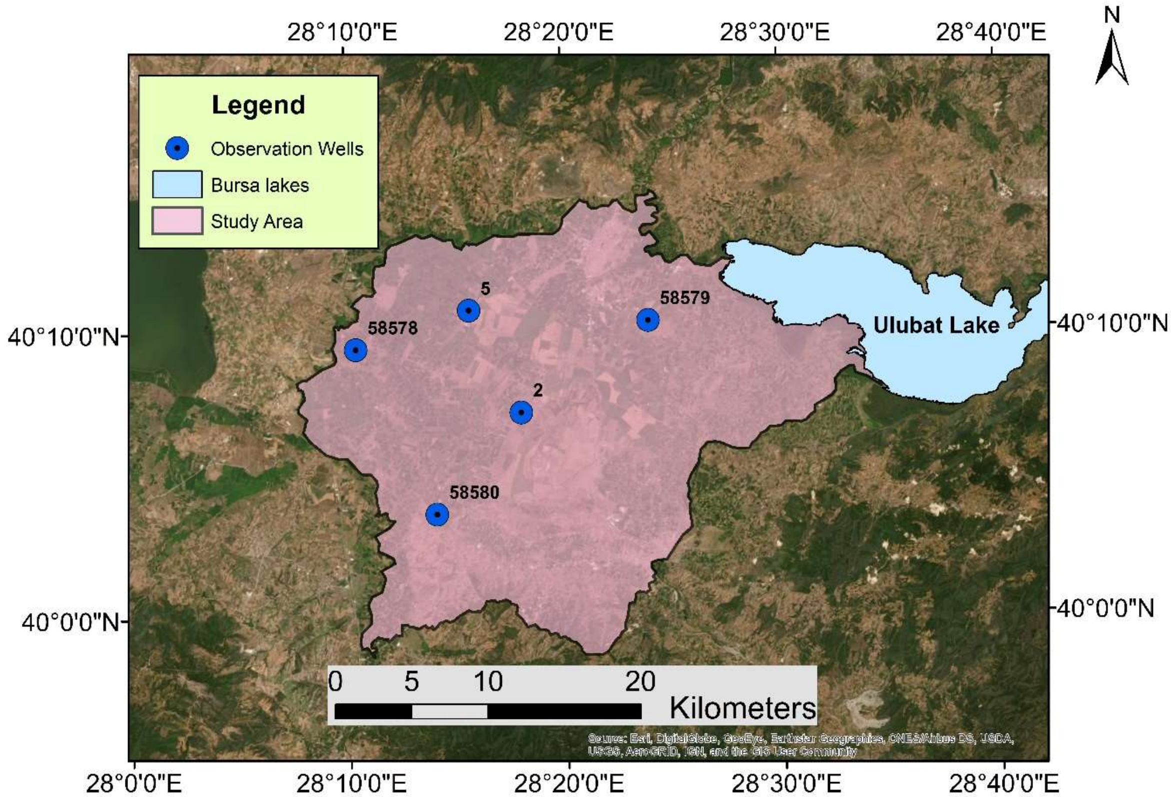

Figure 4.1. Location of the observation wells for groundwater head.

The depth to water table was calculated as the difference between the ground surface elevations and the groundwater head values. In the south of the Mustafakemalpaşa and Karacabey plain, which has a ground elevation of about 280 m AMSL, the depth to water table is around 240 m. In some areas in the study area, the depth to water table is less than 1.5 m. Figure 4.2 below shows the resulting depth to water table values.

The depth to water table values was used to calculate the rates depending on the categories summarized in Table 3.3. The data processing is conducted using GIS. Raster format was used to calculate the rates effectively; each cell depending on the depth to water table, was given an appropriate rate. Finally, the rate of each cell was multiplied by the parameter weight. Figure 4.3 shows the raster map resulting from the multiplication of the weight and rate for the depth to groundwater (Dr x Dw) for the study area.

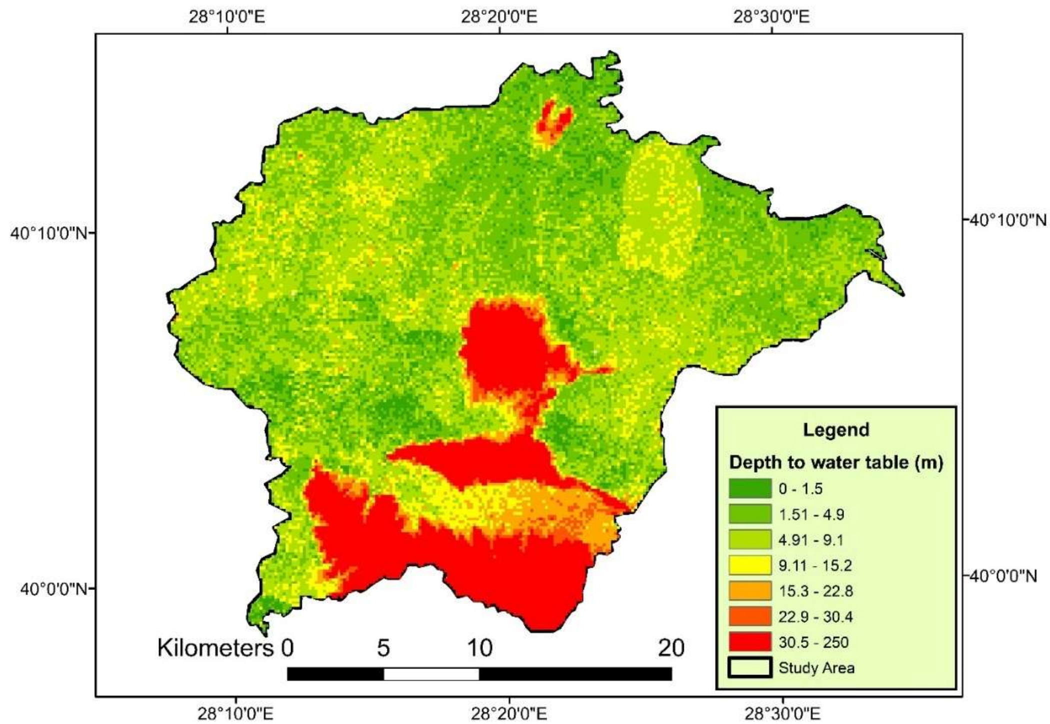

Figure 4.2. Depth to water table for the Mustafakemalpaşa and Karacabey plain.

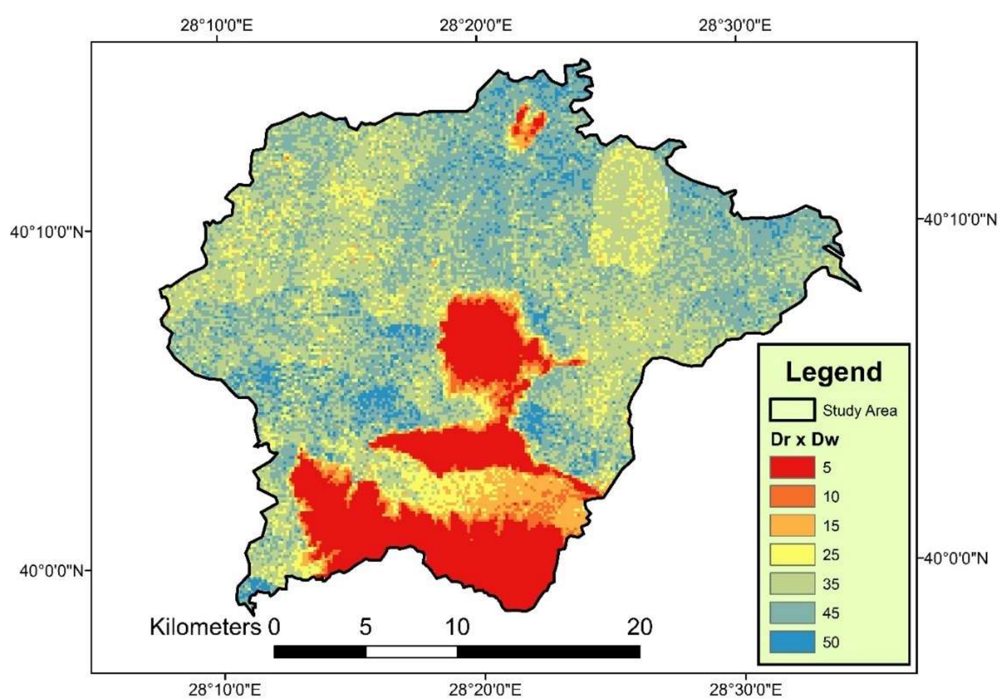

Figure 4.3. Raster map resulting from the muliplication of the weight and rate for depth to water table (Dr x Dw) for the Mustafakemalpaşa and Karacabey plain.

4.1.2. Net Recharge

According to Keskin (2019), the net recharge is calculated to be more than 254 mm in the study area. Two rain gauge stations were used to calculate the aquifer recharge. At the first rain gauge station (ID = 17673), the rainfall is 660 mm, and at the second gauge station (ID = 17675), it is 420 mm (Figure *3.5*). Another point should be mentioned here, that the permanently irrigation activities have a significant role in increasing the net recharge more than 254 mm.

According to Table 3.4, both net recharges are more than 254 mm, so the rating value is 9 and it was expected because the slope of the area is low and about 66% of the land area is permanently irrigated. Figure 4.4 shows the raster map resulting from the multiplication of the weight and rate for net recharge (Rr x Rw) in the study area.

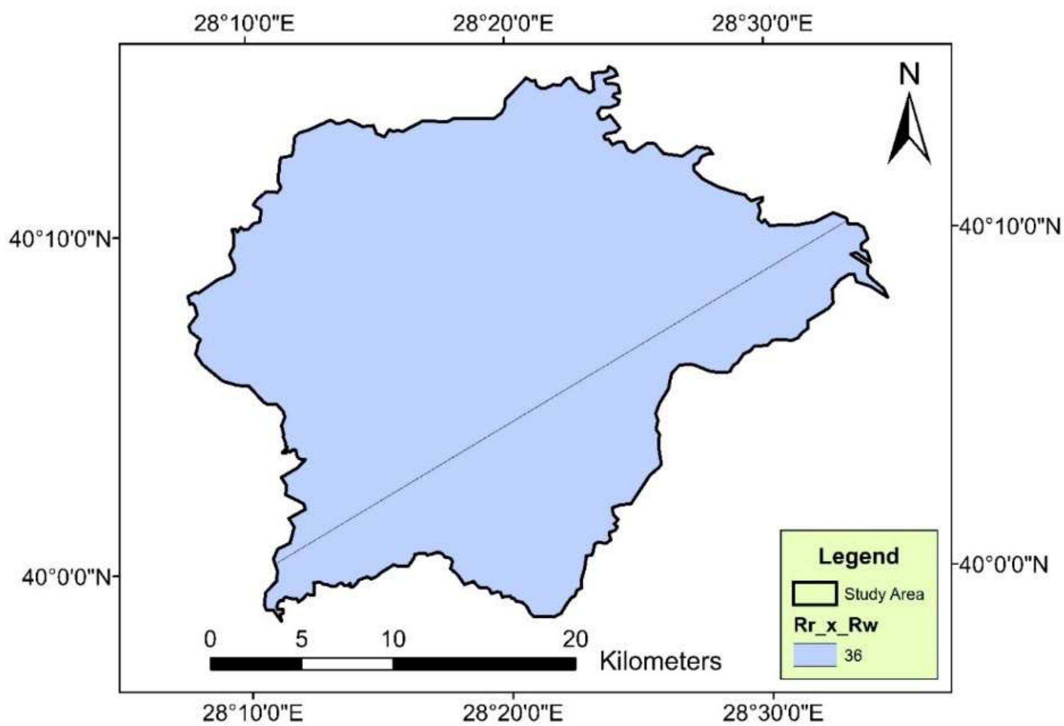

Figure 4.4. Raster map resulting from the multiplication of the weight and rate for net recharge (Rr x Rw) in the study area.

4.1.3. Aquifer media

As mentioned earlier, the aquifer media is the rock that works as a storage of water. In shallow aquifers, the aquifer medium is an extension of the vadose zone medium and have the same properties. Thus, both have the same formation which is alluvium with different weight, the weight of the aquifer media is 3, while the weight of the vadose zone is 5. Figure 4.5 shows the raster map resulting from the multiplication of the rate and weight for aquifer media (Ar x Aw) in the study area.

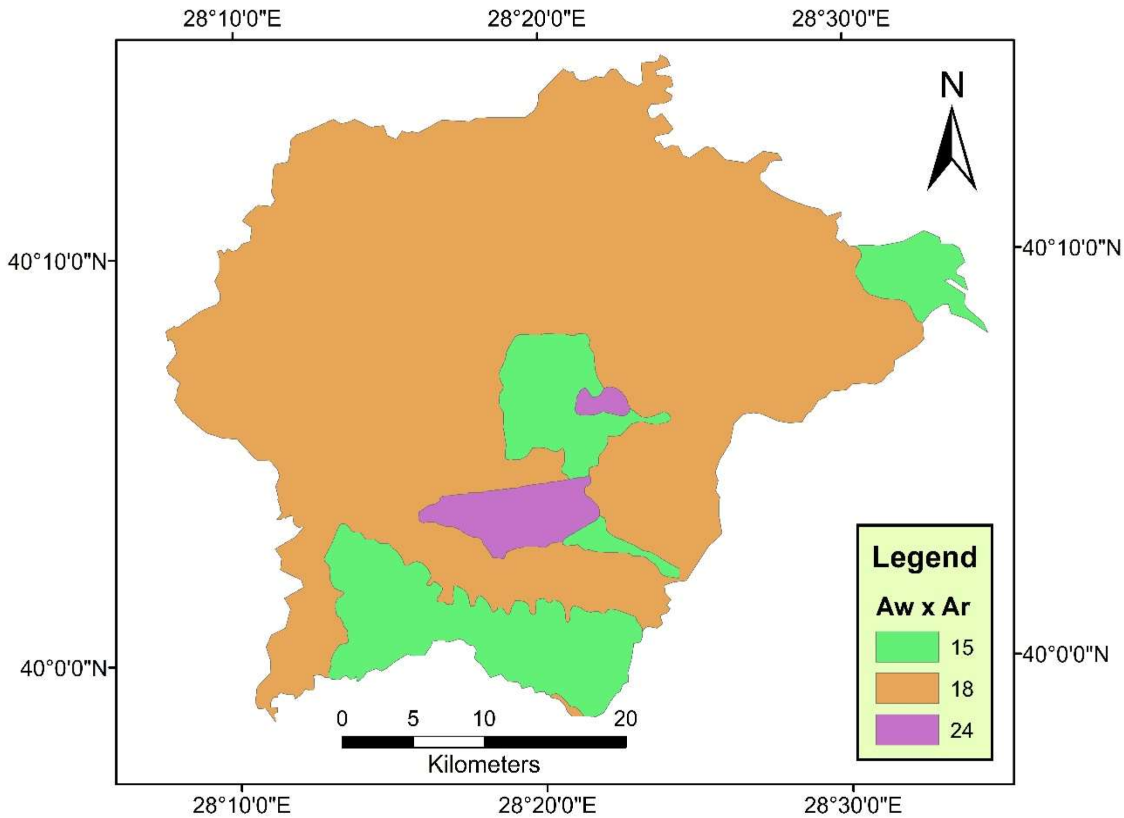

Figure 4.5. Raster map resulting from the multiplication of the weight and rate weight for aquifer media (Ar x Aw) in the study area.

4.1.4. Soil type media

The assessment of soil impact on the groundwater vulnerability in the Mustafakemalpaşa and Karacabey plain was investigated. The map includes only 3 types of soil (Figure 4.6). Table 4.1 below summarizes the soil type, soil texture, area covered and its overall percentage.

- Alluvium soil: The texture of alluvium is widely ranged from gravel to clay. Table 3.6 mentioned above shows that the alluvium rate is taken as 5, which is an average value between gravel and clay. The study area can be considered alluvium soil media since almost 90% of the study area is covered by alluvium soil.

- Terra Rosa soil: The source material of terra rosa is dolomite and hard limestone. The main soil texture is silty clayey soil, and the rate is taken as 6 (limestone classification). And as mentioned in the table below, terra rosa soils cover about 7% of the study area.

- Brown Forest soil: The main soil texture is clay, so the rate is taken as 1, low vulnerability to contamination. Brown forest soils cover about 3% of the study area.

Figure 4.6 and Figure 4.7 below show the soil type and the raster map resulting from the multiplication of the weight and rate for soil media (Sr x Sw) in the study area.

Table 4.1. Soil type media in the Mustafakemalpaşa and Karacabey plain.

Soil type	Soil texture	Area covered (km^2)	Area percentage %
Alluvium soil	Ranged from gravel to clay	571.81	89.67 %
Terra Rosa soil	Silty clayey soil	43.22	6.78 %
Brown Forest soil	Clay	22.63	3.55 %

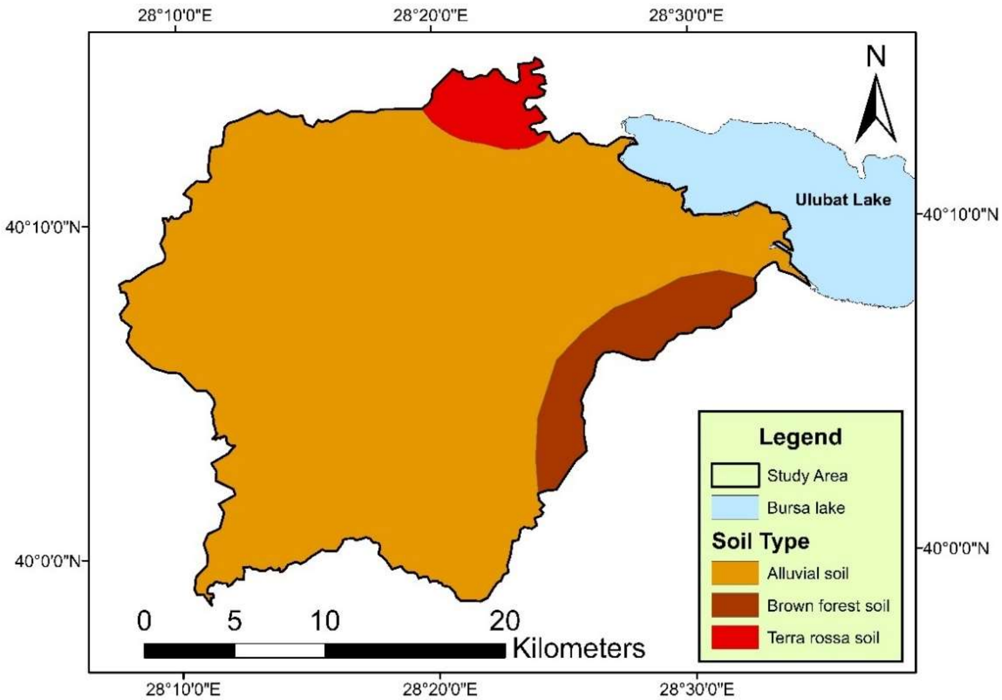

Figure 4.6. Soil type media in the study area.

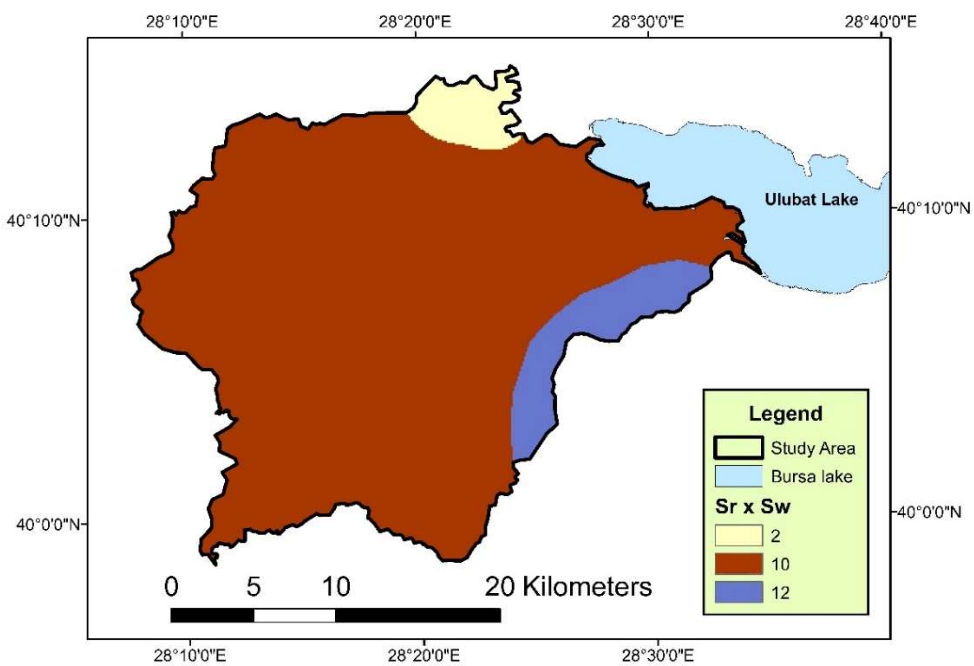

Figure 4.7. Raster map resulting from the multiplication of the weight and rate for the soil media (Sr x Sw) in the study area.

4.1.5. Topography:

As mentioned in Table 3.7 , the slope of the ground surface should be in percentage to be utilized in the GIS-based DRASTIC method. The slope was computed from Digital Elevation Model (DEM) using GIS. About 90 % of the Mustafakemalpaşa and Karacabey plain has a slope value less than 12 %, and the southern part has a slope ranged between 12 % and 80 %. That means these areas with a low slope have a high potential for pollution. Figure 4.8 below shows the slope map (percentage), and Figure 4.9 shows the raster map resulting from the multiplication of the weight and rate for topography (Tr x Tw) in the study area.

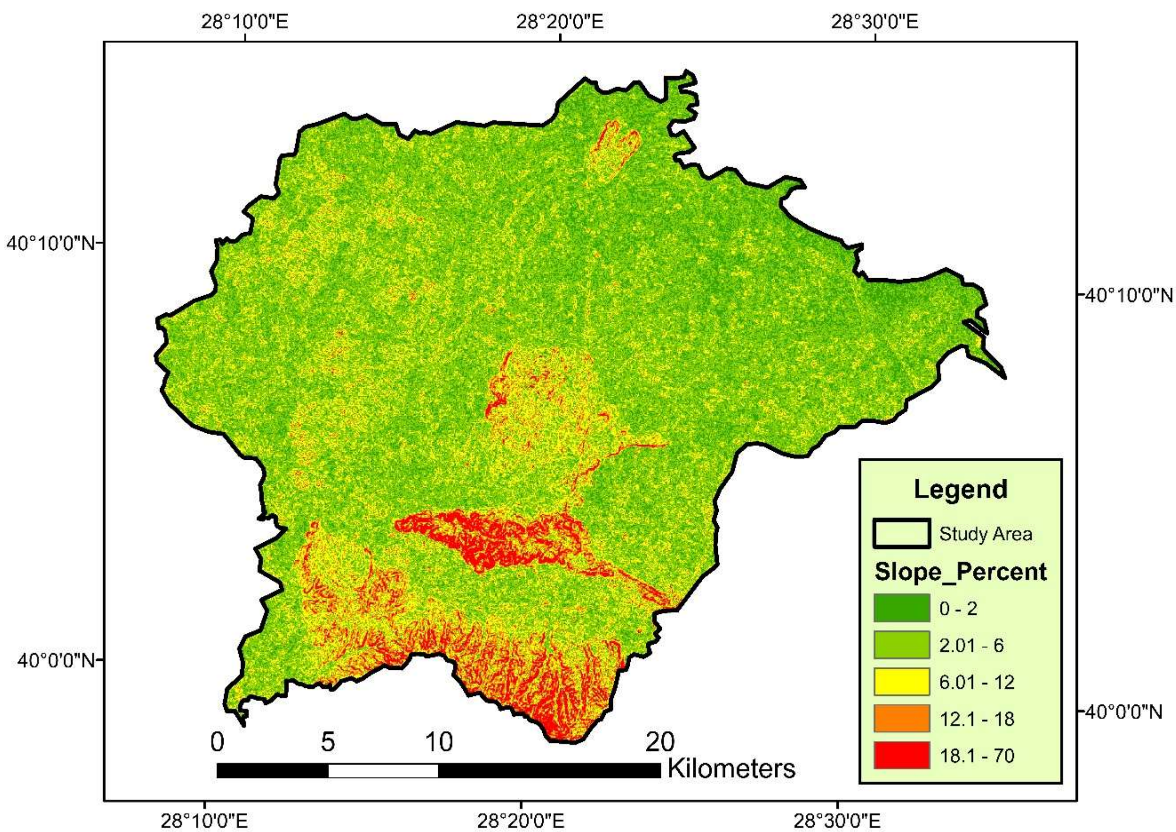

Figure 4.8. Slope map of the study area.

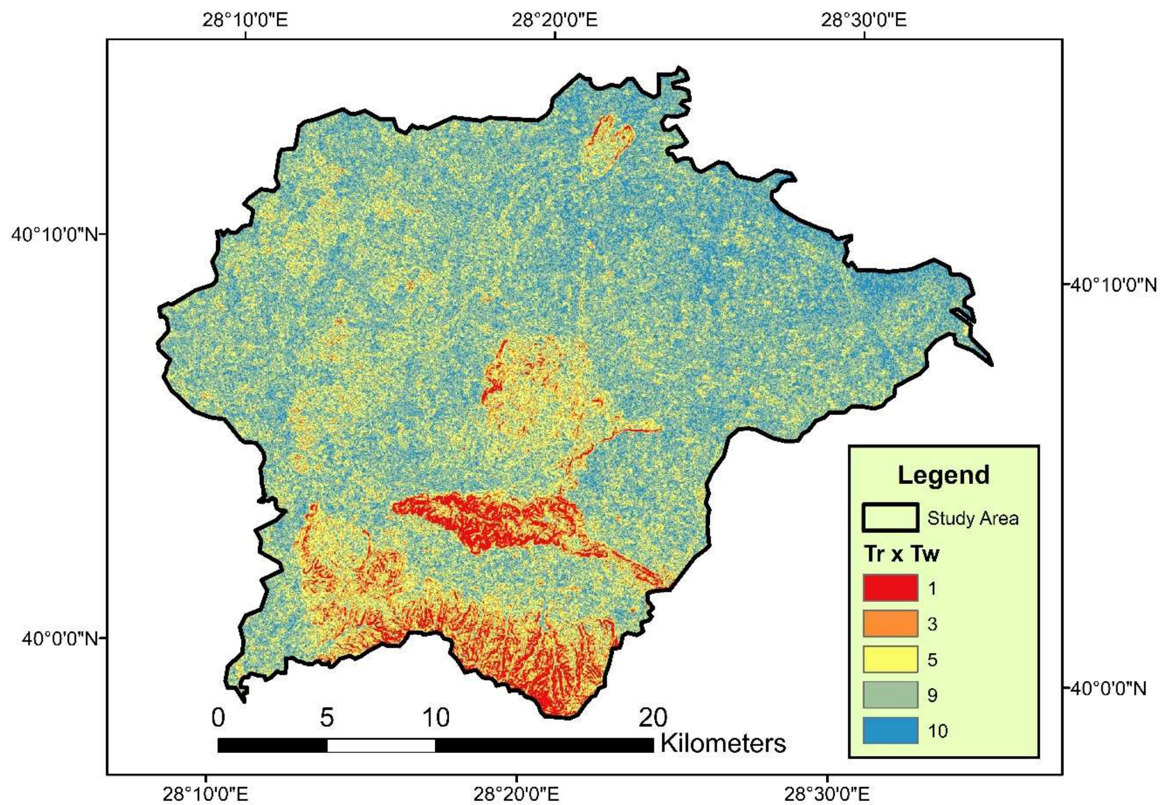

Figure 4.9. Raster map resulting from the multiplication of the weight and rate for topography (Tr x Tw) in the study area.

4.1.6. Impact of the vadose zone

As mentioned earlier, the vadose zone is the unsaturated section of aquifer locating over the water table. Data were obtained from the General Directorate of Mineral Research and Exploration, 2016 (Maden Tetkik ve Arama Genel Müdürlüğü). The geological formation map was used to get the vadose zone material. Figure 4.10 below shows the geological formation of the Mustafakemalpaşa and Karacabey plain. About 80% of the study area is undifferentiated quaternary sediments consisting of siliciclastic, organics, and carbonates. These types of sediments that occurred in flood plains is similar in its features to the limestone and sandstone. Thus, this type of geological formation rating is about 6 because it is similar to limestone and sandstone.

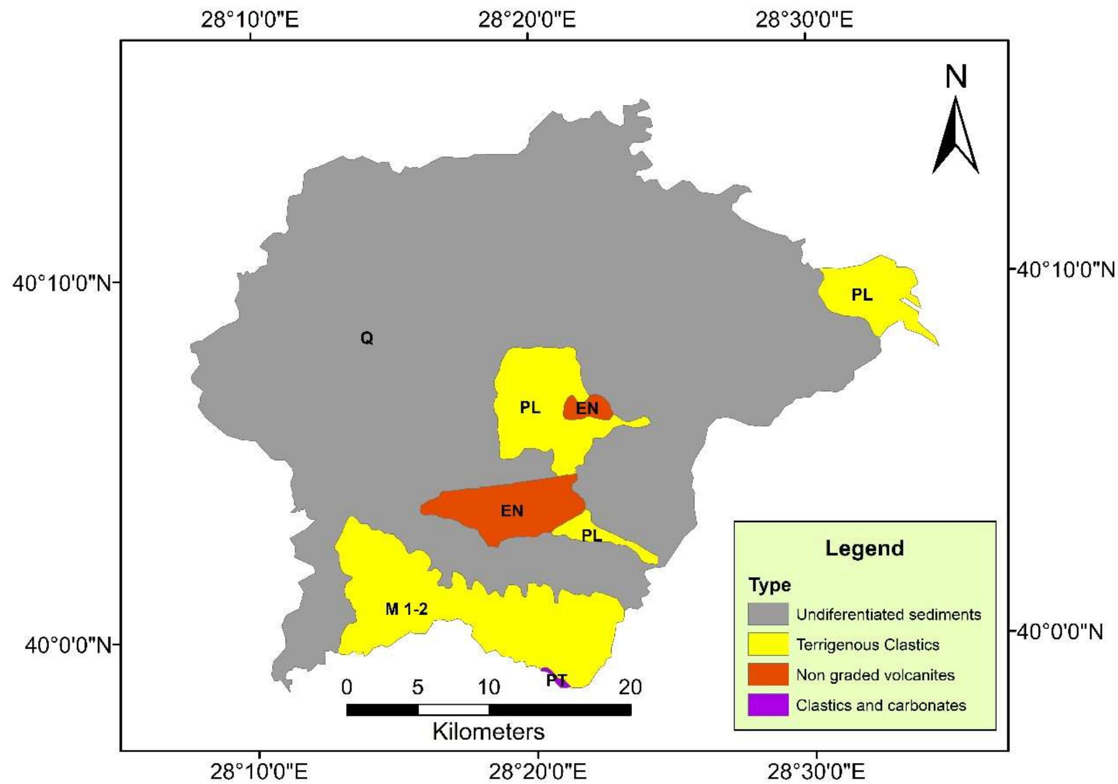

Figure 4.10. The geological formation of the study area.

The second geological formation is terrigenous clastic and it covers about 7% of the area. The age of the terrigenous clastic rock is Pliocene Epoch, which extends from 5.3 million to 2.6 million years ago. It is a period of global cooling after the Miocene, which is a warmer epoch. It consists of sedimentary rock; with pre-existing minerals and rocks. And, generally, they can be considered as clastic sedimentary rocks. Clastic sedimentary rocks have a high percentage of silica. Based on clast diameter, it is subdivided into siltstone, sandstone, and finer than silt (like shale). So, its rating in DRASTIC model is taken as 5 (Britannica 2018).

The third type of geological formation is non-graded volcanic. It covers about 4% of the study area and the age of this type of rock is Eocene Epoch, which extends from 56 million to 33.9 million years ago (Britannica 2018). In general, the permeability of volcanic rocks is high, and it can be considered as Basalt. The rating value is about 8.

The last type of geological formation is clastic and carbonates, covering less than 1% of the area, as shown in Figure 4.10 above. It consists of the mineral dolomite, aragonite, and calcite. It is a sedimentary rock, and it's very similar to limestone, the rating on DRASTIC model is taken as 6.

Figure 4.11 below shows the raster map resulting from the multiplication of the weight and rate of the vadose zone (Ir x Iw) for the Mustafakemalpaşa and Karacabey plain.

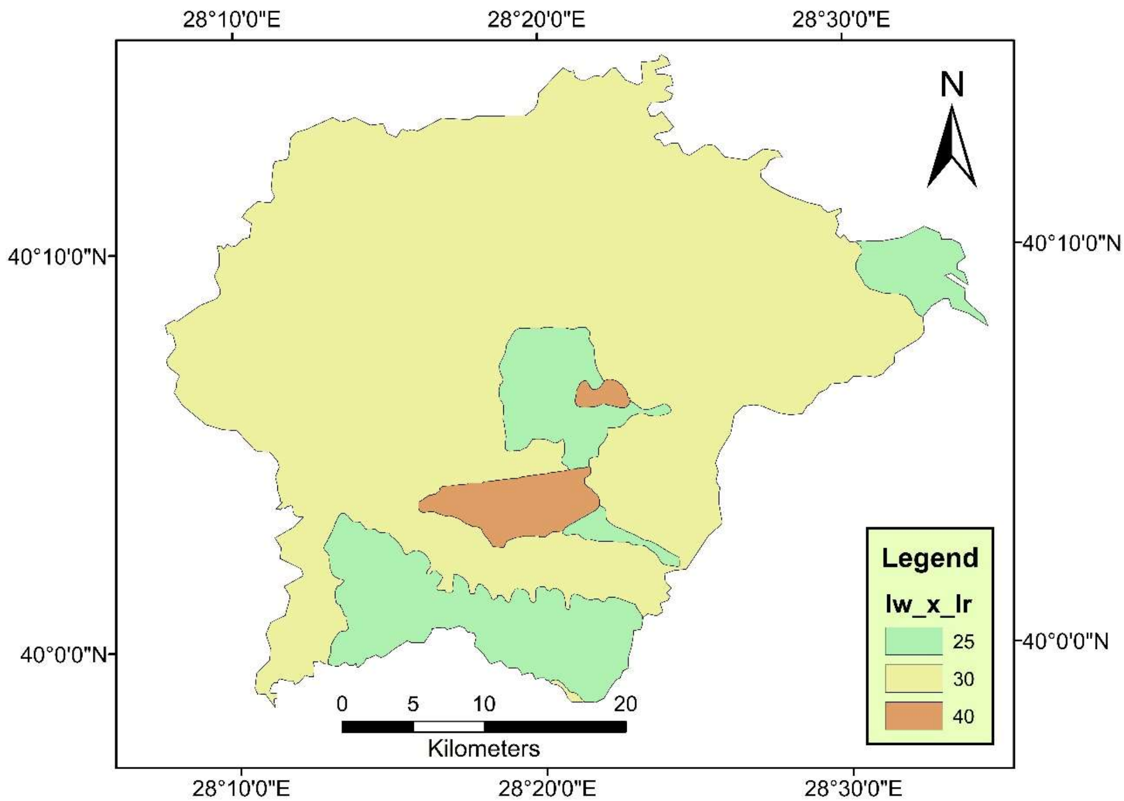

Figure 4.11. Raster map resulting from the multiplication of the weight and rate for the impact of vadose zone (Ir x Iw) for the study area.

4.1.7. Hydraulic Conductivity

Hydraulic Conductivity is the last parameter considered in the GIS-based DRASTIC method. As mentioned earlier, the assigned weight for this parameter is 3. It is an essential parameter since it represents the movement of water and pollutants in the aquifer. The hydraulic conductivity values are assigned based on the results of numerical groundwater flow model

MODFLOW which is previously performed by Keskin (2019) The aquifer has a high hydraulic conductivity value around most areas, which is up to 100 m/day. Table 4.2 below summarizes the hydraulic conductivity values in the observation wells. GIS was utilized to represent and visualize hydraulic conductivity values; Raster format was used with a cell size of 100 m x 100 m. Figure 4.12 and Figure 4.13 below show the hydraulic Conductivity and the raster map resulting from the multiplication of the weight and rate for hydraulic Conductivity (Cr x Cw) in the study area.

Table 4.2. Resulting hydraulic conductivity values for different regions in the study area using calibration model (PEST) (Keskin 2019).

Observation Well (Code)	Hydraulic Conductivity (m/day)
5	4.15
58578	2.34
58579	100
58580	47.78
2	6.63
Remaining area	100

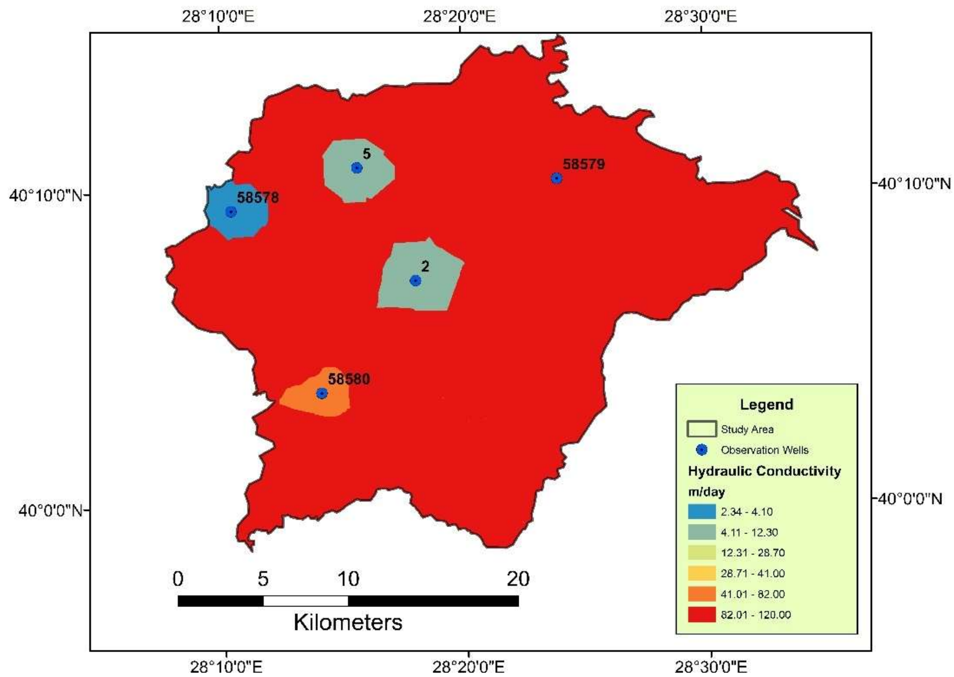

Figure 4.12. Hydraulic Conductivity distribution in the study area.

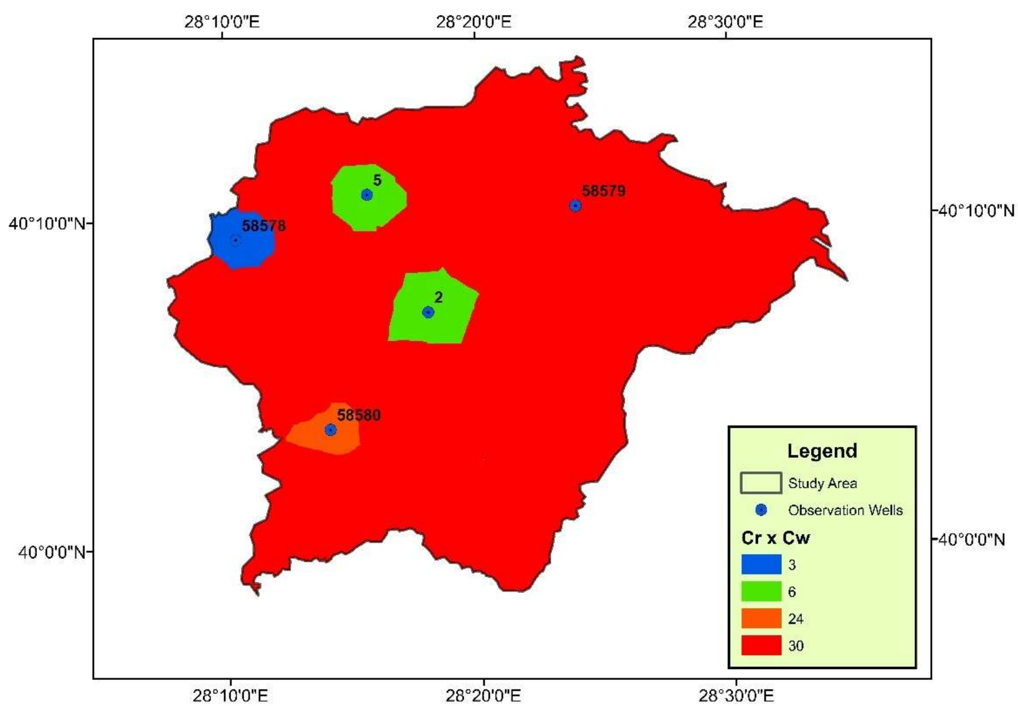

Figure 4.13. Raster map resutling from the multiplication of the weight and rate for the Hydraulic Conductivity (Cr x Cw) in the study area.

4.2. Results

The obtained data was prepared with the associated rate for each parameter. After that, raster maps resulting from the multiplication of the cell rating by weight of parameter were obtained. The maps for each parameter are shown in Figs 4.3, 4.4, 4.5, 4.7, 4.9, 4.11, and 4.13. To get the resulting vulnerability index map, seven parameter maps were superimposed using GIS. Figure 4.14 shows DRASTIC Index map.

DRASTIC Index values are classified into 5 categories: very low, low, moderate, high, and very high vulnerability to pollution as shown in Figure 4.15. According to this, about 1 % of the MKP&KP has very low vulnerability with an area of 5.5 km^2, 15.3 % has low vulnerability with an area of 96.7 km^2, 18.8 % has moderate vulnerability with an area of 119 km^2, 39 % has high vulnerability with an area of 250 km^2, and the very high vulnerability region covers 25.5 % of the Mustafakemalpaşa and Karacabey plain with an area of 161 km^2. Table 4.3 below summarizes the vulnerability index, risk level, area and percentage for each class.

Table 4.3. Summary of vulnerability index classification.

Vulnerability index	Risk level	Area (km^2)	Percentage %
98 – 120	Very low	5.47	0.87 %
121 – 140	Low	96.73	15.33 %
141 – 160	Moderate	118.96	18.8 %
161 - 177	High	249.57	39.5 %
178 - 200	Very high	161.19	25.5 %

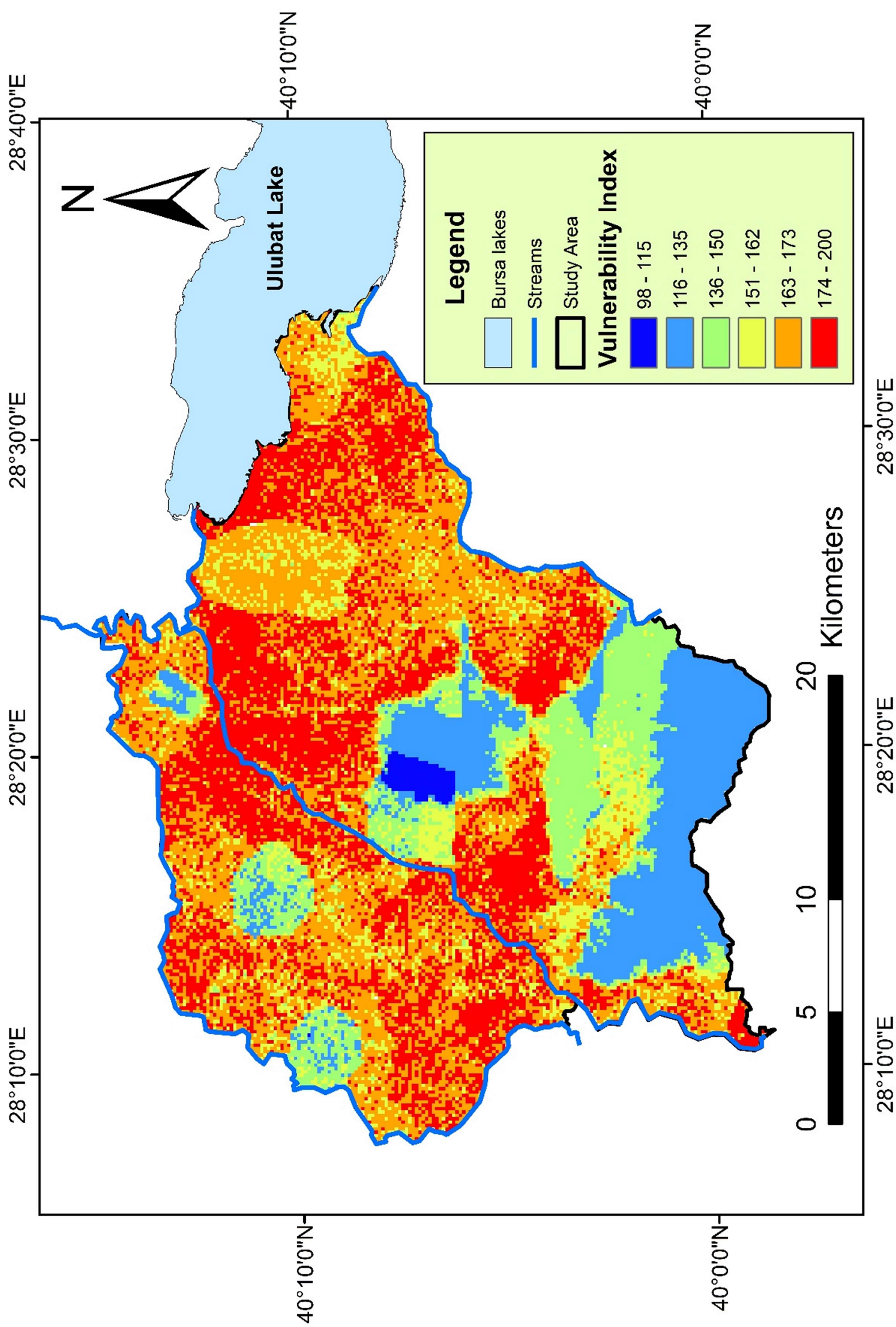

Figure 4.14. Vulnerability index for the Mustafakemalpaşa and Karacabey plain.

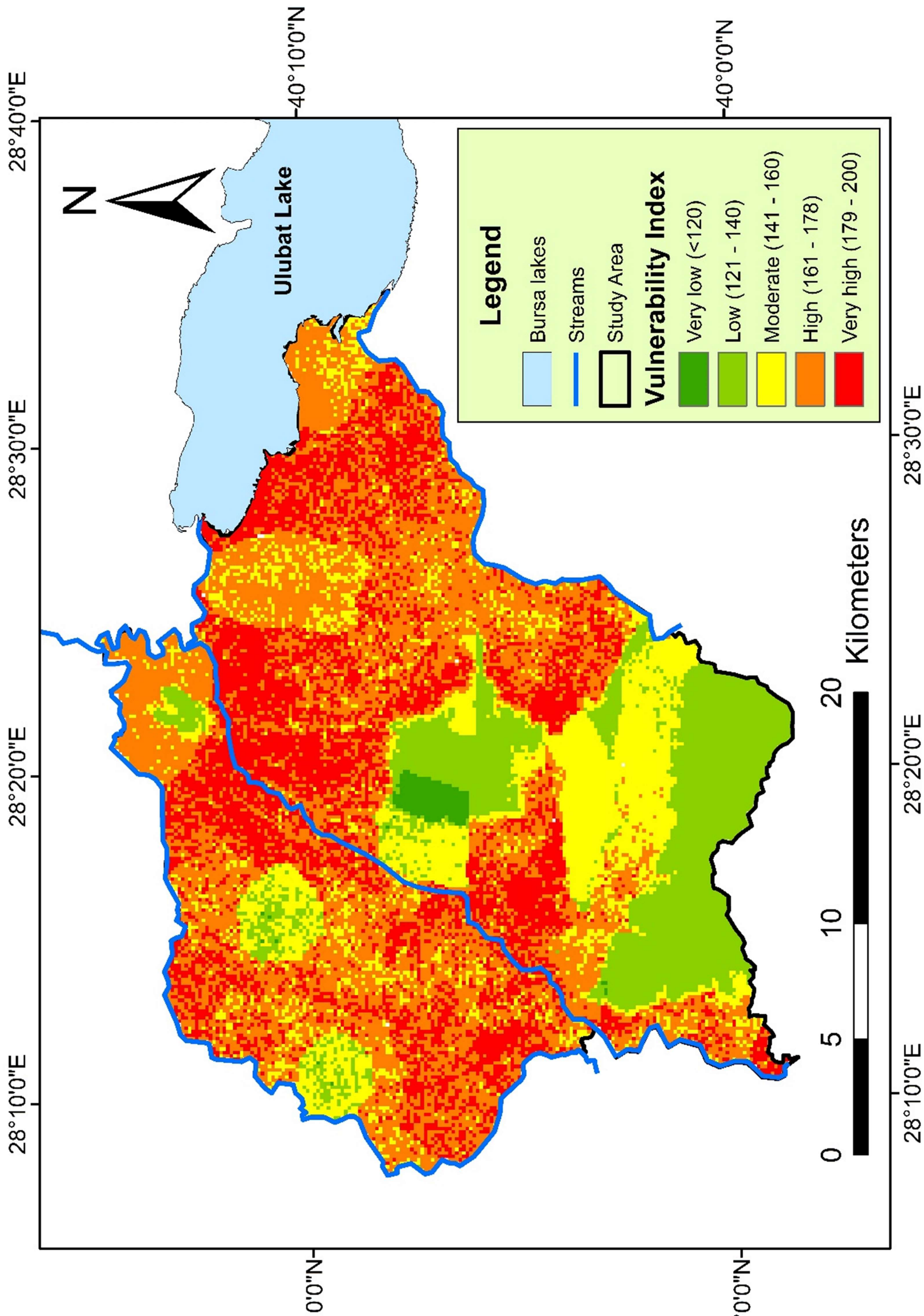

Figure 4.15. Vulnerability classification for the Mustafakemalpaşa and Karacabey plain.

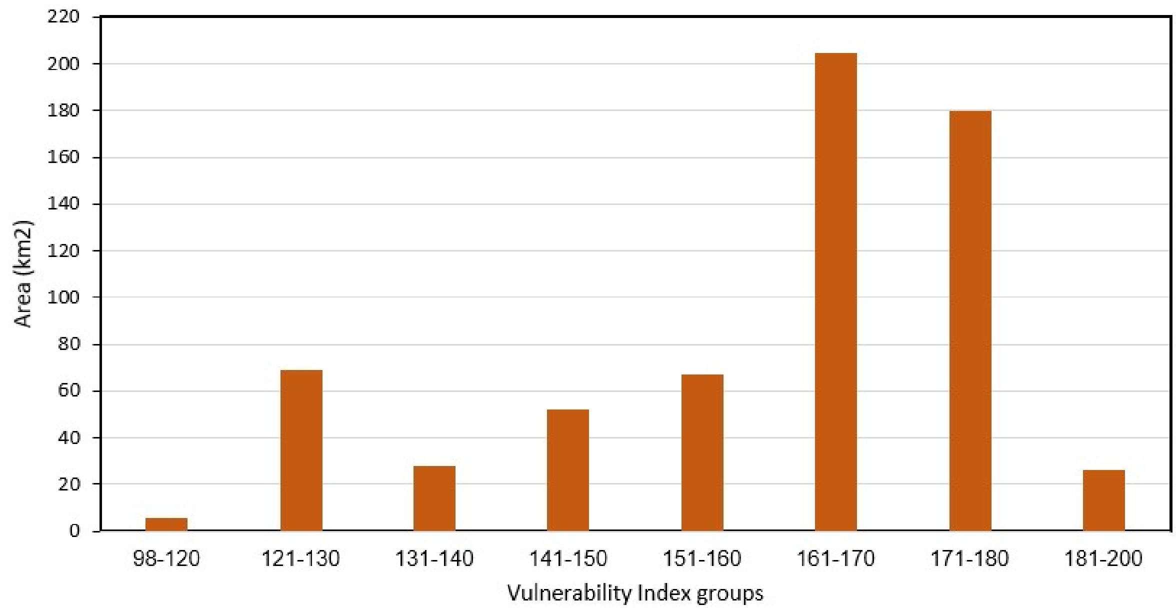

Figure 4.16. Area covered by DRASTIC vulnerability index groups for the study area.

Figure 4.17 shows that about 410 km^2 out of 630 km^2 have a high and very high vulnerability index. Also, it depicts the total percentage of the area for each qualitative vulnerability index.

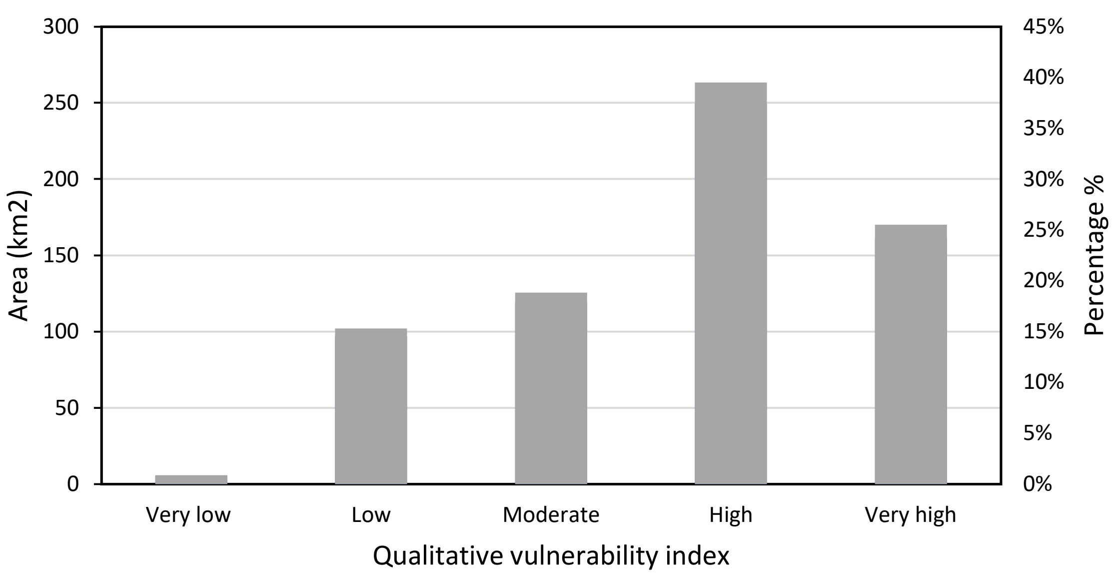

Figure 4.17. The total area and percentage for each DRASTIC vulnerability index in the study area.

Table 4.4 contains the statistical summaries (minimum, maximum, mean, and standard deviation SD) of the rating values for each parameter of DRASTIC parameters obtained from the parameter maps represented above.

Table 4.4. Summary of the DRASTIC parameters.

Parameter	Minimum	Maximum	Median	Mean	Standard Deviation (SD)
D	1	10	7	6.44	2.83
R	9	9	9	9	0
A	5	8	6	5.9	0.38
S	1	6	5	4.92	0.79
T	1	10	9	7.57	2.5
I	5	8	6	5.9	0.53
C	1	10	10	9.48	1.9

According to the means of the parameters in Table 4.4, the highest risk of groundwater pollution in the Mustafakemalpaşa and Karacabey plain originated from the aquifer's high hydraulic conductivity (mean value is 9.48). Also, the high net recharge has a high mean (mean value is 9). The aquifer media, soil type, and the impact of the vadose zone reveal a moderate risk of pollution (mean values are 5.9, 4.92, and 5.9, respectively).

Figure 4.18 shows the relationship between each type of land cover and the resulting vulnerability indices. As noticed in the figure, permanently irrigated land, complex cultivation patterns, and Inland marshes have the highest percentage of area that is highly and very highly vulnerable to contamination; meanwhile, they are not covered by very low vulnerable zones. Also, the Non-irrigated arable land has the highest percentage of low and very low vulnerable zones. The main reason can be attributed to being non irrigated; thus, the infiltration is less than other areas.

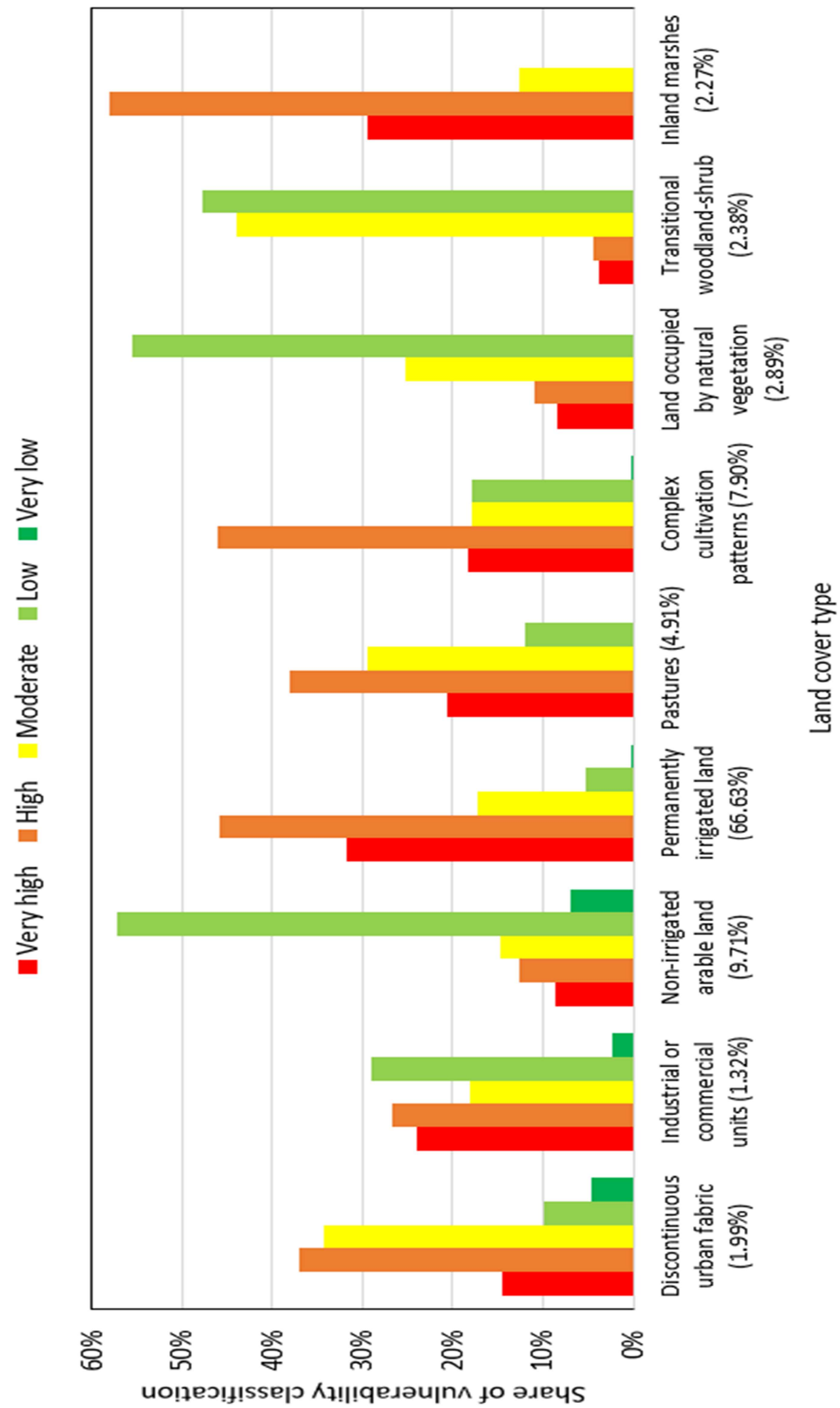

Figure 4.18. Relationship between land cover and the resulting vulnerability indices. Number in parentheses indicates the percentage of each type of land cover in the study area.

4.3. Sensitivity Analysis

4.3.1. Single parameter sensitivity analysis

As mentioned earlier, the single parameter sensitivity analysis was developed to calculate the effect of each parameter of the DRASTIC parameters on the resulting vulnerability map. The essential objective of this kind of sensitivity analysis is to compare and evaluate the "theoretical" weight for each parameter obtained by (Aller et al. 1976) with the "effective" weight calculated by DRASTIC model. The "effective" weight can be defined as the ratio between the value of each parameter to the resulting vulnerability index (V) for each cell. Table 4.5 reveals that net recharge, and hydraulic conductivity tend to be the most "effective" parameters in the assessment of groundwater vulnerability, since the mean "effective" weights, 22.22 % and 17.09 %, respectively, are higher than their "theoretical" weights. The topography presented that its "effective" weight (4.45 %) and its "theoretical" weight (4.35 %) were almost equal. The rest of the parameters showed less "effective" weights than the "theoretical" weights.

Table 4.5. Statistical summary of the single parameter sensitivity analysis.

Parameter	Theoretical Weight	Theoretical Weight (%)	Effective Weight (%)			
			Mean	Minimum	Maximum	Standard Deviation (SD)
D	5	21.70	18.71	3	32	7.68
R	4	17.40	22.22	18	36	2.92
A	3	13.05	11.6	8	16	1.32
S	2	8.70	7.11	1	10	1.28
T	1	4.35	4.45	1	10	1.29
I	5	21.75	18.82	14	28	2.24
C	3	13.05	17.09	1	24	4.16

4.3.2. Map removal sensitivity analysis

According to equation (3), the variation index analysis was carried out for all raster cells within the study area. Table 4.6 summarizes the resulting variation index (%) by taking one parameter from the calculation.

Table 4.6 and considering the statistical values for each parameter, the vulnerability index sound to be most sensitive to depth to water table (D) and groundwater recharge (R). Also, the impact of the soil type (S) was high on the groundwater vulnerability. For the first two parameters, the main reason for high sensitivity can be referred to the high theoretical weight and rating assigned to them. For the soil type, the apparent reason to high sensitivity can be referred to high rating values assigned to this parameter. In addition, Table 4.6 shows that the aquifer media (A) and the vadose zone (I) have the lowest influence on the groundwater vulnerability.

Table 4.7 summarizes the statistical measures of the variation index (%) for the removal of multiple parameters. Figure 4.19 shows the boxplots of the distribution of variation index for the used parameters in map removal sensitivity analysis in the study area. As shown in the Table 4.7, it has been started by removing two parameters until removing six parameters, the vulnerability index and the variation index was measured for each case. It can be noticed that the variation index increases when the number of removed parameters is increased.

Table 4.6. Map removal sensitivity analysis statistics for the removal of one parameter.

Parameter removed	Variation index (%)			
	Minimum	Maximum	Mean	SD
D	1.16	2.93	1.42	0.59
R	0.62	3.02	1.39	0.49
A	0.31	0.96	0.55	0.16
S	0.67	2.19	1.34	0.21
T	0.82	2.29	1.02	0.24
I	0	2.34	0.70	0.36
C	0	2.05	0.78	0.44

Table 4.7. Statistics of the map removal sensitivity analysis for the removing of multiple parameters of DRASTIC parameters.

	Variation Index (%)			
Parameter used	Minimum	Maximum	Mean	SD
D, R, S, T, I	0	2.95	0.56	0.66
D, R, S, T	0	5.38	1.27	1.19
D, R, S, I	0.05	6.43	2.33	0.99
R, S, T	0	6.68	3.14	1.15
D, R, I	2.38	11.06	5.80	1.44
D, R	0.09	13.45	6.65	2.63
S, T	4.28	13.41	8.81	0.87
T	4.28	13.72	9.52	1.48

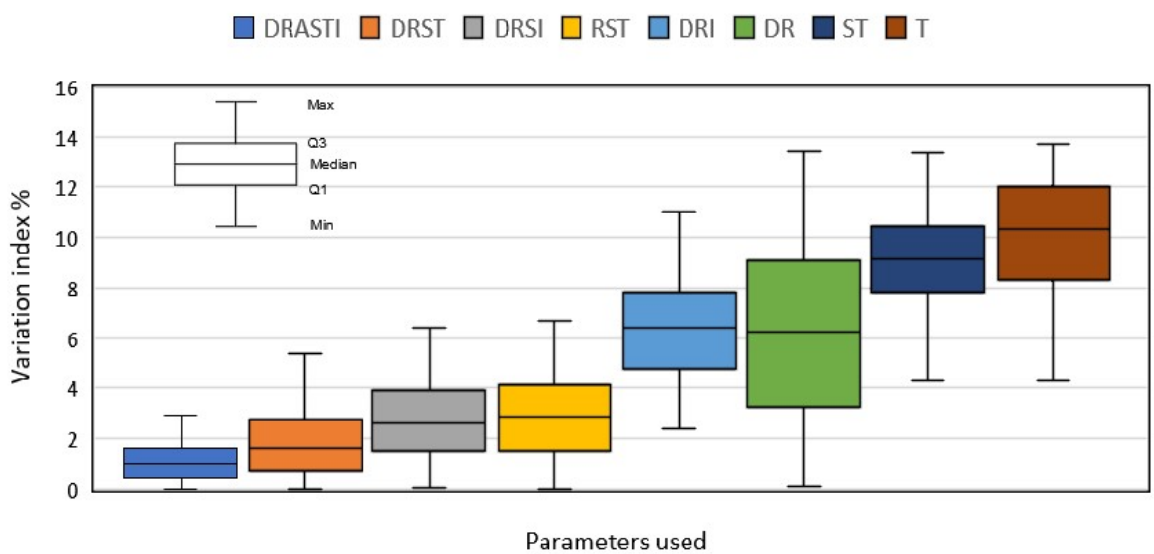

Figure 4.19. Boxplots of the distribution of variation index for the used parameters in map removal sensitivity analysis in the study area.

4.4. Water Quality Parameters and Validation of the Results

As mentioned earlier, there are 22 observation wells in the study area (Table 4.8). 12 of them is under the supervision of BUSKI, and 10 under the supervision of DSI. 13 observation wells are located in the Mustafakemalpaşa (MKP), and 9 observation wells are located the Karacabey (K). Table 4.8 summarizes the whole observation wells located in the study area, and Figure 4.20 depicts the location of the observation wells in the study area.

Table 4.8. Observation wells in the study area.

Id	Name	Source	Location*	Code
1	Adaköy	BUSKI	MKP	B1
2	Doğancı	BUSKI	MKP	B2
3	Yeşilova	BUSKI	MKP	B3
4	Tepecik	BUSKI	MKP	B4
5	Yamanlı	BUSKI	MKP	B5
6	Boğaz	BUSKI	MKP	B6
7	Celtikçi	BUSKI	MKP	B7
8	Ovahamidiye	BUSKI	K	B8
9	Ulubat	BUSKI	K	B9
10	Gönü	BUSKI	K	B10
11	Tatkavakli	BUSKI	MKP	B11
12	Kuşuboğazı	BUSKI	MKP	B12
13	Gönü	DSI	K	D1
14	Çeltikçi	DSI	MKP	D8
15	Hamidiye	DSI	K	D7
16	Küçük karaağç	DSI	K	D6
17	Ovasesemen	DSI	K	D5
18	Bakirköy	DSI	K	D4
19	Yalıntaş	DSI	MKP	D3
20	Kumkadı	DSI	MKP	D2
21	İsmetpaşa	DSI	K	D9
22	Kuşuboğazı	DSI	MKP	D10

*MKP: Mustafakemalpaşa, K: Karacabey.

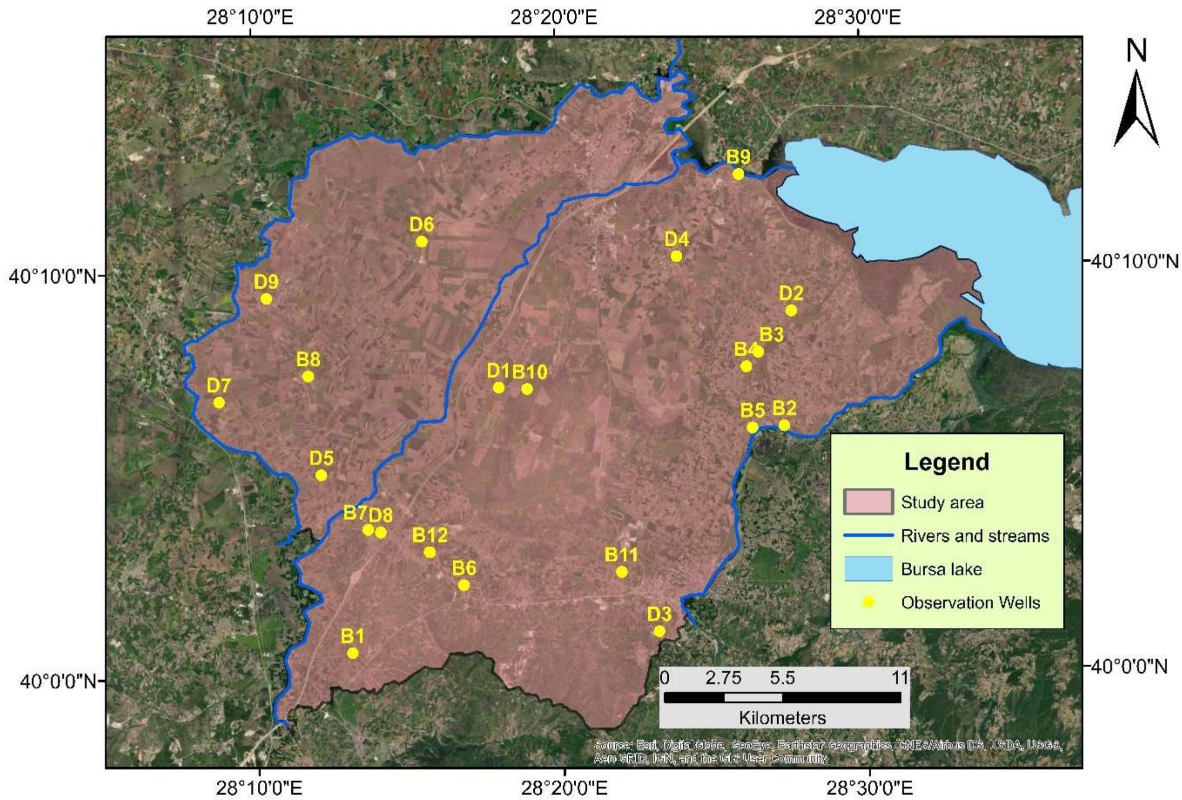

Figure 4.20. Observation wells in the study area.

4.4.1. Nitrate Contamination

To find the relationship between groundwater vulnerability and nitrate contamination of groundwater, GIS was used to join the resulting vulnerability map and the nitrate values in the study area. Figure 4.21 shows DRASTIC vulnerability indices related to groundwater nitrate concentration. These values, using simple linear regression (SLR) analysis, show a correlation ($R^2 = 0.103$).

It can be noticed from Figure 4.21 that there is no relationship between the nitrate concentrations and DRASTIC vulnerability indices. Also, the highest nitrate concentration, which is less than the maximum concentration level (MCL) (MCL is 50 mg/L), is located in the high vulnerability group. The main reason for that is DRASTIC method does NOT consider the possible transport and fate of the nitrate into its calculation in the aquifer. In addition, the hydraulic conductivity is very high in the aquifer. The weights and rates assigned to the parameters could also be other causes.

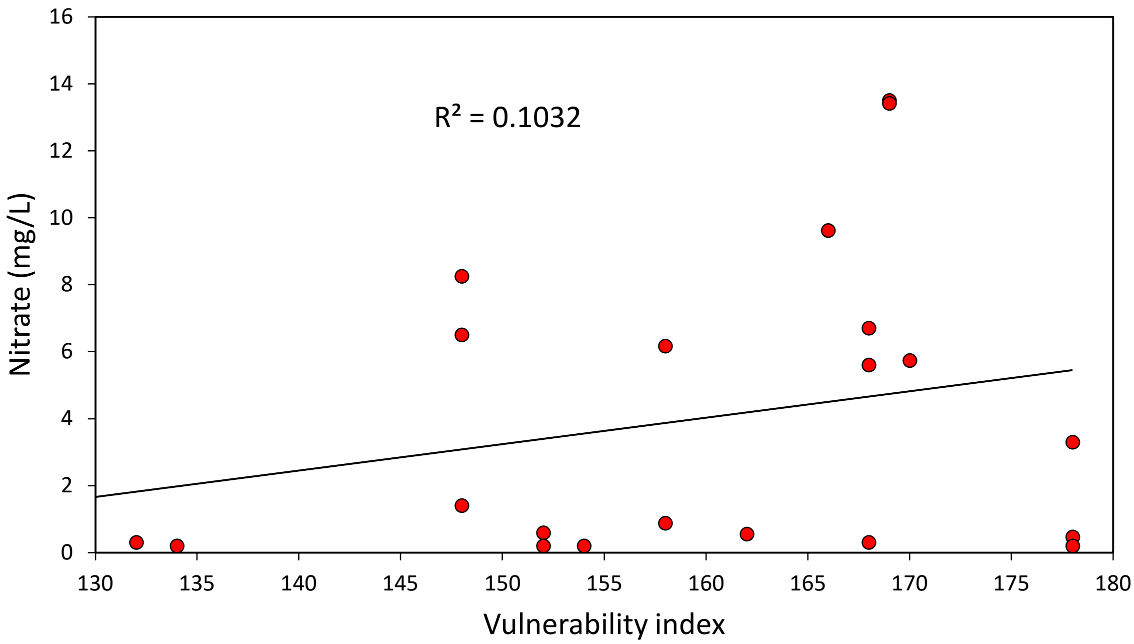

Figure 4.21. Linear regression between measured nitrate and resulting vulnerability indices. MCL of nitrate is 50 mg/L.

4.4.2. Total Dissolved Solids (TDS) and Vulnerability Index

As mentioned earlier, the main purpose of TDS measurements is to validate and describe the last state of the aquifer. TDS measurements are done by BUSKI and DSI at 22 observation wells (Table 4.8), and the values ranged between 48 and 782 mg/L. Figure 4.22 below shows the TDS measurements and vulnerability indices. These values, using SLR analysis, show a correlation (R^2 = 0.074).

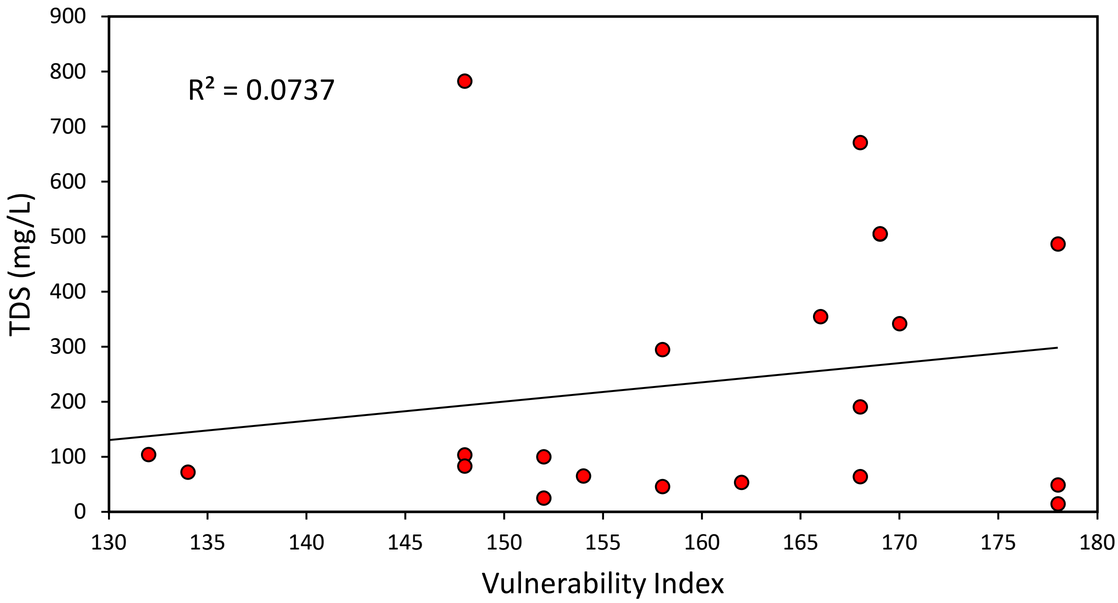

Figure 4.22. Linear regression between measured TDS and vulnerability index evaluated by DRASTIC method. See **Table 3.10** for TDS classification and permissible values.

The correspondence between total dissolved solids content and vulnerability index values can be concluded from the above figure. The moderate vulnerable areas show a higher TDS content in the aquifer. There is no conclusive relationship between TDS and vulnerability indices. For example, at the B11 observation well, the vulnerability index was 148 and the TDS was 782.08 mg/L. While at the B1 observation well, the vulnerability index was 178, and TDS was 48.68 mg/L. One possible reason for that is DRASTIC method considers the vertical movements of the pollutants without considering the possible fate TDS in the groundwater system. Also, dissolved salts can be referred to as TDS, which is not calculated using DRASTIC method. Other reasons can be soil type media which is alluvium, and the weights assigned to the parameters.

4.4.3. Sulfate

It can be concluded from Figure 4.23 that there is a direct relationship between SO4 measures and vulnerability indices resulted from DRASTIC method. Using SLR analysis, the correlation (R^2) is 0.648. The high vulnerability values are covered by industrial and urban areas; industrial wastes can be the main source of high concentrations of sulfate.

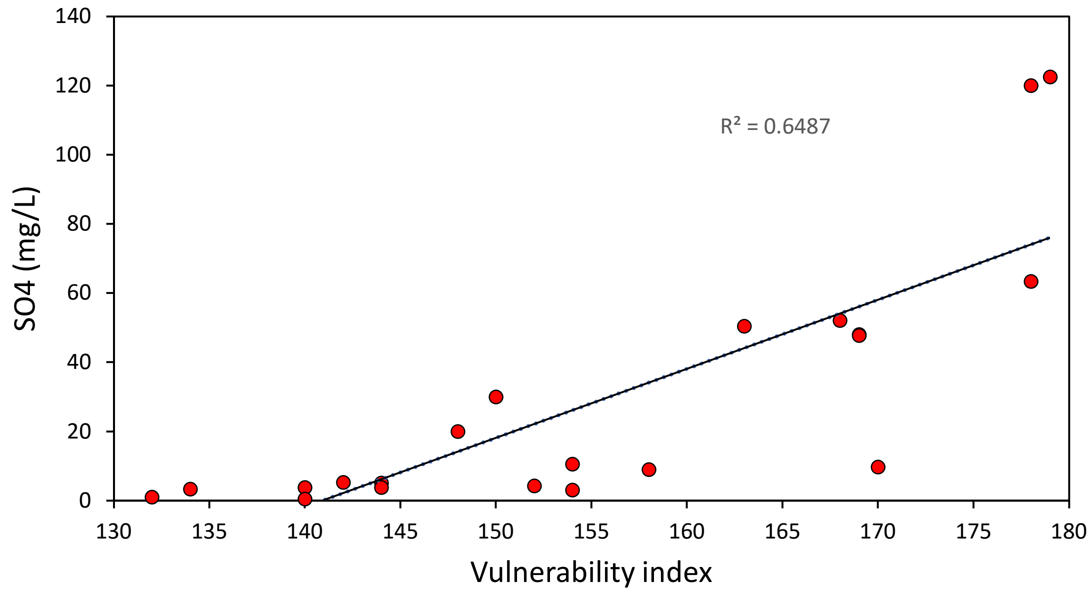

Figure 4.23. Linear regression between SO4 and vulnerability index resulting from DRASTIC method. MCL of the sulfate is 250 mg/L.

4.4.4. Coliform Bacteria Measurements

The coliform bacteria measurements were carried out in 5 wells in 2016 by Bursa Public Health Directorate (Bursa Halk Sağlığı Müdürlüğü). The measured coliform bacteria range between 11 to 100 CFU/100 mL, and the main source of these coliform bacteria is the intestinal tract of warm-blooded mammals, soil, and other animals. Figure 4.24 shows the relation between the resulting vulnerability indices and the measured coliform bacteria in the study area. In the first sample, the vulnerability index is 169, which is very vulnerable to contamination. Meanwhile, the coliform bacteria concentration is 100 CFU/100mL. This area is covered by residential buildings regarding the land use map, so the main source may be the septic tanks or sewerage system. However, in another well, the vulnerability index is 148, which is moderately vulnerable to contamination, and the coliform bacteria is relatively moderate (38 CFU/100mL). According to WHO (2011), the drinking water must be free of coliform bacteria. These values, using SLR analysis, show a correlation (R^2 = 0.8954).

In DRASTIC method, the ground surface is considered as the source of the contamination. And the contamination goes down from the surface to the aquifer through the unsaturated and saturated zone. Consequently, soil, vegetation, the intestinal tract of warm-blooded mammals, and other animals have formed an essential source of contamination. Figure 4.24 below shows that there is a relation between coliform bacteria values and resulting vulnerability values.

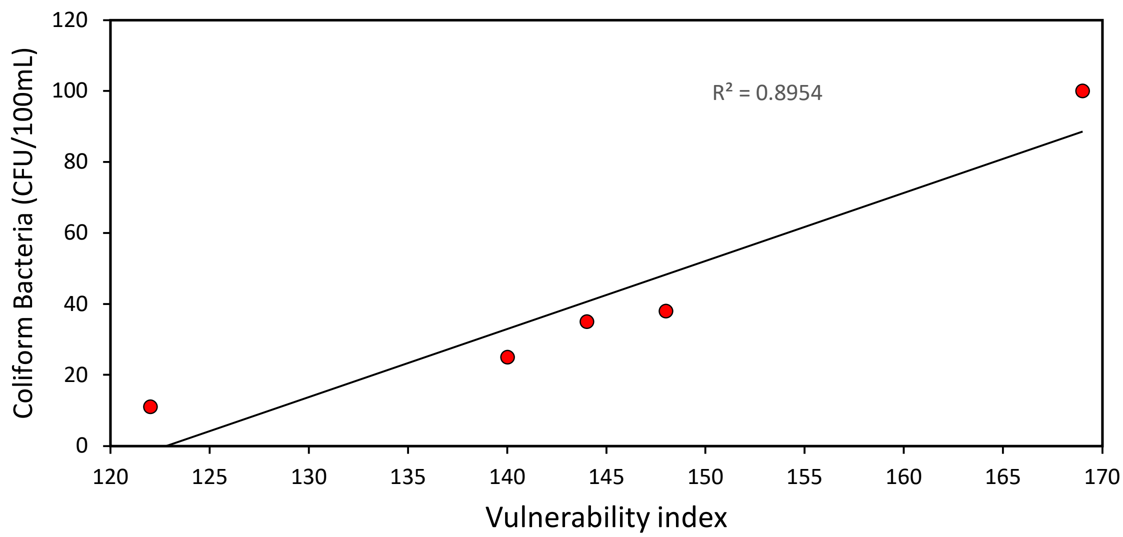

Figure 4.24. Linear regression between measured coliform bacteria and vulnerability index calculated by DRASTIC method. MCL is zero.

4.4.5. Groundwater Contamination Analysis

The main objective of groundwater contamination analysis is to evaluate the relationship between the resulting groundwater vulnerability map and some water quality parameters concentration in groundwater. The concentration of these parameters, Arsenic (As), Iron(Fe), and Aluminum (Al), are shown in Figure 4.25, 4.26, and 4.27, respectively. It is found that three well samples have high arsenic (As) concentrations which are beyond the (MCL) (MCL of Arsenic is 0.01 mg/L). These wells map was spatially joined to the resulting vulnerability map to check how many wells with high arsenic concentrations are located in highly vulnerable zones. All sampled wells with very high arsenic concentrations were found in highly vulnerable zones. Also, in the B1 well, the Al concentration is more than MCL, which is 200 μg/L. However, the Al concentration in the remaining well is less than MCL. On the other hand, the Fe values are less than permissible limits (Fe maximum limit is 0.2 mg/L) according to WHO (2011).

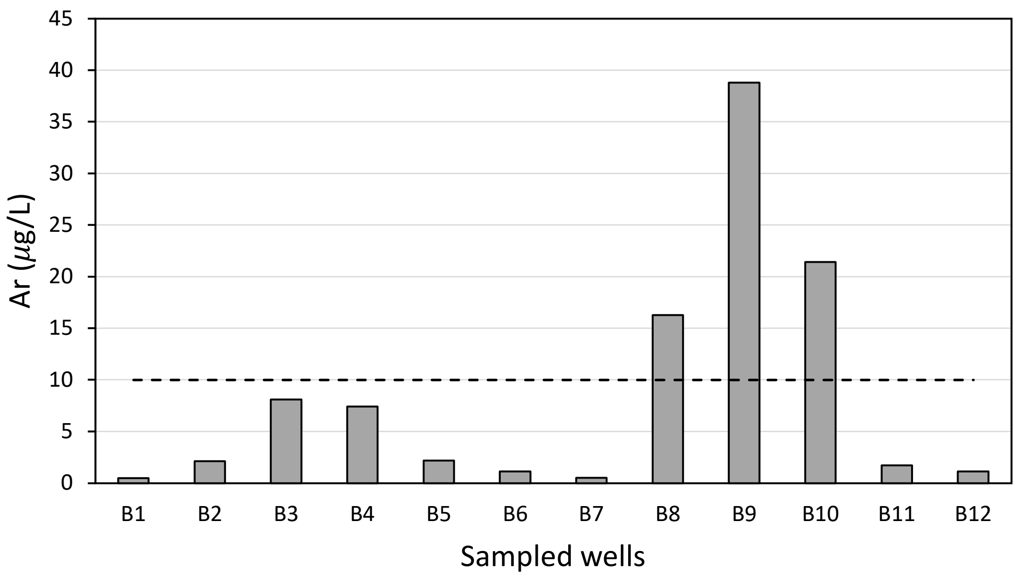

Figure 4.25. Arsenic concentration in different wells. The dotted line indicates the MCL.

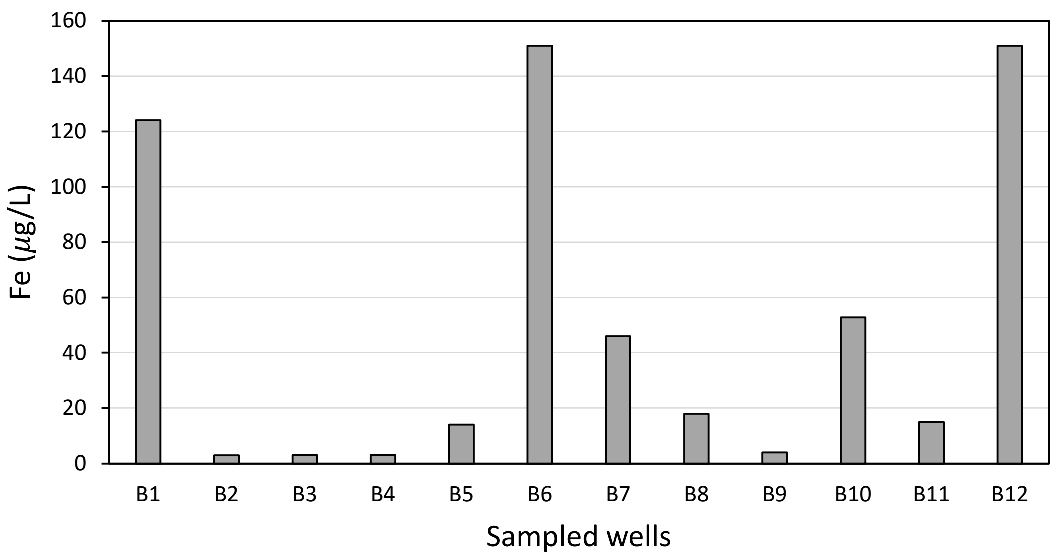

Figure 4.26. Iron concentrations in different wells. MCL is 0.2 mg/L.

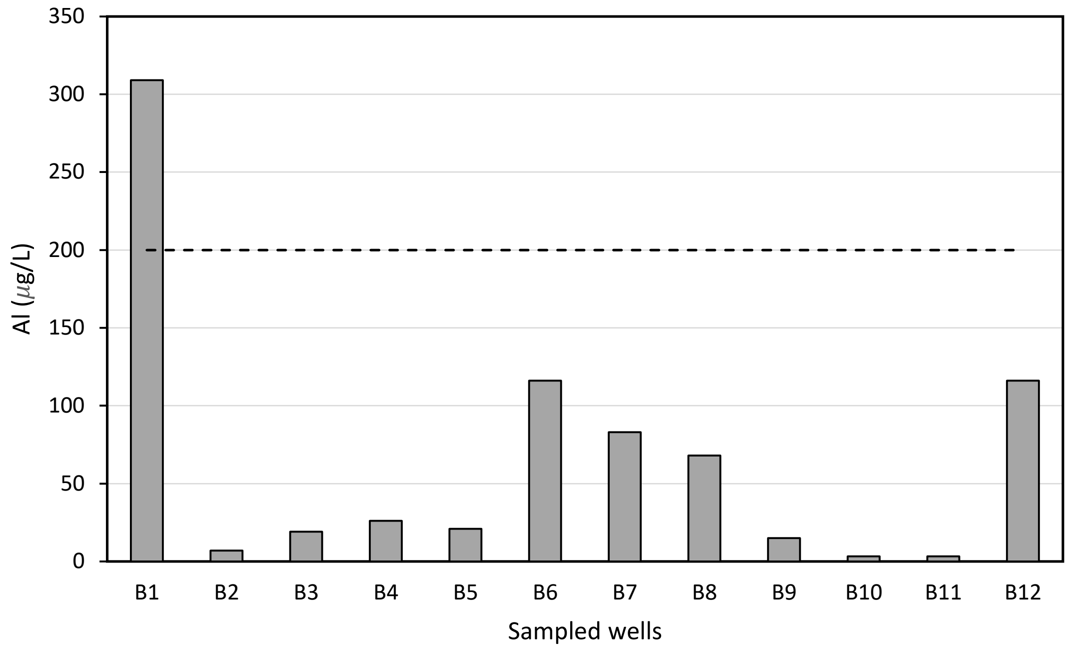

Figure 4.27. Aluminum concentrations in different wells. The dotted line indicates the MCL.

5. CONCLUSION

5.1. Conclusions

In this research, an assessment of groundwater vulnerability to contamination has been implemented using the GIS-based DRASTIC method. Based on the groundwater vulnerability analysis and the DRASTIC index values, about 25.5 % of the Musfatakemalpasa and Karacabey plain is under very high vulnerability, 39.49 % is under high vulnerability, 18.82 % has a moderate vulnerability, 15.31 % has a low vulnerability, and 1 % has very low vulnerability to contamination. Figure 4.15 and Table 4.3 show that the vast majority of the Musfatakemalpasa and Karacabey plain (65%) is under a high degree of groundwater vulnerability.

Depending on the research, the highest risk of contamination in the study area is created from the net recharge and the hydraulic conductivity of the aquifer. The GIS tool is an efficient, valuable, and helpful tool for preparing data, assessing and analyzing the groundwater vulnerability to pollution.

From the water quality parameters and validation of the results section, the conclusion can be as follows:

- The last state of the aquifer quality is good. In general, it is free of contamination. Nitrate, TDS, sulfate, and other water quality parameters concentrations are less than MCL.
- There is a direct relationship between the sulfate concentrations and DRASTIC vulnerability indices. Thus, sulfate concentration can validate and investigate the accuracy of the DRASTIC vulnerability map to monitor and protect the aquifer (R^2 is 0.648).
- Regarding the coliform bacteria measures done by BUSKI in 2016, the aquifer contains coliform bacteria (R^2 is 0.895), which is an indication that the aquifer may be contaminated by pathogenies. The drinking water must be free of coliform bacteria.

- There is no definite relationship between DRASTIC vulnerability indices and nitrate and TDS concentrations in the study area. The reason may be that the DRASTIC method does not consider the possible fate of the TDS and nitrate concentrations throughout the pathway until reaching the aquifer. Regarding the relationship between the nitrate concentration and DRASTIC vulnerability indices, Almasri 2007 concluded the same result.

5.2. Recommendations

The following recommendations can be extracted from this research, and should be shared with Bursa municipality, Bursa Su ve Kanalizasyon Idaresi – Bursa Water and Sewerage Administration (BUSKI), Devlet Su İşleri – State Hydraulic Works (DSI), and the environmental policy-makers.

- Because the current research includes the assessment of intrinsic groundwater vulnerability to contamination, specific vulnerability assessments are recommended to determine areas with high vulnerability to specific contamination. For example, specific vulnerability assessments to nitrate and sulfate are recommended since the study area has high agricultural activities.
- Bursa Municipality and other stakeholders that deal with city planning are recommended to consider groundwater vulnerability maps for groundwater protection. For example, locations of the establishment of facilities and activities which are hazardous to groundwater should be determined meticulously, such as wastewater treatment plants, sewer mains, and disposal sites.
- The research suggests that the GIS-based DRASTIC method can be utilized to prioritize the protection of highly vulnerable zones from additional pollution. Based on the resulting groundwater vulnerability maps and to specify areas where monitoring and protection are required, detailed and periodic monitoring should be carried out.

- Coliform bacteria are considered as an indication for some pathogenies. Continuous monitoring for the coliform bacteria in the aquifer must be carried out. Also, a disinfection process should be taken to kill disease-causing microorganisms.

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