

Yeşilköy Aquifer Vulnerability Assessment with DRASTIC Method

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ABSTRACT

Among various vulnerability indicating methods, DRASTIC method is one of the best known and accepted assessment model to map the aquifer pollution risk. DRASTIC method was introduced by United States Environmental Protection Agency (USEPA) and utilizes seven hydro-geologic parameters; depth to water table, net recharge, aquifer media, soil media, topography, impact of the vadose zone medium and the hydraulic conductivity of the aquifer to map the aquifer pollution risk. This can be achieved by developing digital maps of above mentioned seven parameters and overlaying them with Geographic Information System (GIS) based software like ArcGIS. Therefore, DRASTIC method is used to determine and evaluate the vulnerability of the Yeşilköy (Agios Andronikos) Aquifer for contamination.

In order to do so, several field visits were performed to collect water samples from 25 pre-selected wells and 12 soil samples from different ground surface locations, and also to measure the ground water levels within the pre-selected wells. The collected information helped to develop soil maps, groundwater level maps and groundwater water quality maps. Other necessary information for the implementation of DRASTIC method was obtained from pertinent literature or Geology and Mines Department. In addition to DRASTIC method, Weighted Arithmetic Water Quality Index method (WQI) and Analytic Hierarchy Process (AHP) were used to compare and validate the finding of DRASTIC method. The results of WQI employing Weighted Arithmetic procedure demonstrated that the Yeşilköy Aquifer has "Poor Water Quality". AHP helped to create effective weights for seven hydro-geologic parameters used in DRASTIC method instead of those proposed by DRASTIC method and help to

perform pairwise comparison of the results. Consequently, consistency index calculated as 0.07 (less than 0.1) showing that, used weight factors were consistent.

Nitrate concentration of the aquifer was then used to check the correctness of the recommended method. It has been observed that, the groundwater vulnerability map obtained by the DRASTIC method applied in the Yeşilköy Aquifer, on which intensive agriculture is carried out, is not compatible with the nitrate concentration map. In addition, when the weight and rate values of the original DRASTIC method were adjusted with AHP, a significant increase could be revealed in the correlation obtained and in the WQI and Nitrate values.

Keywords: Groundwater Vulnerability Assessment, Analytic Hierarchy Process, Geographic Information System, Water Quality Index, DRASTIC, Cyprus. Yeşilköy.

ÖZ

Zaafiyet belirlenmesinde kullanılan birçok yöntem arasında DRASTIC metot en iyi bilinen ve kabul gören yeraltı suyu kirlilik riski haritalandırma yöntemidir. DRASTIC yöntemi, Amerika Birleşik Devletleri Çevre Koruma Ajansı (USEPA) tarafından önerilmiştir. Akifer kirlilik riskini haritalandırmak için yedi hidro-jeolojik parametreden faydalanılır; su tablasının derinliği, net reşarj, akifer ortamı, toprak ortamı, topografya, vadoz bölge ortamının tesiri, akiferin hidrolik iletkenliği. Yukarıda belirtilen yedi parametrenin dijital haritalarının geliştirilmesi ve bunların ArcGIS gibi Coğrafi Bilgi Sistemi (GIS) tabanlı bir yazılımla üst üste bindirilmesiyle bu elde edilmiştir. Bu nedenle, Yeşilköy (Agios Andronikos) Akiferinin kirlenmeye karşı zaafiyetini belirlemek ve değerlendirmek için DRASTIC yöntemi kullanılmıştır.

Bunun için, önceden seçilmiş 25 kuyudan su numuneleri ve farklı bölgelerdeki zemin yüzeyinden 12 toprak numunesi alınmış ve önceden seçilmiş kuyulardaki yeraltı suyu seviyelerini ölçmek için de birkaç saha çalışması gerçekleştirilmiştir. Toplanan bilgiler, toprak haritalarının, yeraltı suyu seviyesi haritalarının ve yeraltı suyu kalitesi haritalarının geliştirilmesine yardımcı olmuştur. DRASTIC yönteminin uygulanması için gerekli olan diğer bilgiler ilgili literatürden veya Jeoloji ve Maden Dairesi'nden alınmıştır. DRASTIC yöntemine ek olarak, DRASTIC yönteminin sonuçlarını karşılaştırmak ve doğrulamak için Ağırlıklı Aritmetik Su Kalitesi İndeksi yöntemi (SKİ) ve Analitik hiyerarşi prosesi (AHP) kullanılmıştır. Ağırlıklı Aritmetik yöntemi kullanılarak SKİ sonuçları, Yeşilköy Akiferinin "Kötü Su Kalitesi" sınıflandırmasına sahip olduğunu belirlenmiştir. AHP, DRASTIC yönteminde kullanılan yedi hidrojeolojik parametre için DRASTIC yöntemi tarafından önerilenler yerine,

alternatif etkin ağırlıkların oluşturulmasına ve sonuçların ikili olarak karşılaştırılmasına yardımcı olmuştur. Sonuç olarak, kullanılan ağırlık faktörlerinin tutarlı olduğunu gösteren tutarlılık indeksi 0,07 (0,1'den küçük) olarak hesaplanmıştır.

Akiferin nitrat konsantrasyonu daha sonra önerilen yöntemin doğruluğunu kontrol etmek için kullanılmıştır. Üzerinde yoğun tarım yapılan Yeşilköy Akiferinde uygulanan DRASTIC yöntemi ile elde edilen zaafiyet haritasının nitrat konsantrasyon haritası ile uyumlu olmadığı görülmüştür. Ayrıca orijinal DRASTIC yönteminin ağırlık ve oran değerleri AHP ile düzenlendiğinde Su Kalitesi İndeksi ve Nitrat değerlerinden elde edilen korelasyonda önemli bir artış ortaya konabilmiştir.

Anahtar Kelimeler: Yeraltısuyu Zaafiyet Değerlendirmesi, Analitik Hiyerarşi Süreci, Coğrafi Bilgi Sistemi, Su Kalite İndeksi, DRASTIC, Kıbrıs, Yeşilköy.

DEDICATION

This work is dedicated to my wonderful family, which includes my father and mother, my wife, and all of my children (Ada, Sinan Deniz), who have always been understanding and encouraging me.

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LIST OF SYMBOLS

A	Aquifer Medium
A	Exponent defined by the IDW user.
a_i	Relative Importance of a_i and a_j
C	Conductivity of Aquifer (m/day)
C_I	Consistency Index
C_R	Consistency Ratio
D	Depth of Water (m)
D_a	Aquifer Average Thickness at Measured Point (m)
D	Distance Between Two Points (m)
G	Acceleration Due to Gravity (cm/s^2)
γ_s	Specific Gravity of Solid (g/cm^3)
γ_w	Specific Gravity of Fluid (g/cm^3)
I	Impact of Vadose Zone
K	Proportional Constant
$\lambda_{\max}$	Largest Eigenvalue of Matrix
μ	Viscosity of Water (g.s/cm^2)
N_r	Rate of Parameter, N
N_w	Weight of Parameter, N
q_n	The Quality Rating for n^{th} Water Quality Parameter
r	Rate of Parameter
R	Net Recharge
R_I	Average Random Consistency Index
R^2	The Coefficient of Determination

S	Soil Medium
S_n	Standard Value of n^{th} Parameter
T	Topography (%)
T_r	Transmissivity of Aquifer (m^2/day)
Y	Particle Settling Velocity (m/sec)
W	Weight of Parameter
w_i	Relative Importance Weight of Check Point
w_n	Unit Weight for n^{th} Parameter
z_i	Check Value of i^{th} Sample Value

LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
DEM	Digital Elevation Map
DI	DRASTIC Index
DIV	DRASTIC Index Value
DO	Dissolved Oxygen
DRASTIC	Depth, Recharge, Aquifer media, Soil Media, Topography, Impact of Vadose Zone, Hydraulic Conductivity
E. Coli	Escherichia Coli Bacteria
EMU	East Mediterranean University
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organization
GIS	Geographic Information System
IDW	Inverse Distance Weighted
MTA	Maden Tetkik ve Arama Enstitüsü, Mineral Research and Exploration Institute
pH	Potential of Hydrogen
TRNC	Turkish Republic of North Cyprus
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WGS	World Geodetic System
WHO	World Health Organization

WQI Water Quality Index

Chapter 1

INTRODUCTION

1.1 Background and Definition of the Problem

The presence of water is a necessity for life's development and continuation. Usable water resources are scarce and being more and more depleted due to anthropogenic activity in many nations with dry and semi-arid climates. The water scarcity problem creates the necessity of proper water resources management and protection.

Considering that only 2.5% of the world's water resources are available as freshwater resources, it is clear how important it is to protect the quality of water resources. Groundwater has long been seen as a crucial and vulnerable source of fresh water that can be used for human consumption. The importance of groundwater in sustaining life and guiding societal development is obvious. Especially the protection of groundwater resources is very important considering how costly and difficult it is to remove unwanted substances from this source. Accordingly, the protection of groundwater resources is an easy and economical way to manage it. Therefore, the prevention of pollution of groundwater resources should be addressed more. This can be achieved by continuous monitoring of groundwater quality and quantity.

Spatial and temporal monitored water quality parameters can be meaningful when they are represented in a quantitative manner. In this sense, the WQI can express the overall water quality in a more understandable and universal way that the public can even

realize. This means that WQI summarizes the water quality data and resolves it into a single value by synthesizing multiple test results of the monitoring process. Various water quality indicators, such as pH, Sodium, Calcium, Magnesium, Hardness, etc., can be listed as the contributor for expressing the Water Quality Index (WQI).

Nitrates are organic molecules that are naturally found in soil and water when oxygen and nitrogen react, and they also can be used in water quality index calculations. Plants use nitrates to synthesize amino acids. Fertilizers with nitrate contents are used in agricultural activities to increase the number of nitrates in the soil and boost crop growth. However, excess use of fertilizers in agriculture results in an overabundance of nitrates in the soil.

Numerous issues might arise from high nitrate concentrations. Nitrates in drinking water are harmful to people's health. Despite the fact that nitrates are a natural occurrence and are safe at low concentrations (and can provide protection against infections), studies reveal that extremely high amounts of nitrates can raise the risk of some malignancies, birth abnormalities, and thyroid disorders.

The selected study area (Yeşilköy Aquifer) has been used since the late 1960s as a water source of settlements at Karpaz Peninsula, both for domestic and agricultural purposes. The aquifer is the third principal aquifer at Turkish Republic of North Cyprus (TRNC) that is used for household water supply purposes. It occupies a 5.46 km² surface area. On the other hand, the recharge area of the aquifer is mainly used for agricultural purposes especially for *Colocasia esculenta* and *Solanum tuberosum* (potatoes). The long-term over-pumping from the aquifer experienced a decrease in groundwater levels and water quality degradation. Meanwhile, agricultural activities

ongoing within the area fear that, the use of fertilizer containing nitrogen in irrigated regions is contributing extensively to nitrate pollution in the habitat of the Yeşilköy Aquifer. Nitrate leaching is affected by the amount and distribution of rain and irrigation below the root zone, through the unsaturated zone, and ultimately in the saturated zone. As a result, nitrate overabundance in groundwater has increased over time. Organic molecules in the soil, animal wastes, and plant residues can also cause to nitrate leaching, however their relative contributions are minimal in comparison to fertilizers.

In this research, a short-term monitoring study for the Yeşilköy aquifer is performed and the vulnerability of the aquifer is delineated by the help of the DRASTIC model. In addition, the deterioration problem of the aquifer by means of the nitrate leaching into the aquifer is assessed together with the water quality index calculations for the whole aquifer.

1.2 The Proposed Methodology

The Environmental Protection Agency (EPA) of United States of America funded a National Groundwater Association initiative in the 1980s to evaluate the country's aquifer's fragility. By 1985, the project studies were completed and the methodology they used was published. This novel methodology for assessing the vulnerability of groundwater and delineating risk of pollution using hydro-geologic conditions is named as DRASTIC (Aller et al., 1987) method. Since then, DRASTIC method become one of the most preferable and used model for the assessment of groundwater vulnerability.

It is an overlay and index model that was developed to provide vulnerability ratings for various sites by combining several hydro-geological layers. In general, it is a model developed based on the influence of various hydro-geological parameters overlaying the pertinent groundwater resources. A coefficient and a weight were assigned to each critical parameter based on their significance effect on quality and quantity of the resources.

The word DRASTIC represents for the parameters used in the original model that considers weighted values of groundwater depth from the top of the soil to the water table, recharge of water in the watershed (net), aquifer medium properties, soil medium properties, topography, impact of the vadose zone, and hydraulic conductivity. The maps of above-mentioned parameters are generated and overlay on top of each other for generating resultant map, that is numerically depicting the vulnerability of a groundwater to contamination.

The DRASTIC index (DI) is calculated by multiplying the weight of each parameters with its assigned rating (Aller et al., 1987). DI is defined as:

$$DI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad (1)$$

In equation (1), two important subscripts representing the ratings and weights are “*r*” and “*w*”, respectively. The capital letters D, R, A, S, T, I and C are conditioning factors corresponding to DRASTIC model. The DI is the sum of the product of the weight coefficients that the method has previously determined separately for each parameter, and the rate values assigned in accordance with the measurement results or existing data within the parameters. In Eq. (1), “*w*” can range between 1 and 5. A high *w* value indicates that the parameter is of great importance in terms of pollution potential. The

“ r ” value takes a value between 1 and 10. When the assigned value is closer to 10, it indicates high pollution potential of the parameter.

In order to develop and modify the DRASTIC method, approaches such as adding and removing some other parameters to the method content were carried out. One of the samples of such modification is the vulnerability analysis of an aquifer to contamination assessed by using the land use pattern of the region (Alam et al., 2012). Voutchkova et al. (2021) introduced a new approach "DRASTIC-N" for measuring aquifer nitrate vulnerability, which for the first time adds a geochemical parameter for redox condition to the seven basic hydrogeologic criteria. Kazakis and Voudouris (2015) have proposed a new method where a modification was made to the quantitative and qualitative parameters. The quantitative parameters were hydraulic resistance, the thickness of the aquifer and the nitrogen losses. The qualitative parameters were the type of the aquifer, the soil and the vadose zone impacts.

The modification of the weights and rates can be improved by using Analytic Hierarchy Process (AHP) method. Many studies have been carried out by using AHP method. Karan et al. (2017) found that, the AHP-Modified DRASTIC model was observed as the best amongst the studied techniques which was added land use and distance from lineaments parameters with a strong positive correlation value.

Several research studies modified the DRASTIC model to achieve better results based on the case studies under consideration, or to improve the results to real conditions (He et al., 2017, Voutchkova et al., 2020). Here, in this study, DRASTIC model is also modified and AHP is used to modify the model. On the other hand, modification of DRASTIC model with any other hydro-chemical parameter can change the philosophy

of the model. The aim of the model is to scale the vulnerability level of any aquifer under natural conditions. Therefore, merely AHP is used in modification, in order to change the weights of parameters and obtain a parallel behaviour with water quality index of the aquifer. The nitrate content at several different locations of the aquifer were also sampled and nitrate contamination map is developed. Thus, the outcomes of modified DRASTIC model is compared with the nitrate contamination map to validate the artificial interference of human beings on the reference conditions of the aquifer. Finally, using the created vulnerability map, a management decision can be generated for the precautions intended to be established in the area in question and the choice of the type and degree of measures to be taken for minimizing the contamination.

1.3 Study Framework

This study aims to assess the Yeşilköy groundwater vulnerability. Seven hydro-geological maps were generated using the parameters suggested by the DRASTIC method to bring to light the vulnerability of the Yeşilköy aquifer. Based on the weights proposed by Allens (1987), the vulnerability index map is derived for the aquifer. In addition, the weights of the DRASTIC method were revised using the AHP, and new coefficients were proposed, and a comparison was made between the classical DRASTIC method and the modified DRASTIC method. While investigating the presence of nitrate, which is the main indicator of groundwater pollution, other chemical pollutants like heavy metals are also analysed through the Water Quality Index methods. The study's route is essentially schematized in Figure 1.1.

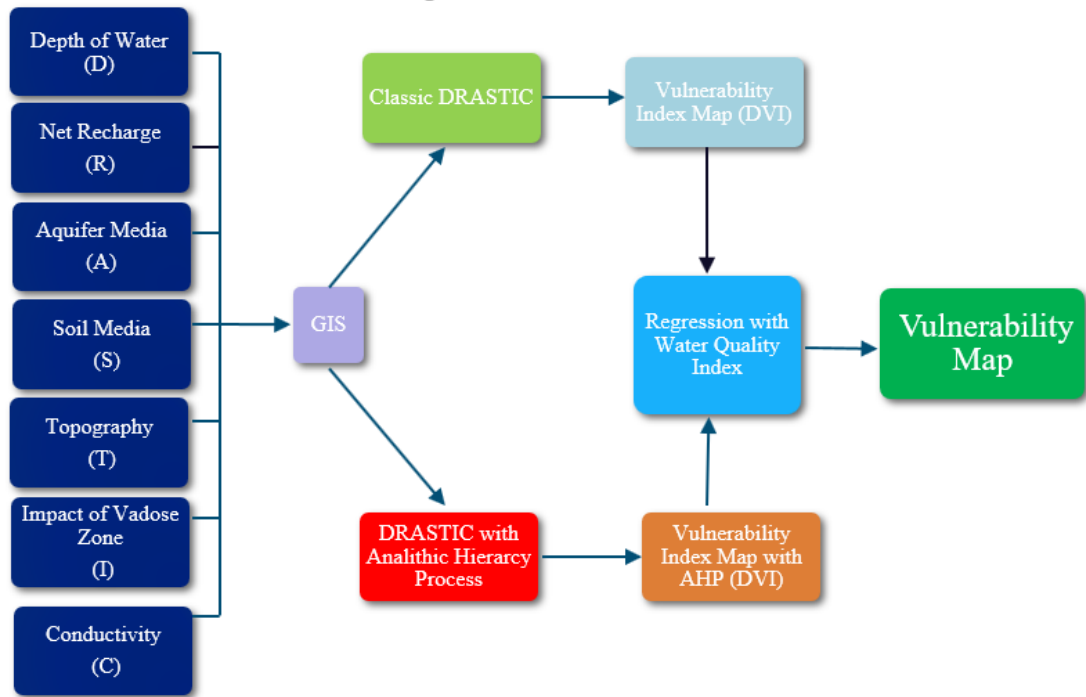


Figure 1.1: Methodology flowchart of the present study.

1.4 Aims and Objectives of Research

The primary goal of this study was to investigate the vulnerability of the groundwater resources of Yeşilköy Aquifer by implementing DRASTIC model and perform field analysis for assessing groundwater quality or deterioration due to agricultural activities. A representative groundwater quality is to be maintained by the help of “Water Quality Index” whereas, the nitrate concentration distribution within the aquifer boundary is expected to demonstrate the diffusion of contamination. It was also intended to change the weights and rates used in the original DRASTIC model within the study area. For this purpose, a new DRASTIC-AHP model is generated. Finally, the goal was to deploy the implementation of DRASTIC model in cooperation with a Geographical Information System (GIS) as an effective tool for groundwater vulnerability mapping and water resource management.

1.5 Research Questions

The motivation of this research is hidden in the questions that will be answered at the end of this research study. Can the management strategies of the Yeşilköy Aquifer be accepted as it is? Will this research help to indicate that, there is a need for improving the quality and quantity of groundwater resources? How much vulnerable the aquifer is, when compared with the water quality index and nitrate content? Should agricultural activities be re-scheduled or follow the traditional methods? What are the contamination levels of the aquifer due to nitrate-containing fertilizers?

Thus, the study and research into the the potential pollution of the Yeşilköy groundwater resources become a priority issue for scientists. In addition to that, even though some other pollution research works were performed for other aquifers of Cyprus, no such studies have been conducted for Yeşilköy aquifer in terms of nitrate pollution, and general contamination. That is why it especially evolves into particular importance.

1.6 Outline of the Study

This research is divided into five chapters. The first section is the introduction, in which the primary facts related to the introduction of the study's aims, information about the research's contribution to the literature, and target methodology are offered. In the next chapter, the Yeşilköy aquifer research region, which is the subject of this study, has been introduced. The DRASTIC methodology, which is to be utilized in determining groundwater vulnerability, and the other procedures to be utilized like Water Quality Index calculations and AHP analysis are introduced in Chapter 3. Chapter 4 consists of the obtained data required for the proposed method, the operational processes of the method, the results obtained, and mapping. In this

Chapter, the obtained data and maps were evaluated and interpreted, and the proposed method was discussed. Chapter 5 is followed by the conclusions of this study.

1.7 Limitation of the Study

The major limitations of the DRASTIC method (Barbulescu, 2020; Kouz et al., 2020; Ouedraogo, 2017; Oke, 2017) are:

- a) The magnitude of various parameters used in model are not matching with the real conditions. This reduces the reliability of the approach.
- b) The diffusion of pollutant within the aquifer are accepted to be vertically. On the other hand, diffusion of the pollutant depends on the shape and size of the lithologic formation of the aquifer and can also be lateral.
- c) The DRASTIC model lack reflecting the uncertainties of the gathered data and the effect of missing data. This gap reduced the reliability of the model.

1.8 Literature Review

1.8.1 Groundwater Vulnerability

In order to raise awareness of groundwater contamination, the idea of groundwater vulnerability was first created in France between 1960 and 1970 (Margat, 1968). The concept of groundwater vulnerability assessment began to spread in the field of hydrogeology in the 1980s (Haertle, 1983; Aller et al., 1987). According to Ibe et al. (2001), there are two types of aquifer vulnerability: (a) intrinsic vulnerability and (b) specific vulnerability. Gogu and Dassargues (2000) stated that, intrinsic vulnerability is the vulnerability of aquifer to contaminants caused by man-made activities while also considering the physical characteristics of the groundwater system, such as its inherent geological, hydrological, and hydro-geological characteristics. The definition of specific vulnerability, on the other hand, is the vulnerability of groundwater to a specific contaminant or group of contaminants, taking into account the contaminant's

properties, its transport characteristics, and its relationship to different aspects of intrinsic vulnerability (Doerfliger et al., 1999; Gogu and Dassargues, 2000). According to Gogu and Dassargues (2000), three general methodologies have been proposed to assess the susceptibility of groundwater to pollution. In the first method, only the media in the unsaturated zone, such as soil, are taken into account when evaluating vulnerability. The medium in the saturated zone, or aquifer, is not taken into consideration. The second approach considers the aquifer flow and the transport processes for the groundwater. The third method for determining the aquifer's vulnerability is somewhat holistic because it considers both soil cases.

1.8.2 Groundwater Vulnerability Modelling

In the vulnerability assessment approach, models are separated into three sections so as to estimate the groundwater risk, (a) the application of index-based techniques and geostatistical interpolation, (b) using numerical modelling, (c) the integration of numerical models with GIS. In the absence of sufficient quantitative data on the groundwater system, preliminary investigation become important. Preliminary investigation covers index-based models and geostatistical interpolation (Kumar et. Al, 2015). Geostatistical interpolation helps to depict the contour maps of groundwater levels and simulate the spatial distribution of pollution. Standard Krigging and inverse distance weighted methods are the most common interpolation approaches that can be reliable based on the quality and the quantity of the data. The intrinsic aquifer vulnerability has been qualitatively measured by means of GIS-based indices. The inherent hydro-geological properties of the aquifer that do not vary over time are taken into consideration to estimate the vulnerability of the aquifer. The most popular and frequently preferred GIS-based vulnerability indices are DRASTIC, GOD, AVI rating system and SINTACS. DRASTIC was initially proposed by Aller et al., (1987) in

which simultaneously, Duijzenbooden and Waegenbooden, (1987) proposed GOD for aquifer vulnerability analysis. Later in 1993 Van Stempvoort et al., generated AVI rating system for the same purposes. Lately, Gogu and Dassargues (2000) developed SINTACS.

An efficient way to manage and interpret water resources is to use geographic information system tools. To determine the rankings and weights for the parametric layers, decision making tools such as the Analytical Hierarchy Process can be used (Saranya, T., and Saravan, S., (2020)).

Chapter 2

STUDY AREA

In Eastern Mediterranean countries, such as, Cyprus, Palestine, and Israel, groundwater resources are the primary source of water supply (FAO 2003; Leduc et al. 2017). Water shortages are evident in Cyprus, and the problem is lately solved by an inter-basin water transfer project through the Mediterranean Sea from Turkey (Kayan et al., 2022). Because of droughts and poor management, the groundwater resources in the northern region of Cyprus are scarce. Nearly 3,300 km² constitute the whole area for Cyprus's northern region. Water that has mainly rainfall can be saved for the use in future since very little of it infiltrates and stored in aquifers. In order to assess the sustainability of the aquifers, it is consequently required to conduct research on groundwater resources. There are 12 main aquifers located throughout the northern section of Cyprus, regardless of the extent of the water-bearing formations (Türker et al. 2013). More than 95% of the yearly water requirement is satisfied by the projected 98.6 million m³ of abstraction from the aquifers, 63.1 million m³ of which are used for irrigation (Gökçekuş et al., 2018). The Kyrenia Range limestone aquifer is the only provider of potable groundwater out of these 12 aquifers (Jamal and Türker, 2015). The Güzelyurt/Morphou Aquifer is currently one of the most important aquifer in the northern part of Cyprus as it used to supply domestic and irrigation water to the two third of the country. It is located on the west coast near Morphou Bay and has an area of approximately 265 km². The aquifer is mainly recharged by direct infiltration of precipitations. Due to over-abstraction, the salinity of the groundwater increased and

the salt water intrusion destroy the quality of the aquifer (Ergil, 2000; Demir et al., 2022). As such, the thickness of the aquifer varies between 45 and 100 meters and is generally located on the impermeable clay layer, 100-120 meters below the sea level aquifer is now seriously endangered by the over-abstraction, saltwater intrusion, mismanagement, and extreme events of climate change such as drought (Payab et al., 2020).

The Yeşilköy aquifer follows the Güzelyurt aquifer and the Beşparmaklar mountain aquifer in significance. The third important aquifer, Yeşilköy (Agios Andronikos) is located in the district of İskele on the Karpaz Peninsula, about 100 km northwest of the Nicosia. The aquifer occupies a surface area of approximately 5.46 km² and its catchment area is approximately 6.39 km². The higher plain to the southeast and the lower plain to the southwest are the two separate geographic regions that constitute Yeşilköy. The high plain side has an altitude between 100 and 150 meters. The gradient is 3.5 % towards the southwest (Türker et al., 2013). Over this aquifer the nearby meteorologic stations are Y. Erenköy, Ziyamet and Yeşilköy.

The yearly rainfall amount is quite variable from year to year and averages 376.7 mm/year based on the average rainfall of these three stations for the years 2013-2021. Table 2.1 details the yearly rainfall of these stations.

Table 2.1: Y. Erenköy, Ziyamet, and Yeşilköy stations yearly rainfall amounts (TRNC Meteorology Department).

Year	Y. Erenköy yearly rainfall (mm)	Ziyamet yearly rainfall (mm)	Yeşilköy yearly rainfall (mm)
2013	221.2	264.7	243.0
2014	315.4	315.4	315.4
2015	407.5	366.2	386.9
2016	393.4	461.2	427.3
2017	178.4	189.2	183.8
2018	550.2	512.7	531.5
2019	545.8	573.2	559.5
2020	415.2	482.6	448.9
2021	362.0	226.5	294.3
Average:	376.6	376.9	376.7

The Göz and the Değirmen are the two main streams at the region. Both creeks are ephemeral and only occasionally flow as a result of rainfall and the discharge of tiny springs. These ephemeral streams are thought to primarily flow to the sea without replenishing the aquifer. In fact, when aquifer water levels had been high, the Göz Stream had fed by a spring that discharges from the aquifer into a wetland region. By the end of 2022, there are approximately 200 wells in the region. Some of these wells lost their function over the time and currently are abandoned. Due to the consistent drop in water level, roughly 50 wells have been deepened in the last decade. In some of the deeper wells, the turba layer was observed by the drillers. Turba is a word meaning high carbon containing soil which is a precursor of coal anthracite and even rare gems. Six wells are under the management and administration of the TRNC Water Works Department. Only one governmental well is actively being used for potable water source. It was determined that one of the wells belonging to this state was completely closed. Almost all of the remained wells were used for agricultural activities. The region was completely dependent on the aquifer, being the main source

of water. With the realization of the water supply project from Turkey, the need for drinking and domestic water was met to a large extent from this project. On the other hand, for agricultural purposes intensive agricultural activities continued, causing depletion of water levels of Yeşilköy aquifer. Yeşilköy has agricultural area of 10.56 km² in which potatoes (*Solanum Tuberosum*) is one of the most common crop that are mainly planted in January and harvested in May.

Cyprus is divided into four different geological zones: the Pentadaktylos (Beşparmaklar) Zone, the Troodos Zone, or Troodos Ophiolite, the Mamonia Zone or Complex, and the Autochthonous Sedimentary Rock Zone. In the area within the borders of the north Cyprus, only the upper part of the Troodos Ophiolite section, Troodos environs sedimentary sequence, Beşparmaklar region and Plio Quaternary has sequence. One of these successions is the impermeable Değirmenlik group succession, which forms the basis of the Yeşilköy region. Apalos, Athalassa, Kakkaristra and Nicosia Formations have overlayed by Pliocene-Pleistocene sedimentary rocks. It covers rock units deposited in the Oligocene-Messinian time interval. Değirmenlik Group channel fill sandstones, conglomerates and olistostromal levels. It consists of flysch type rock units, shelf mudstones and gypsum. Yeşilköy aquifer is over the impermeable flysch units located on the Karpaz peninsula which is a Pleistocene and Quaternary aged calcarenite aquifer (MTA, 2000) as defined in Figure 2.1.

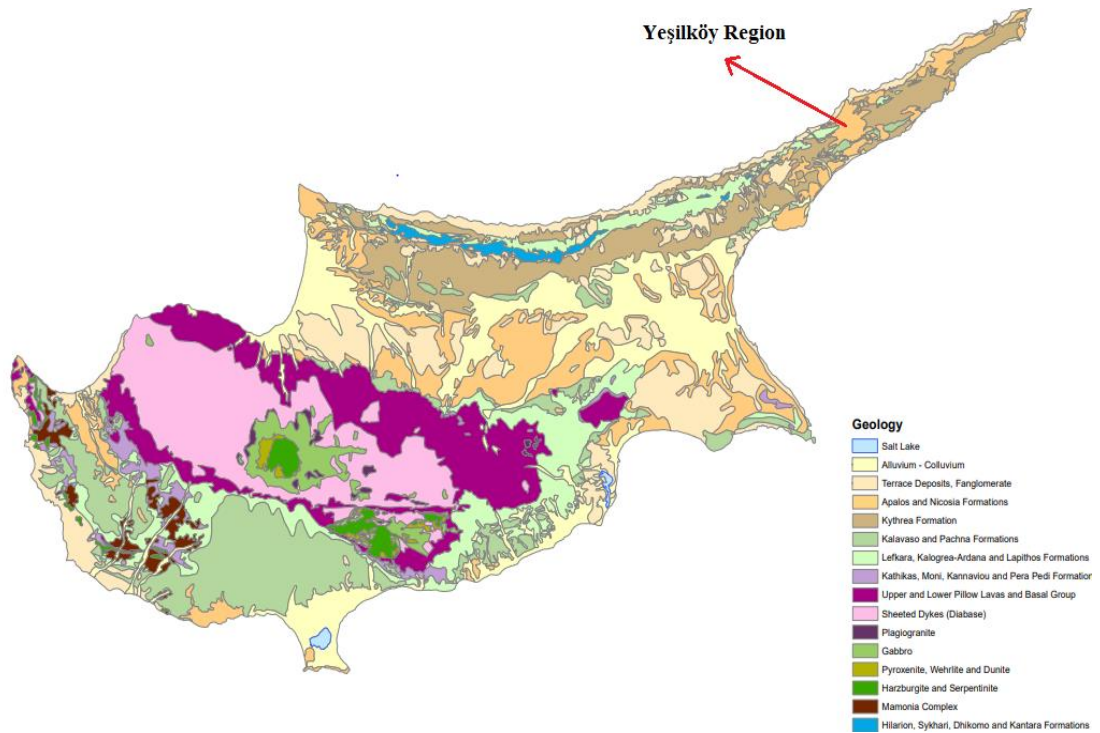


Figure 2.1: Cyprus Geological Map (<http://www.moa.gov.cy>) The layers that give the aquifer characteristics to the Yeşilköy aquifer are found in the parts up to the flysch; sandstone, calcarenite and secondary limestone.

Chapter 3

MATERIAL AND METHODS

Risk mapping is a helpful tool for environmental planning and decision making that combines indexing approaches with GIS-based spatial analysis, which is widely used to determine aquifer vulnerability. The key advantage of GIS-based vulnerability mapping is that, it combines numerous data types and changes in parameters used to identify groundwater sensitivity (Wang et al., 2007). In this study, Arc-Map 10.8 (ArcGIS software) was used to map each parameter and integrate all maps based on weights and rates.

Because of their low reliance on field data, the overlay and index methods are the most often used technique in vulnerability mapping. These methods employ a system of subjective ratings and weights that take into account various physical and hydro-geological elements in order to control the passage of pollutants through the unsaturated zone until they reach the water table and propagate (Aller et al., 1987).

3.1 Data Resources

Many types of data are needed to operate the DRASTIC method. With field studies, the depth of the water levels from the surface of the active wells were measured. In order to assign this measurement as the static water level, the period in which agricultural irrigation has not yet been made has been selected. Due to reasons such as the lack of physical access to many wells or the fact that, the wells have collapsed, in total 33 static water level of the well could be measured. In addition, as a field study,

samples were taken from 26 wells during irrigation for physico-chemical analyses. In order to produce the slope map, the 11-meter resolution Digital Elevation Model (DEM) map of the region was processed in the GIS environment. The DEM data was obtained from TRNC Water Works Department. The DEM was standardised to Universal Transverse Mercator Zone 36 N Datum WGS 1984 projection using ArcGIS 10.8. While calculating the recharge rate and hydraulic conductivity values, the results of previous studies were used. By obtaining borehole data from the geology and mining department, value assignment processes were made about the aquifer medium. Due to the insufficient maps related with soil data, soil samples were taken on site, sieve analysis and hydrometer analyses were made in the East Mediterranean University, Civil Engineering Department Soil Laboratory, and this data is used to generate soil map of the region. Table 3.1 summarizes how the data related with the research study is gathered.

Table 3.1: Summary of the data sources and the obtaining methods of this study.

<i>Symbol</i>	<i>Parameters</i>	<i>Requirement</i>	<i>Data sources</i>	<i>Data obtaining method and processes</i>
<i>D</i>	Depth of Water	Need to be measured distance between water table and ground level	Boreholes	Obtained by on-site measurement
<i>R</i>	Net Recharge	Rainfall, Infiltration, Transpiration, Evapotranspiration data	Compiled from previous study	Compiled from previous study
<i>A</i>	Aquifer Medium	Aquifer Lithology	Geology and Mines Department	Compiled from previous work
<i>S</i>	Soil Medium	Soil Map	Geology and Mines Department	Obtained by on -site measurement and laboratory study
<i>T</i>	Topography	DEM	USGS	Via ArcGIS
<i>I</i>	Vadose Zone	Lithology	Geology and Mines Department	Via ArcGIS
<i>C</i>	Hydraulic Conductivity	Measured from wells	Observation wells	Compiled from previous study (Türker et al., 2013)
<i>N</i>	Nitrate Concentration	Sampling Data	Observation wells	Obtained by on-site measurement and laboratory study

3.2 DRASTIC Method

The objective of this method is to divide the aquifer into various sections, where each section indicating different vulnerability levels of the aquifer. DRASTIC method consists of combination of 7 parameters with different weights and rates, aiming to analyse the vulnerability potential. The hydro-geological factors that make up the abbreviation of DRASTIC can be listed as follows;

- 1) D; Depth of water
- 2) R; Net Recharge
- 3) A; Aquifer Media
- 4) S; Soil Media

- 5) T; Topography
- 6) I; Imposition of vadose zone
- 7) C; Conductivity

The DRASTIC method is based on the following four main assumptions:

- a) The contaminants first appear at the ground's surface.
- b) Precipitation drives the pollutant into the aquifer.
- c) With water, the contaminant is transportable.
- d) The minimum area that can be evaluated by using DRASTIC method is 0.405 km² (Aller et al., 1987).

3.2.1 Weights

Each DRASTIC factor has been assigned a relative weight between 1 and 5. Each DRASTIC factor has been evaluated with respect to the other to determine the relative importance of each factor. The most important factors have weights of 5; the fewest key factors have weights of 1. These weights are fixed and cannot be modified (Aller et al., 1987). The explanation of each parameter and the weights assigned for each of them is given in Table 3.2.

Table 3.2: Weights and explanations of the DRASTIC parameters.

<i>Symbol</i>	<i>Parameters</i>	<i>Explanation</i>	<i>Weights</i>
<i>D</i>	Depth of Water	Distance between water table and ground.	5
<i>R</i>	Net Recharge	The quantity of water that seeps through the ground surface and into the water table is known as net recharge.	4
<i>A</i>	Aquifer Media	Aquifer Lithology, description of the physical environment in which the aquifer is located.	3
<i>S</i>	Soil Media	The uppermost zone of the vadose zone with the greatest level of biological activity is referred to as the "soil media." Earth's upper weathering zone.	2
<i>T</i>	Topography	The statement "topography" refers to the slope and slope variation of the earth's surface.	1
<i>I</i>	Vadose Zone	The material's attenuation properties beneath the typical soil horizon and above the water table are dependent on the type of vadose zone medium utilized.	5
<i>C</i>	Hydraulic Conductivity	Hydraulic conductivity is the capacity of aquifer materials to carry water, and it regulates the rate at which ground water flows down a specific hydraulic gradient.	3

3.2.2 Rates

Each range for each DRASTIC component has been compared to the others in order to assess the relative importance of each range in terms of pollution potential. Each DRASTIC element has been appointed a rating ranging from 1 to 10 (Table 3.3). The factors D, R, S, T, and C have each been allocated one value. Aquifer media and impose vadose zone have been appointed a "typical" and a variable rating, correspondingly. The variable rating gives the user the option of selecting a standard number or adjusting the value based on more specific knowledge.

Table 3.3: Original DRASTIC Parameters (Aller et al., 1987).

<i>LAYER</i>	<i>Range</i>	<i>Rating</i>	<i>Typical Rating</i>	<i>Weight</i>
Depth to water (m)	0-1.5	10		5
	1.5-4.5	9		
	4.5-9	7		
	9-15	5		
	15-22.5	3		
	22.5-30	2		
	30<	1		
Recharge (mm/y)	254<	9		4
	178-254	8		
	102-178	6		
	51-102	3		
	0-51	1		
Aquifer Medium	Karst Limestone	9-10	10	3
	Basalt	2-10	9	
	Sand and Gravel	4-9	8	
	Massive Limestone	4-9	6	
	Massive Sandstone	4-9	6	
	Bedded Sandstone, Limestone and Shale Sequences	5-9	6	
	Glacial Till	4-6	5	
	Weathered Metamorphic/Igneous	3-5	4	
	Metamorphic/Igneous	2-5	3	
	Massive shale	1-3	2	
Soil Medium	Thin or Absent	10		2
	Gravel	10		
	Sand	9		
	Peat	8		
	Shrinking and/or Aggregated Clay	7		
	Sandy Loam	6		
	Loam	5		
	Silty Loam	4		
	Clay Loam	3		
	Muck	2		
Topography (%)	Nonshrinking and Nonaggregated Clay	1		1
	0-2	10		
	2-6	9		
	6-12	5		
	12-18	3		
	18<	1		
	41-82	8		
	29-41	6		
	12-29	4		
	4-12	2		
	0-4	1		

<i>LAYER</i>	<i>Range</i>	<i>Rating</i>	<i>Typical Rating</i>	<i>Weight</i>
Impact of the Vadose Zone Medium	Karst Limestone	8-10	10	5
	Basalt	2-10	9	
	Sand and Gravel	6-9	8	
	Metamorphic/Igneous	2-8	4	
	Sand and Gravel with significant Silt and Clay	4-8	6	
	Bedded Sandstone, Limestone and Shale Sequences	4-8	6	
	Sandstone	4-8	6	
	Limestone	2-7	6	
	Shale	2-5	3	
	Silt/Clay	2-6	3	
	Confining Layer	1	1	
Hydraulic Conductivity (m/d)	82<	10		3
	41-82	8		
	29-41	6		
	12-29	4		
	4-12	2		
	0-4	1		

By utilizing current hydrogeologic characteristics in a GIS setting, DRASTIC has been used as a screening instrument to analyze the locations where the aquifer is most prone to contamination. Delineation of vulnerable zone is based on seven elements, corresponding to seven layers to be used as input elements for modelling. Weight and rate values are assigned for each parameter which are varied according to the importance of influence. The DRASTIC vulnerability index is calculated by summing the product ratings by the weights of the corresponding parameters according to Eq. (1) (Zghibi et al.,2016).

Original DRASTIC model does not propose any classification for the method. However, the user is free to interpret the vulnerability index based on his/her own field knowledge and hydro-geological expertise (Gogu et al., 2003), as it was proposed in Table 3.4. Another classification is proposed by Angle (1995) as shown in Table 3.5

Table 3.4: Guidelines for the DRASTIC method of assessing vulnerability (Gogu et al., 2003).

Vulnerability Class	Very Low	Low	Medium	High	Very High
Calculated Index Value	≤ 79	80-119	120-159	160-199	> 199

Table 3.5: Guidelines for the DRASTIC method of assessing vulnerability (Angle et al., 1995).

Vulnerability Class	Low	Medium	High	Very High
Calculated Index Value	≤ 100	101-140	141-200	> 200

3.3 Modification of DRASTIC Method

Despite its simplicity and success, the DRASTIC vulnerability mapping technique has numerous flaws. The main disadvantage is its subjectivity and doubts about the choice of specific factors and rejection of others. The EPA committee established factor weights using a Delphi (consensus) approach, which means they were mostly based on a subjective knowledge of real-world conditions in several well-studied areas. Rates and weights are selected by qualitative methods therefore, method has contained subjectivity. The particularities of the studied areas are not considered in this method (Pacheo et al., 2014). Moreover, there is no standard evaluation method of this technique.

3.4 Analytic Hierarchy Process (AHP)

The AHP which was developed by Saaty in between 1971 and 1975 is a popular and commonly utilised multicriteria tool. This technique incorporates the procedures of rating alternatives and assigning to find the most significant alternatives. The method is used to prioritize a set of choices or to pick the most suitable option from a set of choices. The ranking/selection is based on an overall goal that is broken down into a series of criteria (Saaty R.W., 1987). Because this method allows users to categorise the problem as a hierarchical and believe a mixing of quantitative and qualitative criteria, the AHP is one of the most inclusive systems for making judgments with various criteria.

Building a hierarchy based on the problem is the first step. The second step entails giving each level of the hierarchy a nominal value and devising a pairwise comparison judgment matrix. The values of these matrices are obtained by transforming the judgments into numerical values according to binary comparison table (Table 3.7) while respecting the principle of reciprocity.

Each class was compared to every other class by giving it a relative rating between 1 and 9, for purposes of comparison. Table 3.6 displays this value along with an explanation of it.

Table 3.6: Saaty's scale of relative importance.

<i>Intensity of importance on an absolute scale</i>	<i>Definition</i>	<i>Explanation</i>
1	Equal importance	To achieve the objective, two activities each contribute equally.
3	Moderate importance	One activity is greatly preferred over another by experience and judgment.
5	Strong importance	Experience and judgement strongly favour one activity over another.
7	Very importance	An activity is strong favoured, and its dominance demonstrated in practice.
9	Extreme importance	The strongest potential order of affirmation can be found in the evidence favouring one activity over another.
2, 4, 6, 8	Intermediate values between the two adjacent judgements.	When compromise is needed.
Reciprocals	If activity i has one of the above numbers assigned to it when compared with activity j , then j has the reciprocal value when compared with i	
Rationals	Ratios arising from the scales	If consistency were to be forced by obtaining n numerical values to span the matrix.

To create a pair-wise comparison matrix (A), the elements of each level and their weights are denoted as $A_1, A_2, A_3, \dots, A_n$ and $w_1, w_2, w_3, \dots, w_n$. The relative importance of a_i and a_j is represented by a_{ij} . The pair-wise comparison matrix of $A_1, A_2, \dots, A_n$ as $A = [a_{ij}]$ is written as;

$$A = \{a_{ij}\}_{n \times n} = \begin{pmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \vdots & \ddots & & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{pmatrix} = \begin{pmatrix} 1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & 1 & \cdots & w_2/w_n \\ \vdots & \vdots & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & 1 \end{pmatrix} \quad (2)$$

In this matrix, the element, $a_{ij} = 1/a_{ji}$ and thus, when $i = j$, $a_{ij} = 1$. A matrix is normalized using Eq. (3)

$$a'_{ij} = \frac{a_{ij}}{\sum_{j=1}^n a_{ij}} \quad (3)$$

Lastly, factor weights are calculated using Eq. (4) as:

$$w_i = \frac{1}{n} \sum_{j=1}^n a'_{ij} \quad (4)$$

The consistency ratio (C_R), which relies on the number of parameters, is used in AHP to check the matrix's consistency. The consistency ratio (C_R) is calculated by comparing the consistency index (CI) to an average random consistency index (R_I). The consistency ratio is determined by Eq. (5), while the consistency index is defined by Eq. (6).

$$C_R = \frac{CI}{R_I} \quad (5)$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (6)$$

where CI is the consistency index, λ_{max} is the major or principal Eigenvalue of the matrix obtained from the matrix, and n is the matrix's order. The average random consistency index (R_I), can be read from Table 3.7.

Table 3.7: Random consistency index (R_I)

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.5	0.79	0.99	1.37	1.44	1.55	1.69

The Consistency Ratio is used to calculate the final result, which consists of the derived factor weights and class rating (C_R). The consistency ratio, which depends on the number of criteria, is used in AHP to assess the consistency utilized to generate a matrix. To accept the estimated weights, the C_R for a 7x7 matrix must be 0.1. Models

with $C_R > 0.1$ were automatically rejected, although $C_R < 0.1$ was frequently acceptable (Balasundareshwaran et al., 2019).

3.5 Inverse Distance Weighted Interpolation Method

The Inverse Distance Weighted (IDW) interpolation method was devised in 1970 and is founded on the concept of Tobler's first statement (also known as the first law of geography). Everything is interconnected to everything else, however close items are more linked than further things, according to this concept. (Chen and Liu, 2012). The interpolation of the numerical data which obtained in this study to the entire aquifer area was distributed and mapped using the IDW method in the GIS environment. IDW interpolation is a deterministic spatial interpolation method for estimating an unknown value at a location by using certain known values with associated weighted values. The IDW is a method for determining cell values that requires averaging sample datasets adjacent to each processing cell. The closer an element is from the cell's centre, the more significance or impact it has on the averaging process. A radius is assigned to the z point, which determines the number of points included in the calculation. The estimated z point according to this method is calculated as follows.

$$\frac{\sum_1^n z_i w_i}{\sum_1^n w_i} \quad (7)$$

where z_i represent the check value for i^{th} sample number, w_i is a weight that determines relative importance of check point. Based on the inverse of distance to power, one alternative weighting approach that gives near locations significantly more impact than distant places are as follows (Bartier and Keller, 1996):

$$w_i = \frac{1}{d_i^\alpha} \quad (8)$$

where d is the distance between two points, α is the exponent defined by the users.

Hence Eq. (7) can be rewritten as:

$$z = \frac{\sum_1^n \frac{z_i}{d_i^\alpha}}{\sum_1^n \frac{1}{d_i^\alpha}} \quad (9)$$

The α value and radius (r) are very important parameters in the efficient use of the method (Chen and Liu, 2012). In this study, the elevation value was not considered in the execution of the IDW method. The distance measured between two points is the horizontal distances.

3.6 Weighted Arithmetic Water Quality Index Method

3.6.1 Water Quality Index

The idea of determining water quality according to certain index values was first proposed by Horton (1965). Brown et al. (1970) and the Scottish Development Department established the WQI. The grade of water used for drinking determines whether or not the water is suitable for consumption by humans. The composition of the water, which is transformed by both natural and human processes, defines the quality of the water. Physical, chemical, and microbiological aspects of water define its grade, and values that are greater than allowed limits are risky for human health. The WQI can inform us whether the overall quality of water bodies poses a hazard to diverse water uses such as aquatic life habitat, irrigation water for agriculture and cattle, recreation and aesthetics, and drinking water sources. The WQI is a single value indicator of water quality. It combines the data pool created after assigning weights to the various parameters (Bouslah et al., 2017).

3.6.2 Weighted Arithmetic WQI method.

Water quality can be evaluated with the Weighted Arithmetic WQI method. The reason for preferring Weighted Arithmetic WQI method is that parameters such as Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD) or Turbidity do not need to be measured.

The execution of this method begins with the calculation of unit weights.

$$W_n = \frac{K}{S_n} \quad (10)$$

where: W_n represents unit weight for n^{th} parameters. S_n is standard value of n^{th} parameter; K represents proportional constant. Then the quality rating is calculated as.

$$q_n = 100 \left[\frac{V_n - V_i}{S_n - V_i} \right] \quad (11)$$

where q_n represents quality rating for n^{th} water quality parameters, V_n represents estimated value of n^{th} parameter. S_n is standard permissible value of n^{th} parameter. V_i represents ideal value n^{th} parameter which all values are taken as zero except the parameter pH ($V_i=7.0$) and dissolved oxygen (DO) ($DO=16,6 \text{ mg/dm}^3$). As the last step in the calculation, WQI is found according to the Equation (12) (Bouslah et al., 2017).

$$WQI = \frac{\sum q_n W_n}{\sum W_n} \quad (12)$$

The calculated overall Water Quality Index is evaluated according to the classification in Table 3.9.

Table 3.8: WQI range and quality status (Bouslah et al., 2017).

<i>WQI range</i>	<i>Water Quality Status</i>
0-25	Excellent water quality
26-50	Good water quality
51-75	Poor water quality
76-100	Very poor water quality
Above 100	Unsuitable for drinking and propagation of fish culture

3.7 Hydrometer Analyses

The soil is one of the crucial items that determine the recharge rate. The part at the top of the vadose zone and at a depth of 1.80 meters (or less) from the surface is called the soil (Aller et al., 1987). When using the 'Soil medium' parameter, which is the DRASTIC method parameter it is necessary to know the soil texture. The amount of ground surface infiltration is influenced by the features of the soil texture. The presence and proportions of fine-grained materials such as sand, clay, and silt in the soil, directly affect the permeability of the soil.

One frequent approach for reliably determining particle size distribution in a soil sample is the hydrometer analyses method. The analyses are performed to identify the particle-size distribution (gradation) of substance that is bigger than about 0.2 μm and finer than No. 200 (75 μm) sieve. The technique is based on Stoke's law (*Eq. 13*), which determines the sedimentation rate of particles suspended in water. All other factors being equal, the grain's size, shape, and weight will govern how fast it will end up settling out of suspension. It is presumed that, the soil particles are spherical and share the same unit weight. Thus, it is assumed that, the heavier particles will precipitate before the lighter ones.

$$w_s = \frac{\gamma_s + \gamma_w}{18\mu} \quad (13)$$

where w_s is representing the settling velocity (cm/sec), γ_s and γ_w are representing the specific weight of solids (g/cm³) and the unit weight of water (g/cm³), respectively. The viscosity of water (g.s/cm²) is represented by μ .

3.7.1 Procedure

When more than 90% of the soil is finer than No. 200 sieve, hydrometer approach is used. The procedure for the experiment is as follows; firstly, 50 g of the sample taken from the oven is thoroughly pulverized and taken into the test container. Then, Sodium hexa-metaphosphate ($Na_6(PO_3)_6$) is added (%4 by weight) to disperse the sample and left for a while. The slurry is then continually mixed for 15 minutes at electrical mixing machine. Then, the suspension is transferred to 1 liter measuring cylinder and additional water is added if necessary. The hydrometer is inserted into the cylinder where the measurement will be observed immediately (but in a way that does not cause fluctuations), and the readings are observed. Elapsed times and temperatures are observed at 30 sec., 1, 2, 4, 8, 15, 30 minutes and 1, 2, 4, 8, 16, 24, 48 hours. If necessary, even 96 hours can also be observed.

The percentages of silt, clay, sand, and loam are calculated. The amount of material is determined, and these are graded using the soil textural classification triangle that provides the soil class (Figure 3.1).

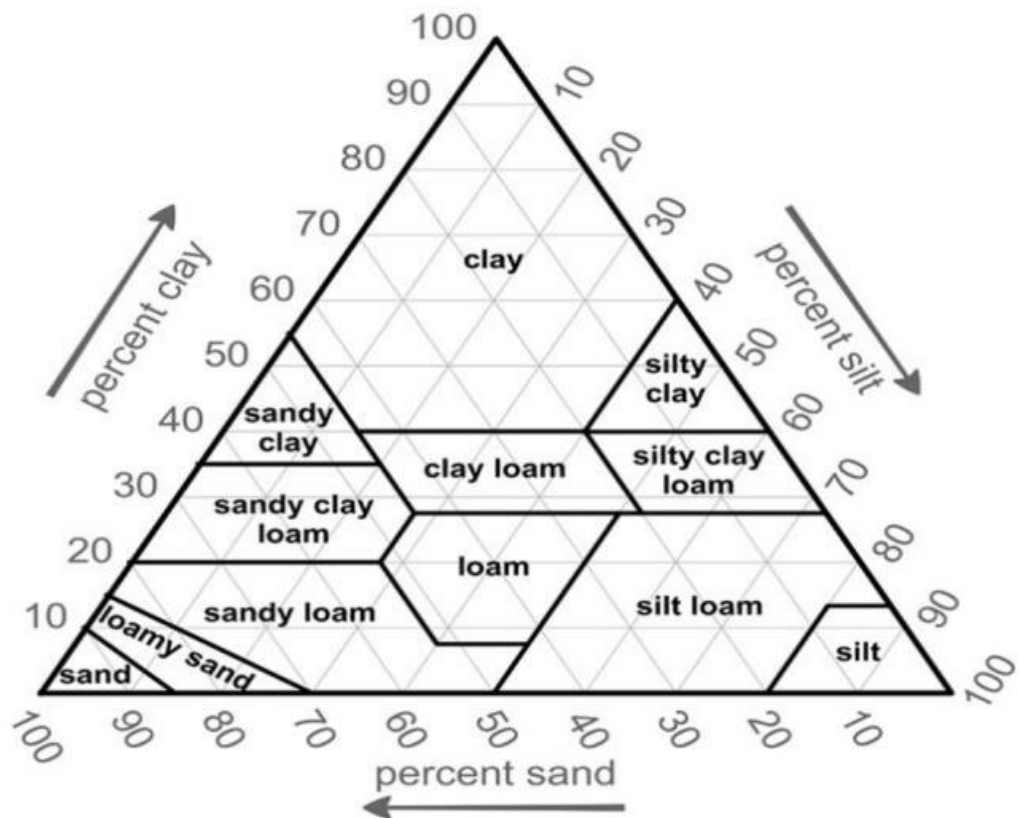


Figure 3.1: Soil Textural Classification Triangle (United States Department of Agriculture (USDA)).

Chapter 4

RESULTS AND DISCUSSION

To implement the original DRASTIC technique, the weight values of the 7 parameters were determined by the original indices, and the other rate values were established by the tables used in the original method's application. Likewise, weight and rate values were calculated via AHP in the ArcGIS context and the vulnerability of the aquifer is recalculated for this new circumstance. The hydro-geological peculiarities of the Yeşilköy aquifer were taken into account when assigning the weight index values in the original approach using AHP. In the Yeşilköy aquifer, for example, where the average water table depth is 64.20 meters, the rate values have been assigned as 1 because it is greater than 30 meters. This condition eliminates the determining factor of the original DRASTIC method's Water depth parameter (D). The deepening of the water table over time has not only caused vadose of the old aquifer medium zone, but also created a rather thick vadose zone. Accordingly, the importance of the vadose zone was taken into account more effectively than in classical method. The significance levels of aquifer media were projected to be greater in the approach, whose coefficients were changed again with AHP, than in the traditional DRASTIC method. Furthermore, the small size of the analysed region results in a lack of precipitation variability and a consistent infiltration rate at each location. As a result, the weight and rate of the "Net Recharge" parameter have been adjusted lower.

4.1 Hydrogeologic Parameters

Many different wells located within the boundaries of the Yeşilköy aquifer were used to obtain data for hydro-geological parameters. In general, the same wells could not be utilized for all data groups because measurements were made at various times to collect the data needed for each parameter, and wells fulfilling the proper conditions were chosen. Within the scope of this study, a total of 65 different wells were used in order to provide the data required by different parameters. In the hereafter, the wells and their data will be given individually for each data category. However, the objectives for which the exploited wells are employed are summarized in Table 4.1.

Table 4.1: Wells as data source for some parameters.

Well name	Water Depth	Aquifer Medium	Sieve Analyses	Hydrometer Analyses	Vadose Zone	Microbiological and Chemical
YK 10	X	X	X		X	
YK 1004	X					
YK 1005						X
YK 103						X
YK 1040						X
YK 106	X		X			
YK 1060						X
YK 107	X					X
YK 108						X
YK 11						X
YK 116						X
YK 117						X
YK 13						X
YK 131						X
YK 15						X
YK 152	X					
YK 16		X			X	
YK 163	X					X
YK 17		X	X		X	X
YK 2			X			
YK 24			X			
YK 24/27						X
YK 25	X					
YK 27		X			X	X
YK 29		X			X	

Well name	Water Depth	Aquifer Medium	Sieve Analyses	Hydrometer Analyses	Vadose Zone	Microbiological and Chemical
YK 3		X			X	
YK 31	X					
YK 32						X
YK 35			X			
YK 36						X
YK 38	X		X	X		
YK 4					X	X
YK 40	X					
YK 42	X	X	X		X	
YK 44		X	X		X	
YK 45			X			X
YK 48		X			X	
YK 49		X			X	
YK 5					X	
YK 50	X					
YK 52		X			X	
YK 55	X				X	
YK 57					X	
YK 61	X					
YK 63		X			X	
YK 65		X			X	X
YK 66	X	X	X	X	X	
YK 67	X				X	
YK 69	X					
YK 7						X
YK 71	X		X			X
YK 73	X					X
YK 77		X			X	
YK 8	X	X			X	
YK 80					X	
YK 95						X
YK 96	X		X	X		
YK 97		X			X	
YK 98					X	
YK 99	X					
YK 107			X			
YK 113					X	
YK 125		X			X	
YK 163			X			
YK 171		X			X	

4.1.1 Depth of Water (*D*)

The distance between the ground surface and the water level is defined as the depth of water. Vadose zone and soil medium pollutant attenuation capacity is increased proportionally by the distance between the water table and the top of the soil. The deeper the water depth, the lesser the vulnerability is. Water depth is one of the most crucial components for the original DRASTIC method, which is weighted by 5.

Despite the fact that, there are numerous wells drilled in the aquifer, the static water level of 22 wells could be measured in March 2022 owing to factors like, well heads totally covered with plants; abandoned wells with tree roots preventing the measuring meter to dive into well; and lack of space for measuring equipment. The observation wells for the water depth measurements were selected in such a way that they represented almost the whole of the aquifer area. Thus, the interpolation methods like krigging method resulted in a most reliable water depth mapping. It is necessary to indicate that, although it was documented that there exist wells in the aquifer's south and southwest, no such wells could be found at that region for observation and monitoring purposes. Figure 4.1 shows the selected observed wells and Table 4.2 details of selected wells.

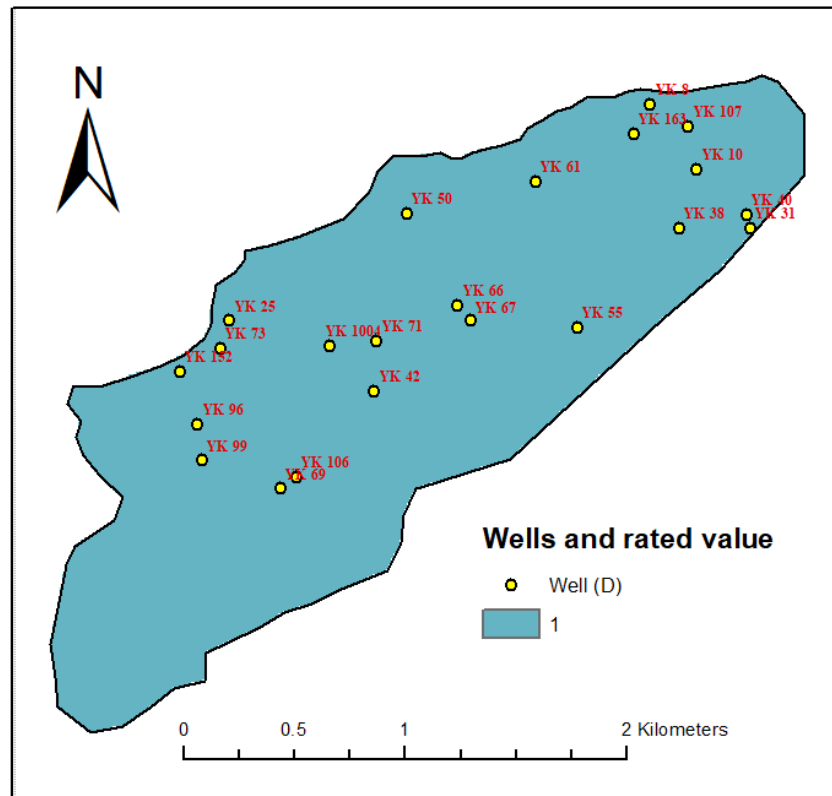


Figure 4.1: Map representing the location of the selected 22 wells.

Table 4.2: Details of selected 22 wells.

No	Well Name	Water Depth (m)	Topographic Elevation (m)	Static Water Level (m)
1	YK 10	68.50	140.00	71.50
2	YK 1004	68.20	139.00	70.80
3	YK 106	61.40	158.00	96.60
4	YK 107	70.00	137.00	67.00
5	YK 152	54.70	130.00	75.30
6	YK 163	63.50	133.00	69.50
7	YK 25	66.30	136.00	69.70
8	YK 31	70.50	145.00	74.50
9	YK 38	68.00	161.00	93.00
10	YK 40	73.40	145.00	71.60
11	YK 42	64.80	145.00	80.20
12	YK 50	60.10	132.00	71.90
13	YK 55	74.00	145.00	71.00
14	YK 61	58.00	126.00	68.00
15	YK 66	62.00	135.00	73.00
16	YK 67	66.00	139.00	73.00
17	YK 69	42.80	161.00	118.20
18	YK 71	64.70	137.00	72.30

No	Well Name	Water Depth (m)	Topographic Elevation (m)	Static Water Level (m)
19	YK 73	63.30	134.00	70.70
20	YK 8	66.40	135.00	68.60
21	YK 96	61.50	144.00	82.50
22	YK 99	63.80	152.00	88.20

The details of selected wells are shown in Figure 4.1. The data was obtained in March 2022. Based on original DRASTIC method, since the water table depth all around the aquifer is more than 30 meters, the rate factor for depth of water (D) is assigned as 1 (Table 3.3).

4.1.2 Net Recharge (R)

The principal source of groundwater is the rainfall. The quantity of water per unit area of land that penetrates the soil and reaches to the water table is referred to as net recharge. The recharge water is a main device of leaking and conveying solid or liquid pollutants within the aquifer towards the water table. In those cases, where solid or liquid pollutants are existing, the more the recharge, the greater the risk of groundwater pollution (Aller et al., 1987). According to the original DRASTIC method, the weight of net recharge is 4.

The comprehensive study carried out by Türker et al. (2012) computed the annual total volume of recharge in the Yeşilköy aquifer as 1.01×10^6 m³/year and drainage area as 6.39 km². Hence, the ratio of the recharge volume to the recharge area results in the recharge rate of the precipitation with in the region. Therefore, it is calculated to be 158 mm/year. Since 158 mm/year stands in between the range of 102-178 in the Table 3.3, the net recharge rate can be selected as 6 for the whole aquifer as seen Figure 4.2.

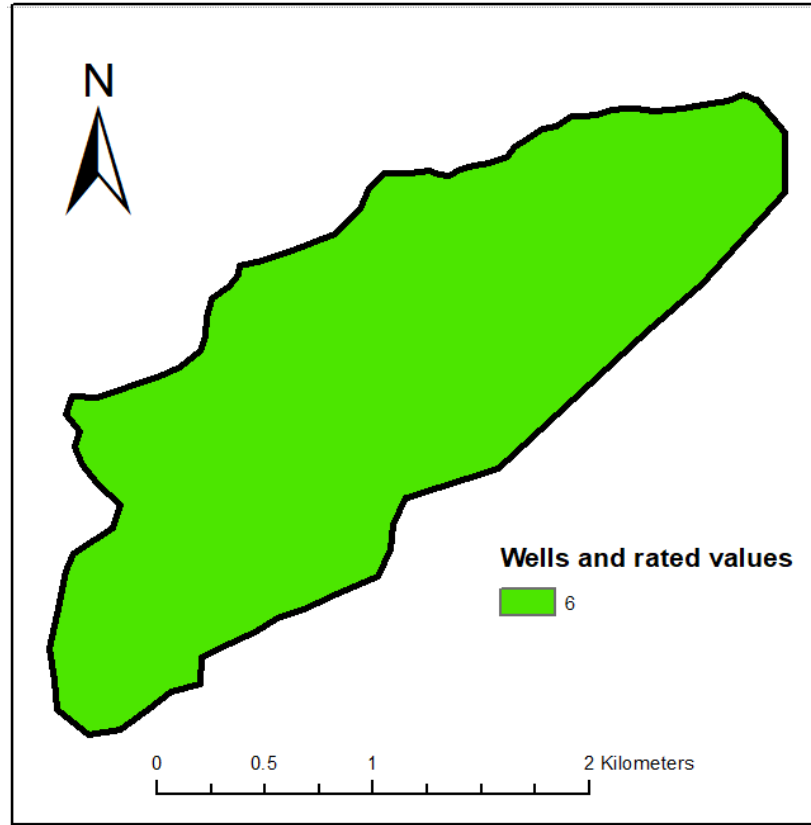


Figure 4.2: The net recharge rate value of Yeşilköy aquifer with original method.

4.1.3 Aquifer Media (A)

Aquifers that store and transmit water have bodies usually made of permeable rock or sediment. Groundwater resources are formed when all the voids within the layers of permeable rock or sediment are completely saturated with water. It can also be defined as a geological structure that provides sufficient water for use (Rahman, A., 2008). The size and the shape of the pores of the aquifer medium impacts the vulnerability of the aquifer. It is well known that, the concentration of pollutants is managed in part, by the aquifer's capacity to reduce them. As the particle diameter of the materials contained in aquifer decreases, its permeability weakens and its vulnerability decreases.

Yeşilköy aquifer is mainly composed of sandstone and calcarenite. The aquifer contains clay, silt, marl, or their combined forms in varying amounts depending on location and depth. The presence of these materials were considered while selecting the appropriate range value to simulate the effect of aquifer media provided by the original DRASTIC method. Assigned rate depending on the aquifer media content observed in each well borehole are as given in Table 4.3.

Table 4.3: Yeşilköy aquifer medium characteristics and assigned rates based on boreholes data.

No.	Well No:	Aquifer Media Content	Rates
1	8	Calcarenite	6
2	10	Calcarenite	5
3	16	Sandstone	8
4	17	Calcarenite	6
5	27	Calcarenite	6
6	29	Calcarenite	6
7	42	Sandstone	8
8	44	Calcarenite	6
9	48	Sandstone	8
10	49	Sandstone	8
11	52	Calcarenite	6
12	63	Calcarenite	6
13	65	Sandstone	8
14	66	Calcarenite	6
15	77	Sandstone	7
16	97	Sandstone	7
17	98	Sandstone	8
18	125	Sandstone	8
19	171	Calcarenite	6

Table 4.3 is established based on the data received from the Geology and Mines Department of TRNC and matching this data with the Table 3.3. The rates assigned for the boreholes of each well were then interpolated through the whole aquifer area using the Inverse Distance Weighted technique by ArcGIS tool. The resultant aquifer

medium distribution rates map is given in Figure 4.3. The reclassification of the data given in Table 4.3 depicts that, the sand and gravel composition is more distributed at the southern part of the aquifer, whereas the calcarenite and limestone is dominant towards the north. Reclassified aquifer medium map is also given in Figure 4.4. According to Table 3.3, limestone, sand and gravel is the main rock formation medium whereas, at the northern and north-western part of the aquifer is also consisting of loam and sandy-loam.

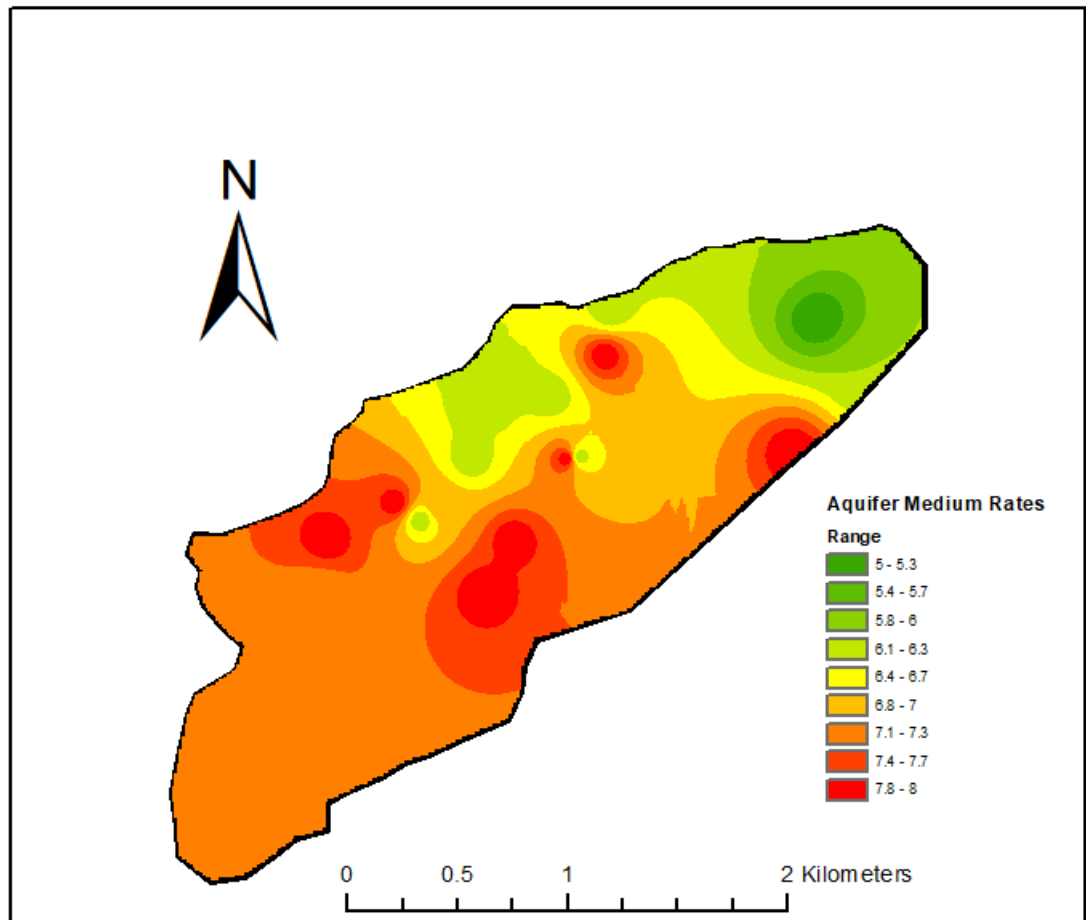


Figure 4.3: Aquifer medium distribution rates of the Yeşilköy aquifer.

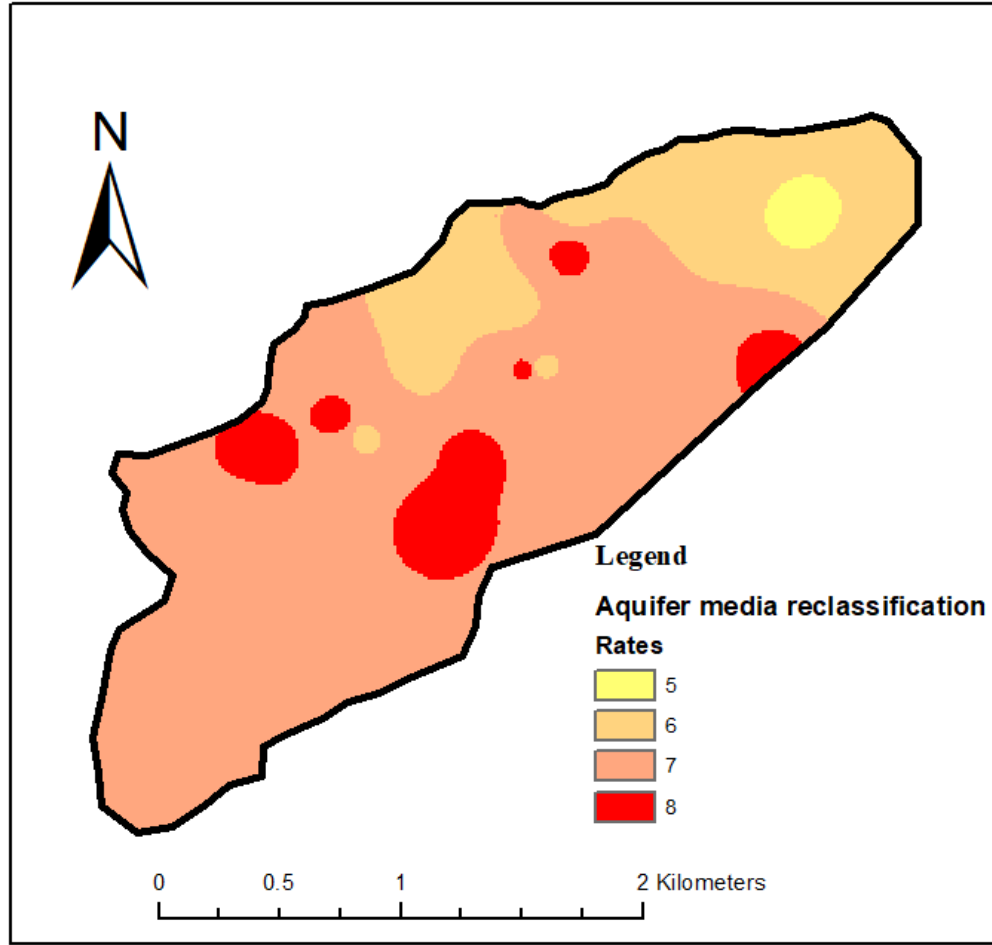


Figure 4.4: Reclassified Yeşilköy aquifer medium map.

4.1.4 Soil Medium (S)

The quantity of infiltration from the soil surface towards the aquifer is affected by the texture of the soil. The texture of the soil layer in the Yeşilköy region was created by using the findings of the field work performed at the site and adapting relevant laboratory testing analyses (Hydrometer Analyses). The soil samples were taken from close vicinity of 15 different wells, (those wells that were used for sampling of water quality analysis) approximately 30 cm below the soil, by means of auger. Sieve analyses were performed in the materials of construction laboratory of Eastern Mediterranean University. The results were grouped, and hydrometer analyses were performed for 3 representative samples in the Geotechnic Laboratories of EMU. Hydrometer analysis results are summarized in Table 4.4.

Table 4.4: Hydrometer analyses results of the samples.

Sample Location	Clay percentage (%)	Silt percentage (%)	Sand percentage (%)
YK 96	15	30	55
YK 66	22	30	48
YK 38	26	42	32

Due to the similarities in the sieve analyse results, soil texture classification was performed for three different soil types. For this, samples from 3 different locations were tested through hydrometer tests. As a result of the hydrometer analysis, the soil samples were categorised using the soil texture chart (Figure 3.2), and then rate values were assigned based on the original DRASTIC method's assigned ranges. Soil texture is separated into loam and sandy loam without any major difference. As a result, the rates for soil media are assigned as 5 and 6 according to the previously given Table 3.3. The results of soil media studies are summarized in Table 4.5.

Table 4.5: Sieve and Hydrometer analyses results and soil textural classes and assigned ratings.

Sample No	Total Weight (gr)	Amount Retained (gr)	Amount Passing (gr)	Passing Percentages (%)	Soil Textural Class	Suggested Soil Rating
YK-42	100	53.67	46.33	46.33	Sandy Loam	6
YK-107	100	49.69	50.31	50.31	-	-
YK-24	100	34.16	65.84	65.84	-	-
YK-38	100	29.80	70.20	70.2	Loam	5
YK-17	100	44.65	55.35	55.35	-	-
YK-66	100	46.63	53.37	53.37	Loam	5
YK-071	100	43.91	56.09	56.09	-	-
YK-044	100	46.63	53.37	53.37	-	-
YK-163	100	43.83	56.17	56.17	-	-
YK-2	100	44.46	55.54	55.54	-	-
YK-96	100	60.07	39.93	39.93	Sandy Loam	6
YK-10	100	36.92	63.08	63.08	-	-
YK-106	100	32.41	67.59	67.59	-	-
YK-35	100	50.63	49.37	49.37	Sandy loam	6
YK-45	100	46.81	53.19	53.19	-	-

The results of the field analyses and laboratory testing at different locates of the aquifer can be interpolated to obtain the soil medium distribution within the boundaries of the aquifer. The distribution of soil medium is given in Figure 4.5.

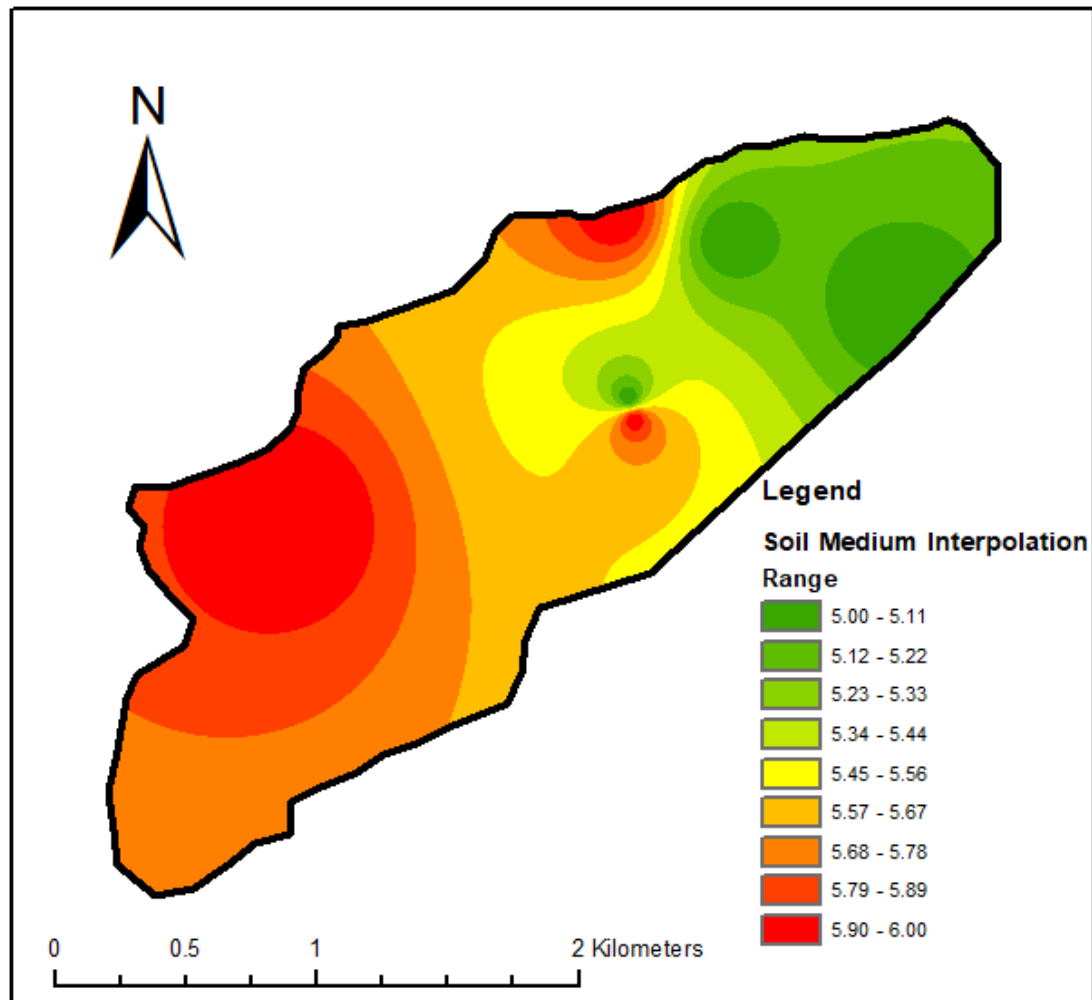


Figure 4.5: The soil media distribution of the soil media representing the 30 cm soil thickness.

The map generated in Figure 4.5 was categorized as being adequate for classification in the DRASTIC method, and the map in Figure 4.6 was obtained.

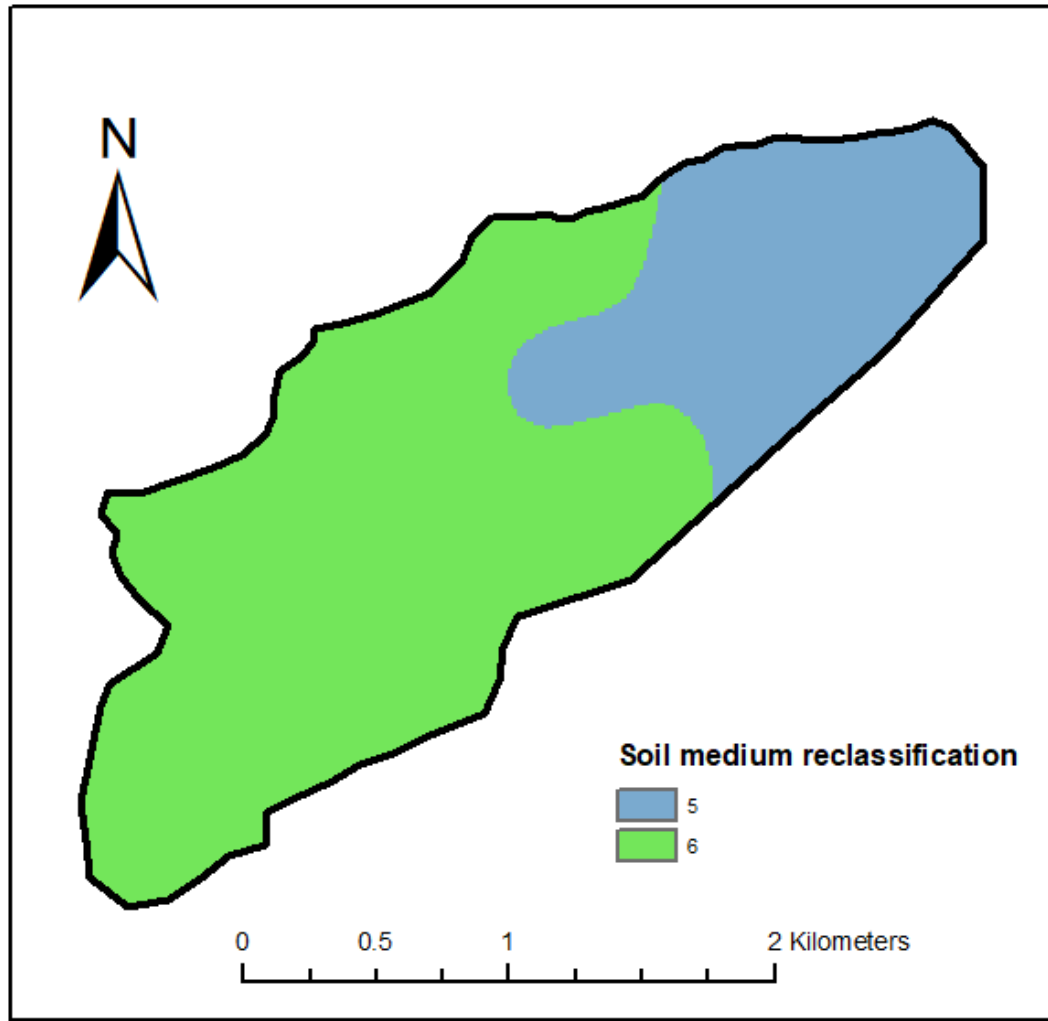


Figure 4.6: Reclassified Soil media map of the Yeşilköy aquifer.

4.1.5 Topography (*T*)

Topography affects the probability of a pollutant running off or remaining on the soil in one location long enough to infiltrate. Pollutants on the soil may also flow away from the region if the slope is greater, rather than percolating into the ground.

A DEM map was processed in an ArcGIS program to obtain a slope map of Yeşilköy aquifer recharging area. Although there are no significant slope variations in this region, inclined areas are concentrated along the aquifer borders. The values obtained with the slope map vary between 0% and 76% as seen in Figure 4.7.

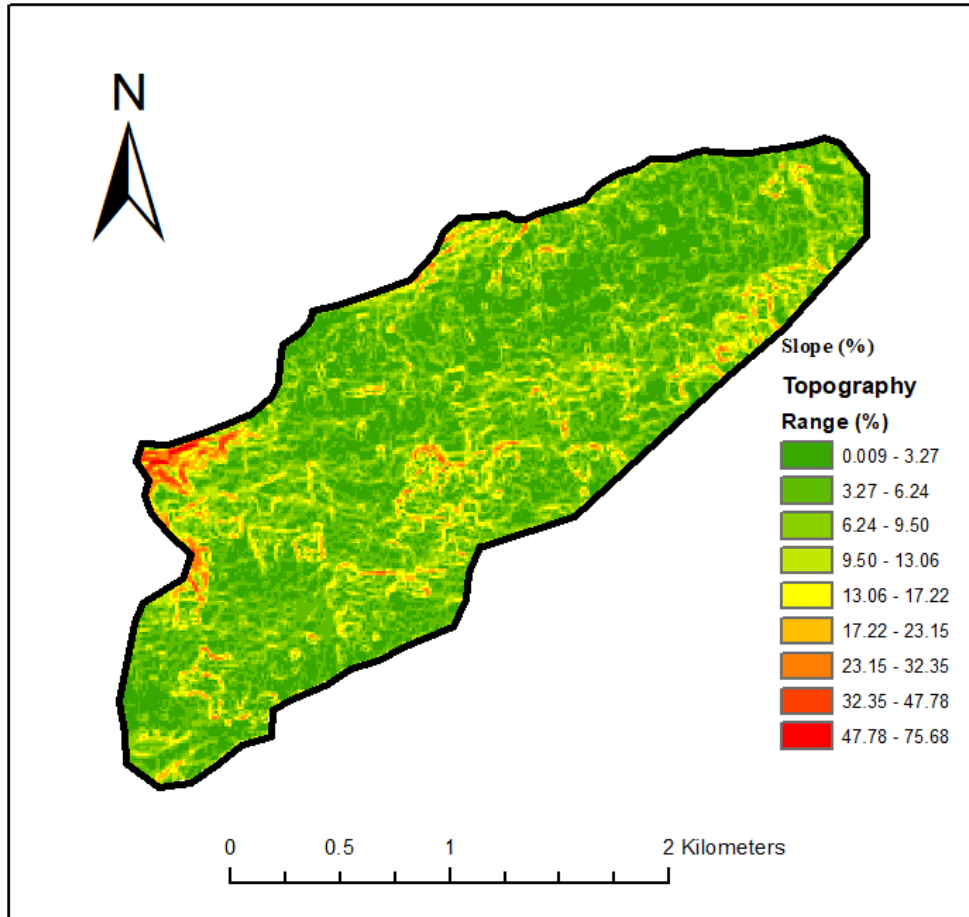


Figure 4.7: Topography map of the Yeşilköy aquifer built from the digital elevation model of Cyprus.

When slope map is reclassified, Figure 4.8 can be obtained. The upper surface of the Yeşilköy aquifer has a very high potential to store water, as seen in Figure 4.8.

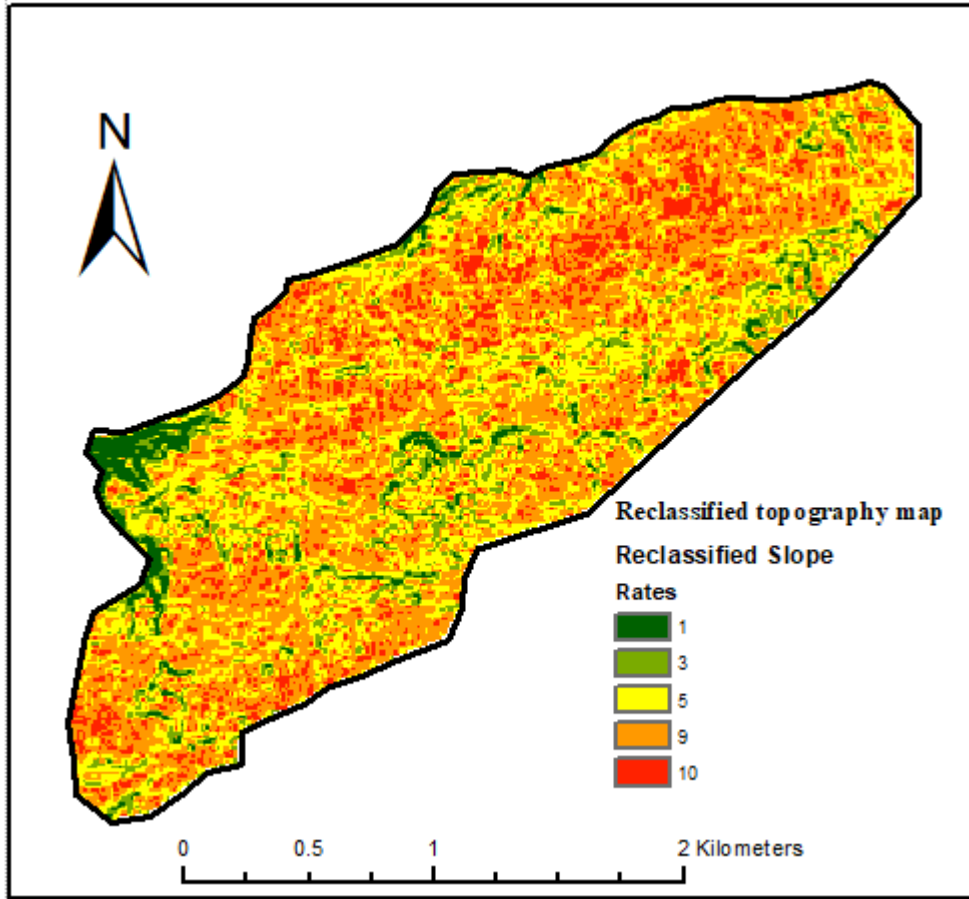


Figure 4.8: Reclassified slope map of Yeşilköy aquifer.

4.1.6 Impact of Vadose Zone (*I*)

The depth of the vadose zone is the distance that pollutants must travel through before impacting the aquifer; thus, the higher the depth, the fewer the contaminants. The Vadose zone's geological formations are as essential as its thickness. The vadose zone is an unsaturated zone that ranges from soil to groundwater.

The sandstone, limestone, and calcarenite dominate the Yeşilköy aquifer's vadose zone. These strata may also contain marl layers. Table 4.6 represents the rating values obtained based on the rating values of Table 3.3 between 3 and 8. These rates are assigned by using the vadose zone borehole data of 27 different wells.

Table 4.6: Vadose zone contents and assigned rates with respect to wells.

Order No.	Well No:	Vadose Zone Content	Rates
1	3	Limestone	6
2	4	Calcarenite+Limestone	7
3	5	Calcarenite+Limestone	7
4	8	Calcarenite+Limestone	7
5	10	Calcarenite+Limestone+Marn	4
6	16	Calcarenite+Limestone+Marn+Sandstone	5
7	17	Calcarenite+Limestone+Sandstone	7
8	27	Limestone	6
9	29	Limestone	6
10	42	Calcarenite+Sandstone	8
11	44	Calcarenite+Limestone+Marn	5
12	48	Calcarenite+Limestone+Sandstone	7
13	49	Calcarenite+Sandstone	7
14	52	Calcarenite+Limestone	7
15	55	Calcarenite+Limestone+Marn	4
16	57	Calcarenite+Limestone+Marn	5
17	63	Calcarenite+Limestone	7
18	65	Calcarenite	7
19	66	Calcarenite+Limestone+Marn	3
20	67	Calcarenite+Limestone+Sandstone+Marn	4
21	77	Calcarenite+Limestone+Sandstone+Marn	5
22	80	Calcarenite+Limestone+Marn+Sandstone	5
23	97	Calcarenite+Limestone+Sandstone	7
24	98	Calcarenite+Limestone+Sandstone	7
25	113	Calcarenite+Marny-Sandstone	4
26	125	Calcarenite+Limestone+Sandstone	7
27	171	Calcarenite	8

The variations on the vadose zone was mapped as seen in Figure 4.9. It is noticed that, the north-eastern part of the aquifer has relatively less vulnerable. Reclassification of Figure 4.9 is given in Figure 4.10.

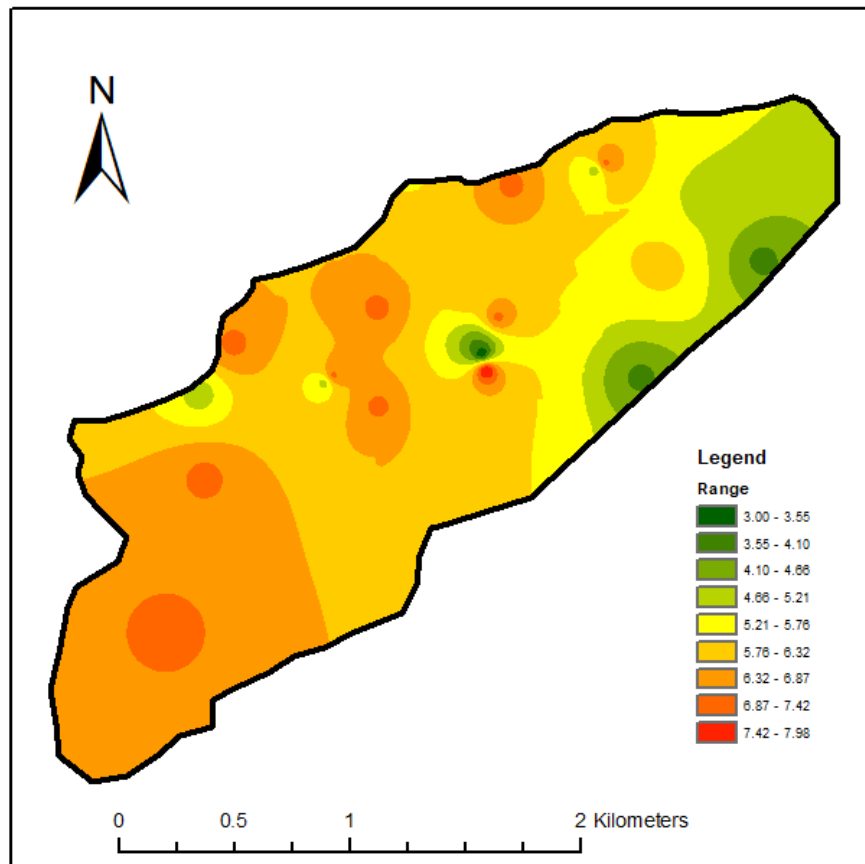


Figure 4.9: Interpolated Vadose zone map of Yeşilköy aquifer.

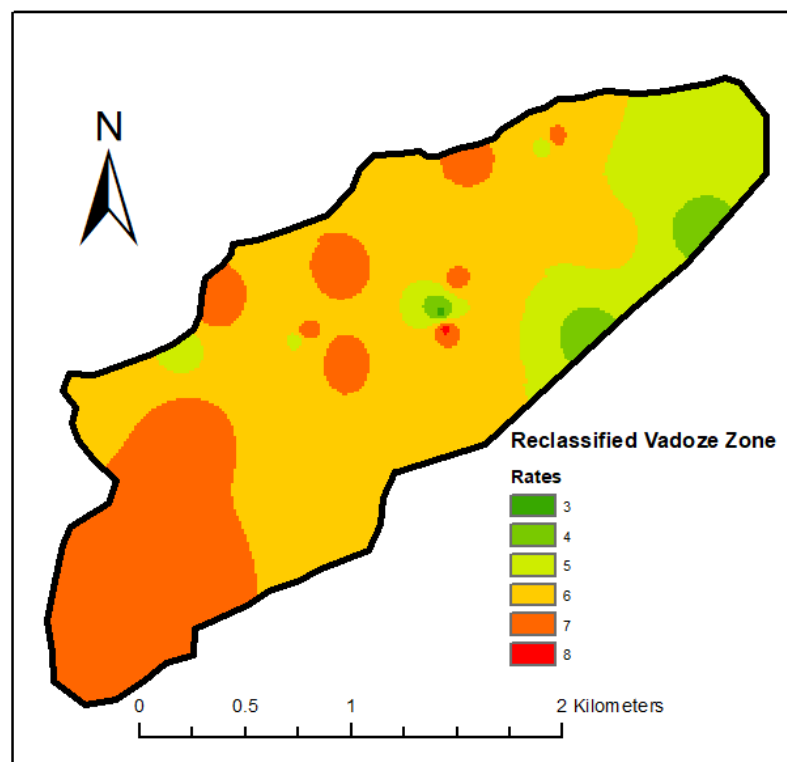


Figure 4.10: Reclassified vadose zone map of Yeşilköy aquifer.

4.1.7 Conductivity of the Aquifer (C)

Hydraulic conductivity is an aquifer medium characteristic that influences the velocity at which groundwater flows. The number and connectivity of empty spaces within the aquifer govern the hydraulic conductivity. The stronger the hydraulic conductivity of the region, the greater the transmission of the pollutants.

Hydraulic conductivity values are obtained from aquifer pumping tests. Türker et al. (2012) have used the Theis method and found that transmissivity of Yeşilköy aquifer was 1,782 m²/day. By dividing the measured transmissivity value with the aquifer thickness, the conductivity of the aquifer formation can be calculated. The aquifer thickness was evaluated using borehole data, and the conductivity values are calculated by using Eq. (14).

$$C = \frac{T_r}{D_a} \quad (14)$$

where C denotes the conductivity (m/day), T_r is the transmissivity of the aquifer (m²/day), and D_a is aquifer average thickness at the measured point (m). The conductivity at various locations of the aquifer are shown in Table 4.7.

The conductivity distribution within the aquifer area is mapped by using IDW in ArcGIS as seen in Figure 4.11. Conductivity was lower due to the higher thickness of the aquifer in the middle region of the aquifer. However, considering the original DRASTIC method, since all conductivity values found are in the range of 0 to 4, the rate value is assigned as 1 as seen in Figure 4.12 as a conductivity reclassified based on DRASTIC method.

Table 4.7: Conductivity values for each well.

No.	Well No:	Aquifer Thickness (m)	Transmissivity (m ² /day)	Conductivity (m/day)
1	3	45.70	1.782	0.04
2	10	18.30	1.782	0.10
3	16	13.70	1.782	0.13
4	17	8.10	1.782	0.22
5	27	57.90	1.782	0.03
6	29	61.00	1.782	0.03
7	42	15.60	1.782	0.11
8	44	18.30	1.782	0.10
9	48	12.20	1.782	0.15
10	49	16.70	1.782	0.11
11	52	56.40	1.782	0.03
12	57	44.20	1.782	0.04
13	63	68.60	1.782	0.03
14	66	21.40	1.782	0.08
15	77	36.60	1.782	0.05
16	97	6.10	1.782	0.29
17	98	12.20	1.782	0.15
18	113	64.10	1.782	0.03
19	125	18.00	1.782	0.10
20	171	24.42	1.782	0.07

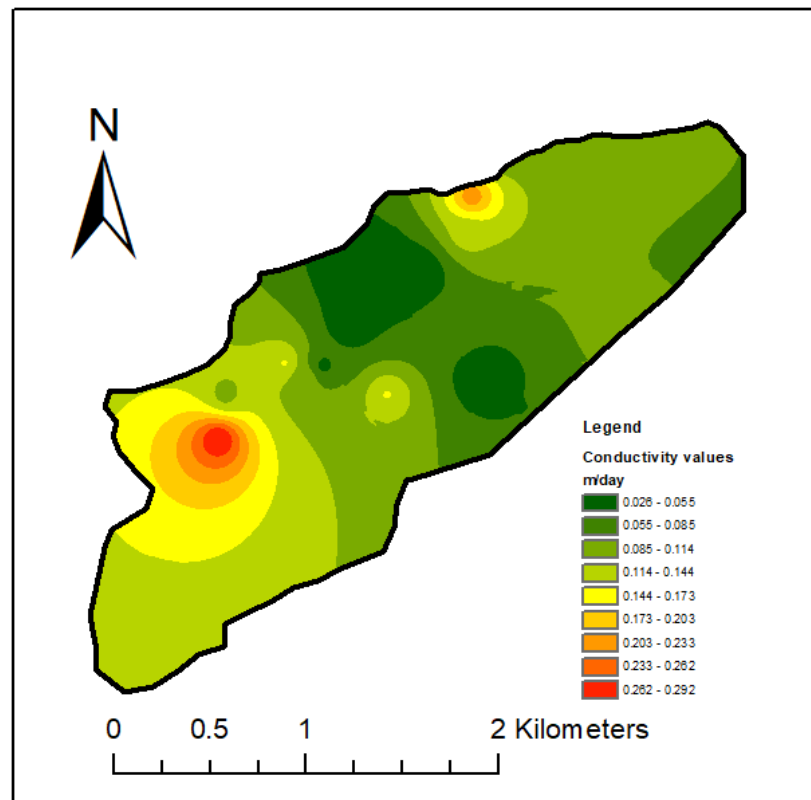


Figure 4.11: Conductivity of Yeşilköy aquifer.

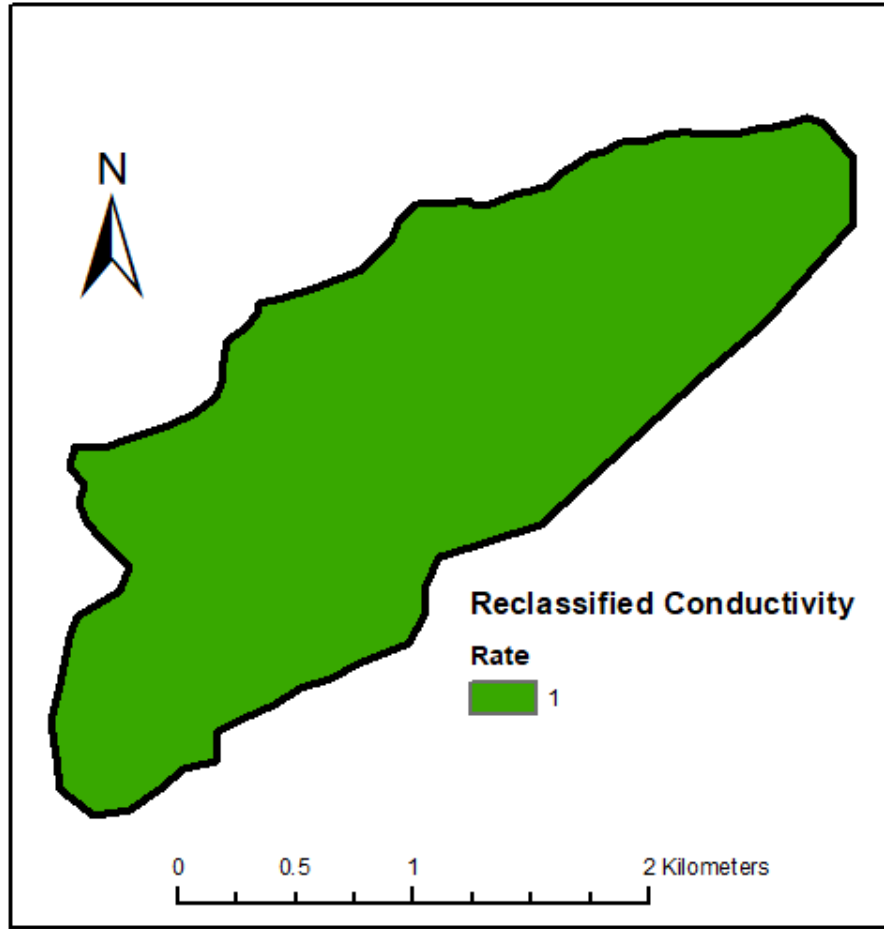


Figure 4.12: Conductivity reclassification according to Original DRASTIC method.

4.2 Vulnerability Map and DRASTIC Index Map

According to the DRASTIC method, seven different hydro-geologic information-based maps are prepared, containing the weight and the rates of each parameter. This process is followed by matching these seven maps to be used in Eq. (1). Therefore, in order to calculate the sum of the product of the rate values and the weight values from produced maps, ArcGIS tool is used. The resultant map is the vulnerability map of the Yeşilköy aquifer, indicating which regions of the aquifer are more vulnerable than the others. The vulnerability map is given in Figure 4.13 in which vulnerability ranges in between 89 – 122. The vulnerability of the map is lower at the North-eastern part of the aquifer (vulnerability ranges in between 89-100), which shifts towards the South-western part (vulnerability ranges in between 100-122).

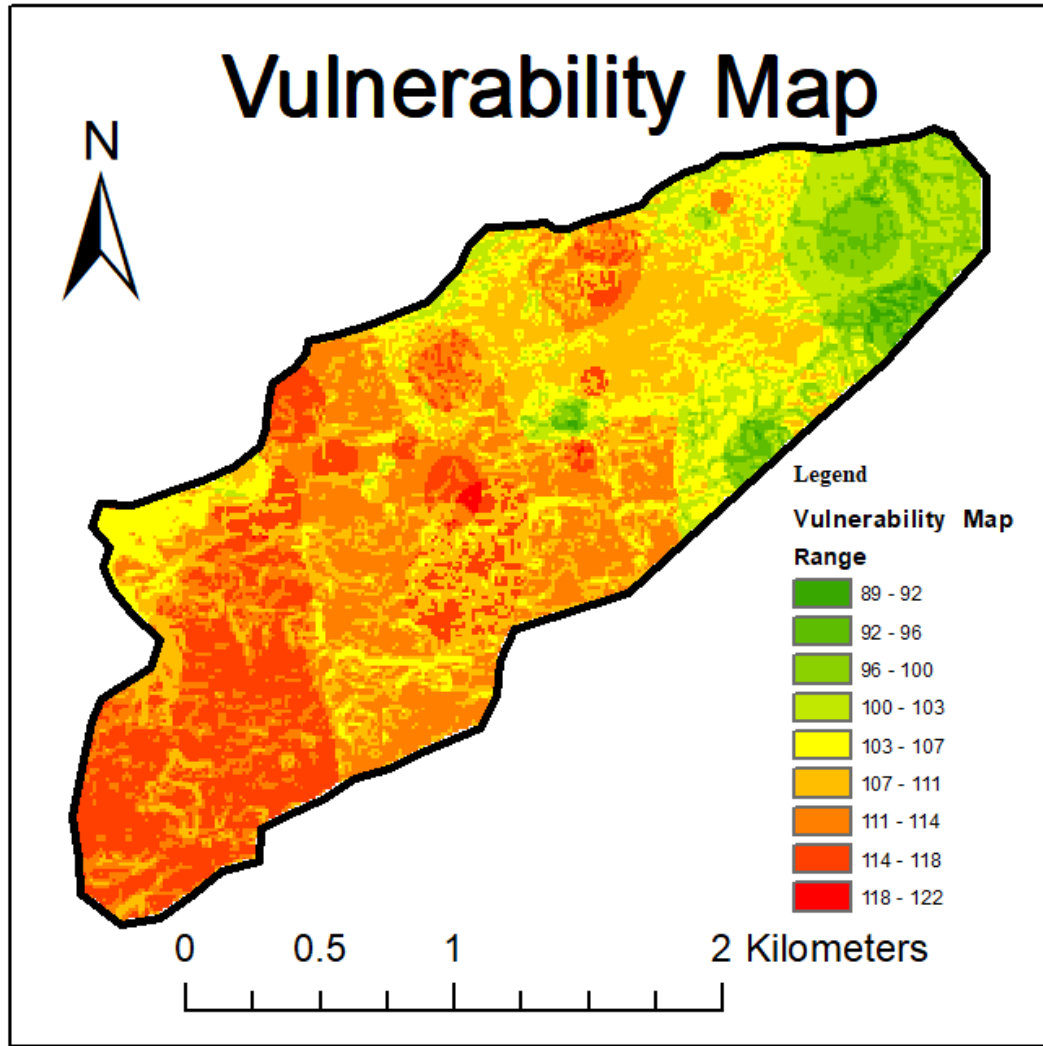


Figure 4.13: Vulnerability Map of Yeşilköy aquifer according to original DRASTIC method.

The vulnerability map can be reclassified into definite ranges so that regional vulnerability can be assigned for Yeşilköy Aquifer. In order to do so, there is no recommended classification index table. Therefore, the reclassified DRASTIC index map was created using the scale suggested by Angle, (1995). The suggested scale was previously mentioned in Table 3.5. Angle (1995) suggested that in cases where DRASTIC index value (DIV) is less than 100, the aquifer can be accepted to be in low vulnerability class. On the other hand, DIV values in between 100-140, the aquifer can be accepted as medium vulnerable to the environmental risks. According to Table 3.5, 8.3% of the studied area can be categorised as “Low vulnerable”, and 91.7% of the

studied area can be categorised as “Medium vulnerable”. Figure 4.14 depicts that most of the aquifer is medium vulnerable, but the vulnerability of the North-East region is less than other regions. The findings of this study through DRASTIC methodology, has shown that, the Yeşilköy aquifer in total is medium vulnerable for environmental risks. On the other hand, there are environmental risks ongoing at the study area. These risks are fertilizers used during the agricultural activities, lack of sewerage system for the settlements in the area (buried septic tanks are active), and, solid waste dumping areas in and around the aquifer replenishing area. Although the vulnerability of the aquifer is at medium levels, hereafter, the impact of these pollution sources on the aquifer system will be studied and their negative effects will be investigated.

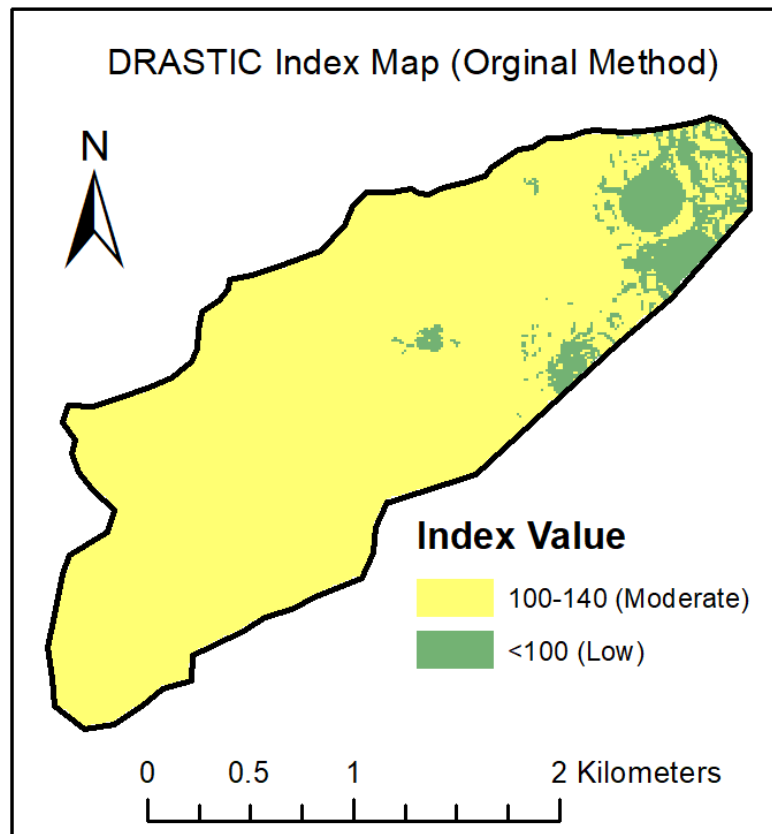


Figure 4.14: DRASTIC index map relative to Angle (1995).

4.3 Nitrate Presence in Groundwater

Nitrate was frequently chosen as an indicator for assessing groundwater pollution risk (Huan et al., 2012). Nitrate is mostly found in nitrogen fertilizers, domestic sewage, livestock waste, and industrial production. Nitrate contamination in groundwater systems can endanger humans, livestock, and the environment. Likewise, the presence of nitrate in aquifer is considered to be a signal of groundwater quality deterioration (He et al., 2017). Excess nitrate in the human body can induce thyroid disorders and methaemoglobinnaemia in bottle-fed infants. Methaemoglobinaemia occurs in humans as a result of nitrite reacting with haemoglobin in red blood cells to generate methaemoglobi, which binds oxygen strongly and does not release it, hence inhibiting oxygen transport (WHO, 2004). Studies have shown that, the presence of nitrate in water above a certain concentration causes colorectal cancer and bladder cancer (Temkin et al., 2019). In addition, it has been demonstrated that high nitrate levels increase the risk of anencephaly (lack of formation of the brain skull bone) (Manassaram et al., 2006).

Water samples were collected from 25 wells during the irrigation period of the farmlands while all the wells were actively pumping water from the aquifer. The samples were then analysed for chemical and microbiological composition in the TRNC State Laboratory. The analyses show that nitrate content was available in all of the wells varying from 2 mg per litre to 183 mg per litre. The Nitrate content at each well is given in Table 4.8.

Table 4.8: Nitrate (NO₃) content of the sampled wells.

<i>Order No.</i>	<i>Well name</i>	<i>Nitrate (NO₃) (mg/L)</i>
1	YK 97	2
2	YK 73	19
3	YK 71	1.1
4	YK 7	128
5	YK 65	47
6	YK 45	38
7	YK 4	52
8	YK 36	11
9	YK 32	15
10	YK 27	52
11	YK 24/27	65
12	YK 17	2
13	YK 163	99
14	YK 15	61
15	YK 131	45
16	YK 13	1.5
17	YK 117	86
18	YK 116	183
19	YK 11	6
20	YK 108	169
21	YK 107	41
22	YK 1060	152
23	YK 1040	47
24	YK 103	31
25	YK 1005	25

While nitrate originates naturally in groundwater, intensities larger than 3 mg/l often indicate pollution, whereas a more recent USA based investigation showed that concentrations greater than 1 mg/l indicates human induced pollution (American Environmental Protection Agency (USEPA)). The nitrate limit determined by the World Health Organization (WHO) for drinking water is 50 mg/l. The USEPA determined the quantity of nitrate in drinking water to protect babies against methemoglobinemia to be 10 mg/l. Based on WHO nitrate limit, 15 wells were still below the threshold nitrate level in Yeşilköy aquifer. There are ten wells above the

critical threshold value, and they are all located in the aquifer's north-northwest region. Places with a high concentration of nitrate pollution are considered to be more inhabited. The high nitrate values such as 128.0, 169.0, and 183.0 mg/l indicate that groundwater use in Yeşilköy regions is quite dangerous for human health. Considering these limits of countries such as America and Canada, where the nitrate limit is determined by 10 mg/l, the use of water in almost all of the aquifer carries health risk.

Using the sampled nitrate values the nitrate distribution map for Yeşilköy aquifer is mapped as shown in Figure 4.15. The map depicts that although the south and south-west part of the aquifer, where aquifer is medium vulnerable, is not severely affected from Nitrate pollution, north and north-east region seems to be affected by nitrate and carries high health risks. In order to see the severe influence of nitrate pollution in aquifer, the nitrate distribution map is reconstructed showing the areas where nitrate content is above 50 mg/l (Figure 4.16). The results show that 16 % of total aquifer area is under the risk of nitrate pollution containing higher than 50 mg/l. In addition, based on the sampled data, the nitrate content in 97% of the aquifer exceeds 10 mg/l (Figure 4.17). Only 3% of the entire region has nitrate concentrations below 10 mg/l. Moreover, based on the available data, if regions exceeding 1% nitrate concentration are regarded an indication that human activities affect groundwater, it is clear that these activities impact the entire groundwater. Nevertheless, even though the Yeşilköy aquifer itself is a medium vulnerable for environmental polluters, the results prove that, the artificial activities related with nitrogen pollution has vast impact on the quality of the aquifer.

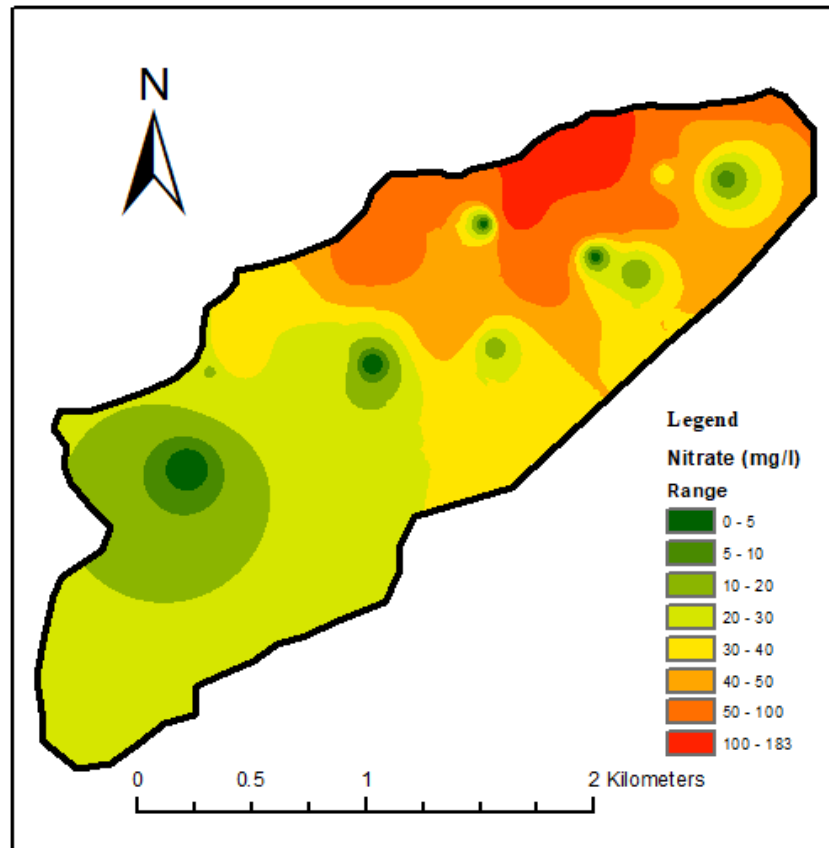


Figure 4.15: Nitrate component map of Yeşilköy aquifer.

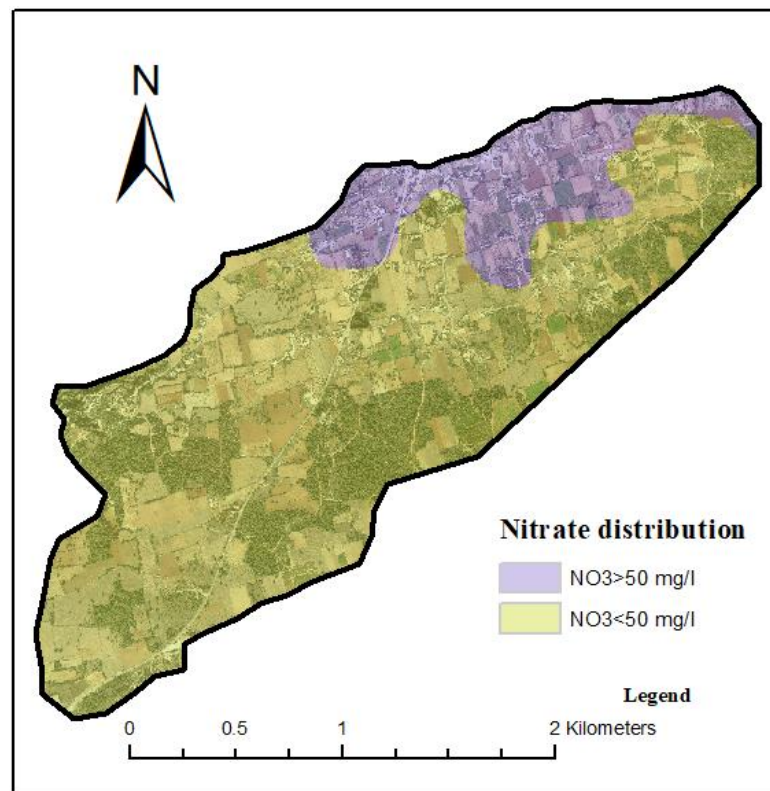


Figure 4.16: Nitrate content map of Yeşilköy aquifer indicating the regions where nitrate content is greater than 50 mg/l.

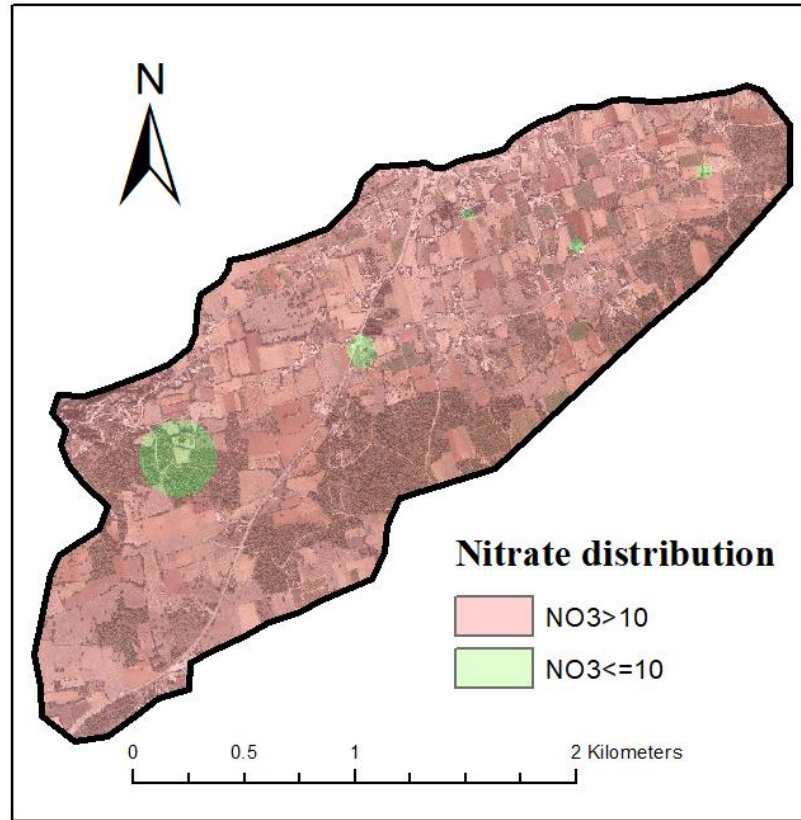


Figure 4.17: Nitrate content map of Yeşilköy aquifer indicating the regions where nitrate content is greater than 10 mg/l.

4.4 Results of Chemical and Microbiological Analyses

Within the scope of this study, samples were taken from 25 wells and 26 analyses were carried out. The distribution of wells in which samples were collected are shown in Figure 4.18. Among these analyses, 23 of them were chemical analyses and 3 of them were microbiological analysis. Totally 26 different parameters were expected to be detected but, Phosphate, Bromate, Carbonate, Lithium and Ammonium were not found in any of the samples taken from the wells. The remaining 21 analyses were detected in varying amounts for each well. These 21 physio-chemical are; Nitrite, Nitrate, Conductivity, Mercury, pH, Chloride, Bromide, Calcium, Fluoride, Sulphate, Bicarbonate, Sodium, Potassium, Magnesium, Salinity (as NaCl), Carbonate Hardness (as CaCO_3), Permanent Hardness (as CaCO_3), Total Hardness, Coliform, E. Coli, and Enterococcus Bacteria. One of the interesting and important outcome was the

observation of microbiological contaminants within the samples gathered from most of the wells. Bacteria were identified in all of the wells. Especially coliform bacteria were found in large numbers, mainly over 2400. For groundwater resources, the most common bacteria source is the soil around the recharging region. The bacterium is typically caused by pollution from an adjacent sewage tank, feedlot, feed storage area, or livestock yard. These bacteria can trigger gastrointestinal illnesses, diarrhoea, and vomiting. Mercury (Hg), as a heavy metal element were found in the range of 0.03 µg/l to 0.07 µg/l from the samples taken from 6 different wells. Mercury may be introduced to the soil via fertilizers. Mercury concentrations were evaluated in a number of standard fertilizers, with calcium superphosphate having the greatest content (5.1 mg/kg) and nitrogen-phosphorus-potassium fertilizer having the lowest concentration. (Zhao and Wang, 2010). The pH value measured in the wells was found to be 7.4 on average and the OH⁻ ions were slightly higher. Since the pH value is in the range of 6.5-8.5, it is at a normal level according to WHO standards. Conductivity results range from 905 µS/cm to 1990 µS/cm, none of which exceeds the 2500 µS/cm threshold. Indicating the prevalence of sulphate in the wells, the critical threshold of 250 mg/l (WHO) was determined to be surpassed in a single well (YK-17) with a value of 485. Considering the total hardness values of the samples taken, these values vary between 0 mg/l and 754 mg/l, and the average value was determined as 370 mg/l. Chloride levels range from 101 mg/l to 405 mg/l, with an average of 192 mg/l. The sulphate value varies between 8 mg/l and 485 mg/l, and the average value is 55.08 mg/l. The magnesium content varies between 21 mg/l and 107 mg/l, and the average value is 45 mg/l. The bromide existence varies between 375 µg/l and 1595 µg/l, with an average of 674 µg/l. The presence of the calcium mineral is between 39 mg/l and 127 mg/l and the average value of 79,84 mg/l.

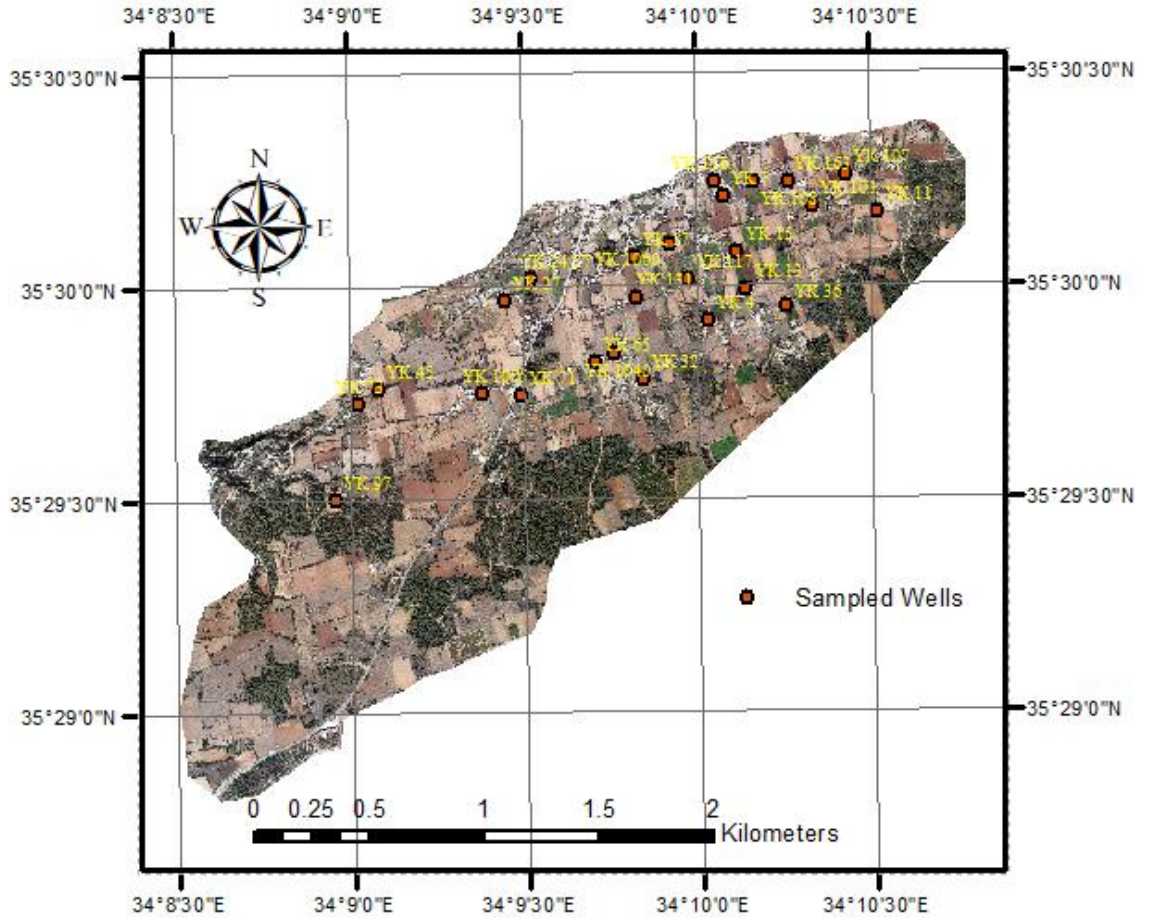


Figure 4.18: Yeşilköy Aquifer and sampled wells.

4.5 Water Quality Index Analyses

The WQI was calculated using the chemical and microbiological data obtained, which are important in terms of evaluating water quality. For this purpose, a total of 11 parameters, one of which is microbiological (Coliform bacteria existence) were selected. These parameters are as follows, Nitrate, Conductivity, pH, Chloride, Bromide, Sulphate, Sodium, Magnesium, Calcium, Total hardness, and Coliform. WQI was calculated using the Weighted Arithmetic Method. The result of WQI for the given 11 parameters was 73. The summary of the WQI method using the Weighted Arithmetic Method is given in Table 4.9. Based on the scale given by Bouslah et al., (2017) (Table 3.7) the WQI range and quality status is referred to as "*Poor Water Quality*" and is classified as "*C*". The main factor for the Yeşilköy aquifer to have such

a poor water quality is the high amount of Nitrate and Coliform. In addition, WQI distribution along the aquifer is mapped by using the ArcGIS tool and classification according to the quality of water is investigated as shown in Figure 4.19.

Figure 4.19 depicts that, the region of "*Poor water quality*" running from the northeast to the south of the aquifer, as well as a relatively minor area on the southwest side. The remaining fractions are primarily categorized as "*Very poor water quality*". Furthermore, a very small section of the aquifer's north-northwest region is designated as "*Unsuitable for drinking water*". According to the classifications of "*Poor water quality*", "*Very poor water quality*" and "*Unsuitable for drinking purposes*" they occupied 37%, 58%, and 5% of the aquifer area, respectively. Figure 4.19 is drawn based on the water quality rating assigned at the locations of each well. Water quality rating at each well is given in Table 4.10.

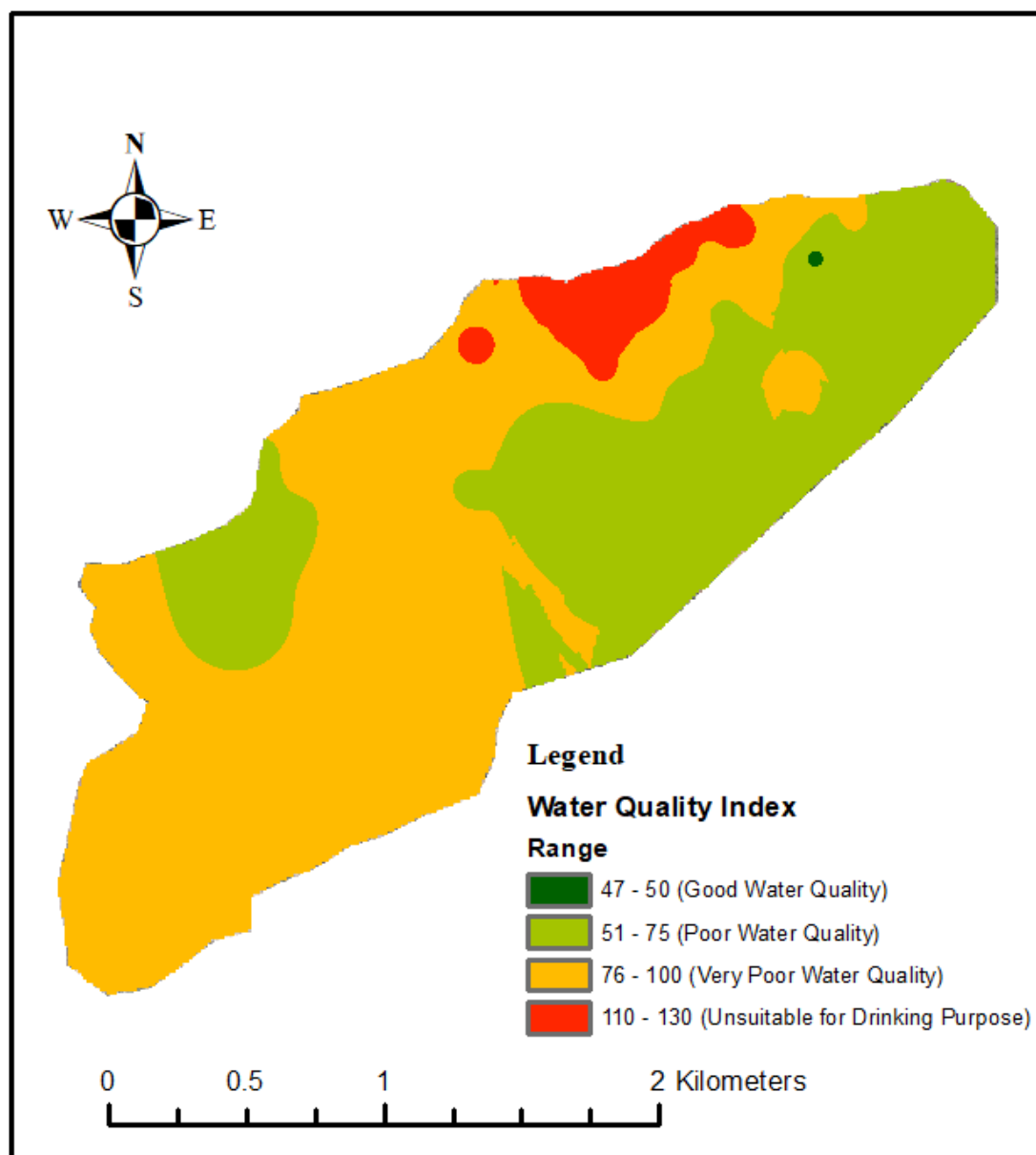


Figure 4.19: Water Quality Index results.

Table 4.10: Water Quality rating at the locations of each well

Well name	Rating Water Quality
YK 97	Poor water quality 'C'
YK 73	Poor water quality 'C'
YK 71	Poor water quality 'C'
YK 7	Very poor water quality 'D'
YK 65	Good water quality 'B'
YK 45	Very poor water quality 'D'
YK 4	Poor water quality 'C'
YK 36	Very poor water quality 'D'
YK 32	Poor water quality 'C'
YK 27	Very poor water quality 'D'
YK 24/27	Unsuitable for drinking purpose 'E'
YK 17	Unsuitable for drinking purpose 'E'
YK 163	Very poor water quality 'D'
YK 15	Poor water quality 'C'
YK 131	Unsuitable for drinking purpose 'E'
YK 13	Poor water quality 'C'
YK 117	Very poor water quality 'D'
YK 116	Unsuitable for drinking purpose 'E'
YK 11	Poor water quality 'C'
YK 108	Unsuitable for drinking purpose 'E'
YK 107	Very poor water quality 'D'
YK 1060	Unsuitable for drinking purpose 'E'
YK 1040	Poor water quality 'C'
YK 103	Good water quality 'B'
YK 1005	Very poor water quality 'D'

WQI index was obtained for each well and the results were compared with Drastic Vulnerability Index (DVI). For this purpose, the regression analysis method was used and the R^2 values obtained were taken as a basis. Accordingly, the regression value R^2 was found to be 0.096, indicating that no WQI-DVI relationship exist (Figure 4.20). Likewise, no relationship was observed in DVI- NO_3 comparison as shown in Figure 4.21.

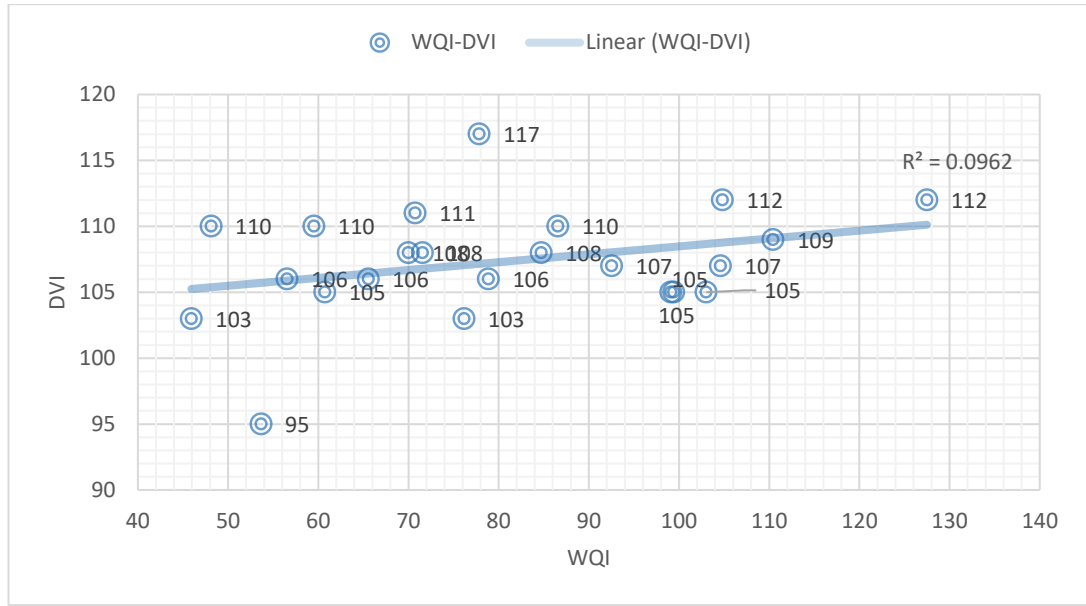


Figure 4.20: The relationship between WQI and DVI by using original DRASTIC method.

The presence of excessive NO_3 , which was utilized as an indication for understanding the DRASTIC vulnerability assessment, in particular, might be worth investigating, as no linear association was identified in the context of DVI- NO_3 regression analysis. The main reason for extreme un-relatedness may be the absence of any regular wastewater system or sewage treatment system in the Yeşilköy aquifer area. In addition, the massive fertilizer consumption in the region can increase the vulnerability of the aquifer. Also, considering that sewage is produced more and stored in septic tanks in the area where the settlement density is high, it should not be surprising to find high NO_3 content especially in the north-eastern part of the aquifer. Furthermore, despite the fact that the water table of the Yeşilköy aquifer descends to an average depth of 65 meters below the surface, high nitrate content in particular locations may imply that nitrate reduction and denitrification capability are active up to a certain depth.

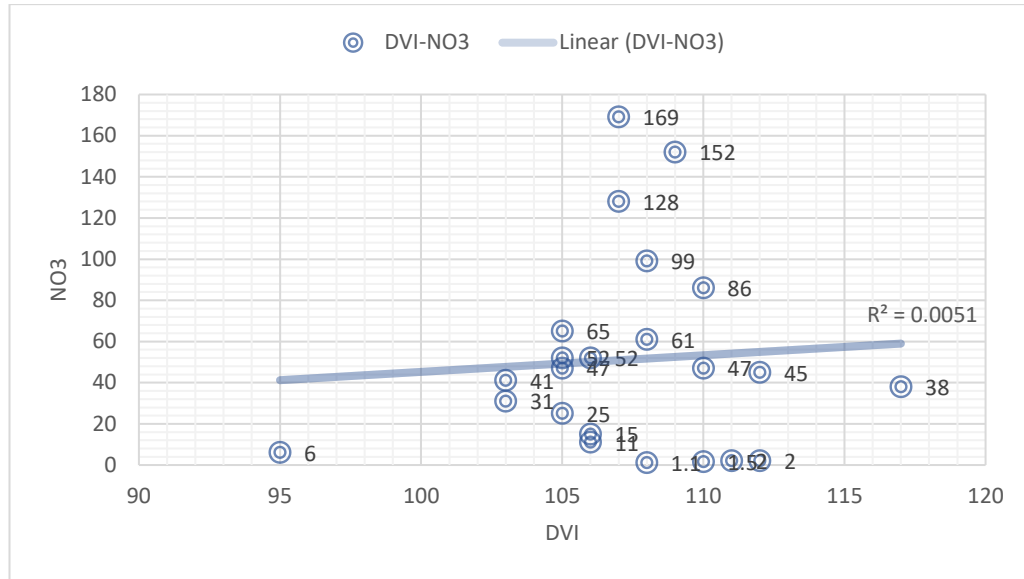


Figure 4.21: The relationship between NO₃ and DVI by using original DRASTIC method.

4.6 DRASTIC-AHP

Within the scope of this study, it is clear that, the vulnerability map derived by original DRASTIC model does not reflect the existing physical conditions. Although the DRASTIC model assigns moderate vulnerability for the Yeşilköy aquifer, the heavy agricultural activities, and the lack of sewerage system within the settlements polluted the aquifer more than it was expected. Therefore, new vulnerability map must be worked out to reflect the available environmental conditions in the aquifer system. Such more acceptable groundwater vulnerability map can be generated by using AHP and changing the rate and weight values specified in the original DRASTIC model. For this purpose, new weight and rate values were obtained by considering the original conditions of the aquifer. The new weight and rate values assigned are shown in Table 4.11 and Table 4.12. Physical conditions such as the aquifer's "Water Depth" parameter malfunctioning and the fact that the "Vadose Zone" comprises of many strata were considered when assigning new weight and rate values. "Pairwise comparison matrix", that ranks the priority of each parameter with respect to others is

given in Table 4.11 and helps to assign new weight values for each parameter of DRASTIC model. For the ranges (sub-classes) of all parameters, the same procedure was used to generate a pairwise matrix. Table 4.12 lists the new weights and rates that were calculated. As anticipated, employing AHP enhanced the influence of the Vadose zone (I) and Aquifer media (A), while decreasing the effect of the water Depth (D) parameter. In terms of other parameters, no substantial changes were made. The results of modified DRASTIC model are then used to generate the new vulnerability index map of the Yeşilköy aquifer. The new index distribution over the aquifer area is given in Figure 4.22.

Table 4.11: Pairwise comparison matrix for AHP.

	Groundwater depth	Net recharge	Aquifer media	Soil media	Topography	Impact of vadose zone	Hydraulic conductivity
Groundwater depth	1	1/2	1/4	3	2	1/5	1
Net recharge	2	1	1/2	2	2	1/3	1
Aquifer media	4	2	1	5	6	1/2	4
Soil media	1/3	1/2	1/5	1	3	1/4	3
Topography	1/2	1/2	1/6	1/3	1	1/7	1/3
Impact of vadose zone	5	3	2	4	7	1	3
Hydraulic conductivity	1	1	1/4	1/3	3	1/3	1

Table 4.12: Sub-Classes, the new rates and weights obtained by using AHP.

<i>Parameters</i>	<i>Sub-Classes (Ranges)</i>	<i>AHP Rating</i>	<i>AHP Weight</i>
Depth of Water (D)(m)	40-50	0.59	0.09
	50-60	0.26	
	60-70	0.11	
	70-80	0.05	
Net Recharge (R) (mm)	254<	0.47	0.11
	178-254	0.26	
	102-178	0.14	
	51-102	0.08	
	0-51	0.04	
Aquifer Media (A)	Calcarenite	0.10	0.26
	Calcarenite with silt	0.05	
	Sandstone	0.63	
	Sandstone with silt	0.22	
Soil Media (S)	Loam	0.33	0.09
	Sandy Loam	0.67	
Topograpy (T) (%)	0-3.27	0.31	0.04
	3.27-6.24	0.22	
	6.24-9.50	0.15	
	9.50-13.06	0.11	
	13.06-17.22	0.08	
	17.22-23.15	0.05	
	23.15-32.35	0.04	
	32.35-47.78	0.03	
	47.78-76.00	0.02	

<i>Parameters</i>	<i>Sub-Classes (Ranges)</i>	<i>AHP Rating</i>	<i>AHP Weight</i>
Impact Vadose Zone (I)	Calcarenite+Limestone+Marn	0.04	0.33
	Calcarenite+Marny Sandstone	0.03	
	Calcarenite+Limestone+Marn+Sandstone	0.06	
	Calcarenite+Limestone+Sandstone	0.17	
	Limestone	0.08	
	Calcarenite+Sandstone	0.29	
	Calcarenite+Limestone	0.13	
	Calcarenite+Sandstone+Marn	0.04	
	Calcarenite	0.16	
Conductivity (C)	0.026-0.055	0.31	0.08
	0.055-0.085	0.22	
	0.085-0.114	0.15	
	0.114-0.144	0.11	
	0.144-0.173	0.08	
	0.173-0.203	0.05	
	0.203-0.233	0.04	
	0.233-0.262	0.03	
	0.262-0.300	0.02	

Figure 4.22 shows the reclassified thematic maps created by inserting the rate data for each parameter into the GIS environment. Thus, vulnerability index map is obtained as shown in the Figure 4.23.

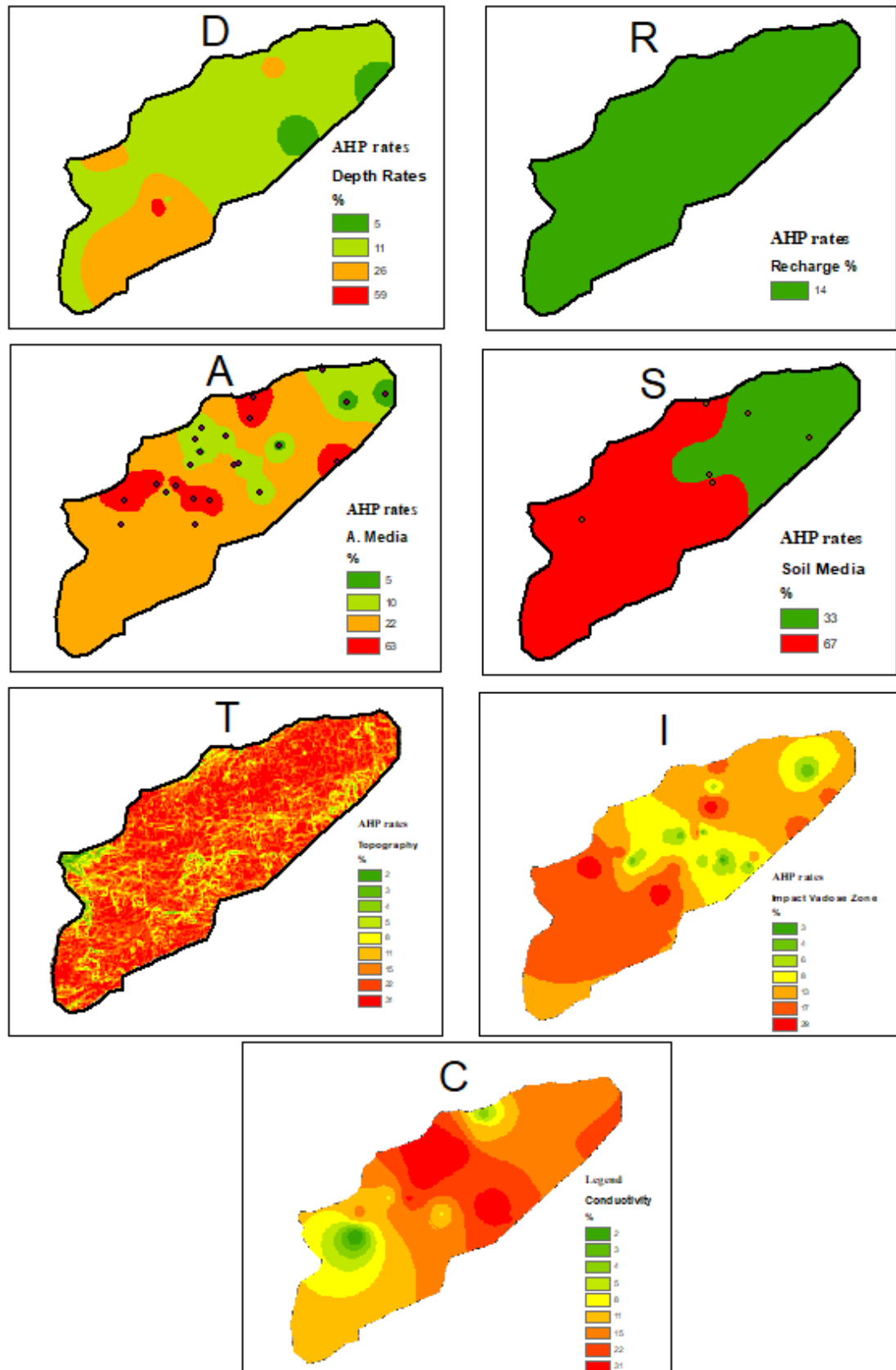


Figure 4.22: Reclassified thematic maps reconstructed with AHP.

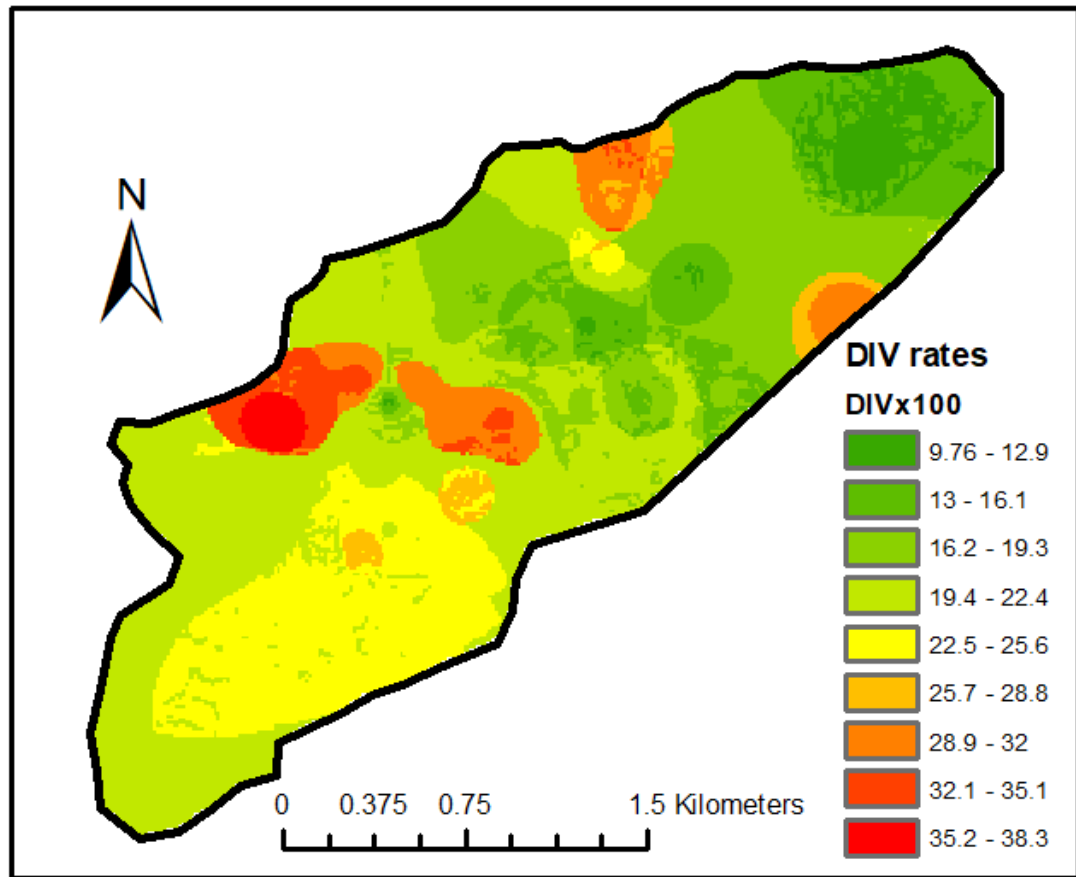


Figure 4.23: Vulnerability Index Map obtained by using AHP to modify the weights of DRASRIC model.

DVI values calculated using the DRASTIC method, modified by AHP, were compared to WQI and the existence of NO_3 relation. It is seen in Figure 4.24 that modification of DRASRIC model with AHP increased apparently the DVI-WQI relationship ($R^2=0.55$) However, as before no relationship was found between nitrate concentration and modified DVI as seen in Figure 4.25.

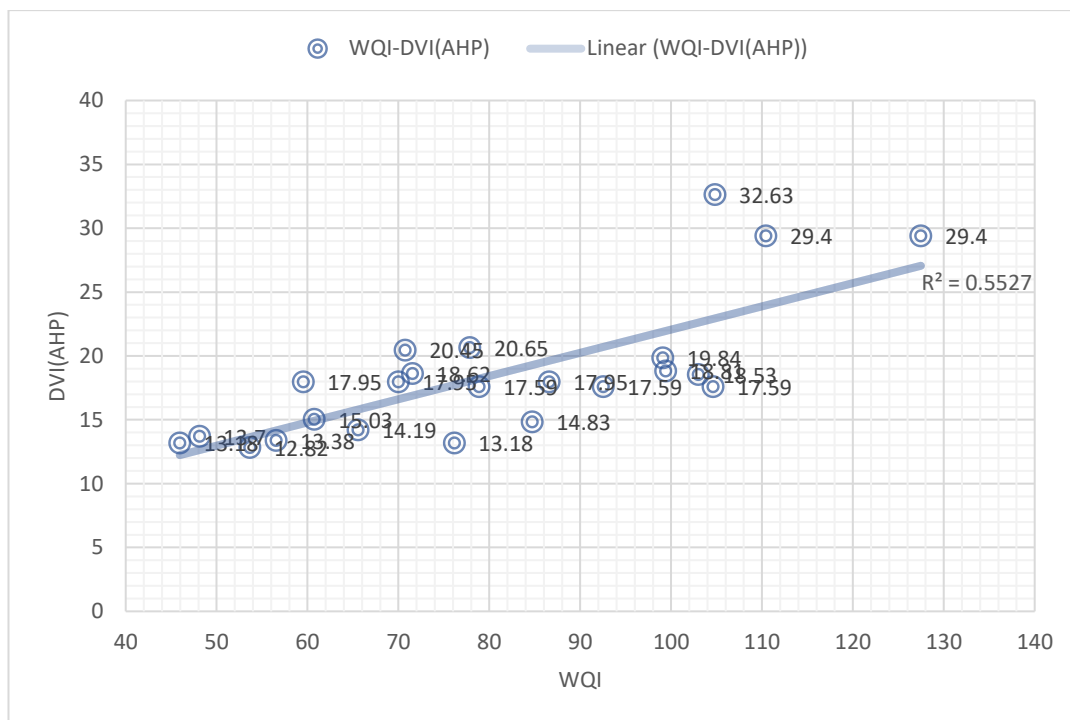


Figure 4.24: The relationship between WQI and DVI by using modified DRASTIC method.

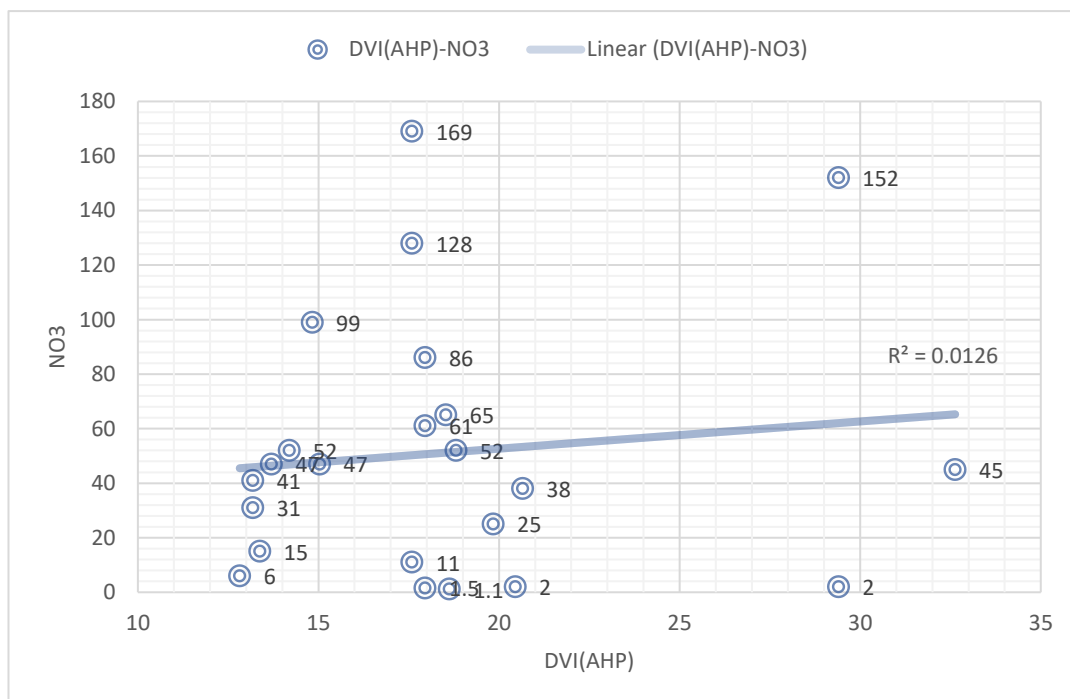


Figure 4.25: The relationship between NO_3 and DVI by using modified DRASTIC method. HP.

4.7 Discussions

The modified DRASTIC model built with AHP was provided as an alternative to the original DRASTIC method. Several chemical and microbiological water quality analyses were performed, particularly the presence of nitrate in groundwater, and WQI were investigated based on samples taken from different wells. There was no concordance between the nitrate values anticipated at the commencement of the study and the "Vulnerability index" values. The modified DRASTIC model established with AHP and the water quality index, on the other hand, were in coherent.

This study, which has been the subject of multiple previous studies (Karan et al., 2018, Saranya & Saravan, 2022), has provided additional support that by modifying the weight and rates of the DRASTIC with AHP, the degree of accuracy can be strengthened. Likewise, a positive correlation value with the WQI data of the DRASTIC method modified with AHP was achieved.

The lack of a sewerage system and treatment facilities in Yeşilköy can be attributed to the incompatibility between DVI and nitrate readings. Such a dilemma can easily be attributed to natural and artificial impacts on the aquifer environment. The original DRASTIC model is built up on natural behaviour of aquifers, excluding the positive and negative effects of artificial impacts. Therefore, the impact of artificial pollution rates by any chemical or biological factors like Nitrate or Sulphate (Karan et al., 2018) does not have to follow similar trends or parallelism with DVI values.

The chemical and microbiological investigations have shown that the anthropogenic activities in the region seriously affect the quality and quantity of the aquifer. In addition, according to Türker et al. (2013) water level of the Yeşilköy aquifer was

expected to continuously decrease by around 0.6 meters per year. When monitored 14 years later, the water level, which was 55.5 meters on average in 2008, was found to be 64.5 meters on average. These studies indicate that, the Yeşilköy aquifer is being deteriorated both qualitatively and quantitatively. It should not be difficult to forecast that the Yeşilköy aquifer will be exhausted in the near future if the current conditions prevail.

Chapter 5

CONCLUSION

5.1 Conclusions

The present vulnerability condition of the Yeşilköy aquifer was evaluated and mapped using the DRASTIC method and GIS environment. Water quality index and nitrate concentration were tested and plotted on maps using both the original DRASTIC approach and AHP modified DRASTIC method. According to the original method, 91.7% of the aquifer is "Medium Vulnerable", the remaining 8.3% of them were classified as "Low vulnerable". Without generating a categorization, the AHP-modified method reveals that the mid-west and north-west zones of the aquifer are more vulnerable.

There was no correlation between the DVI findings produced using the original DRASTIC approach and the AHP modified DRASTIC method and the NO_3 concentration. The lack of an adequate correlation between the presence of nitrate in the aquifer and DVI is due to the absence of sewage and treatment systems at the regions where villagers' mainly settled. The nitrate pollution is so large that, even though the aquifer was medium vulnerable, nitrate concentration polluted the aquifer more than expected. Therefore, nitrate concentration has no significance in accuracy control of DRASTIC and AHP modified DRASTIC methods.

In addition, "Poor Water Quality" was identified for the whole Yeşilköy aquifer as a result of chemical and microbiological analyses performed on samples obtained from 25 wells and WQI assessed throughout 11 elements. A statistically significant relationship was found between the development of the DRASTIC method with AHP and the WQI. This situation allows for the following deductions.

- 1- It is a correct approach to set the weights of the "Vadose Zone" and "Aquifer Media" factors higher than the others when evaluating the Intrinsic Vulnerability of the Yeşilköy Aquifer in terms of the DRASTIC method.
- 2- The "Water Depth" criterion was less essential due to the aquifer water table's high distance from the surface.
- 3- It is the "Topography" parameter that has the least effect among the parameters.

The "DRASTIC Vulnerability Index Map," which is obtained by analyzing and adjusting numerous factors in the DRASTIC method and AHP approaches, is a map that can be assessed in terms of management to protect the Yeşilköy aquifer and minimize probable contamination. This study will assist regional planners and policymakers with sustainable ground water development and management.

5.2 Recommendations for Future Studies

This study is important for assessing the vulnerability of the Yeşilköy aquifer as well as defining the current status of the aquifer by examining various chemical and microbiological analyses. More frequent and regular chemical and microbiological analyses should be performed in this location, and the status of the groundwater should be regularly monitored. Although groundwater vulnerability maps give useful

information to users, the major source of information is tangible and up-to-date chemical and microbiological data.

For evaluating groundwater contamination risk from anthropogenic activities in general and determining a holistic strategy, vulnerability mapping of all aquifers throughout the island and a common pollution categorisation are required.

Many pollutants can be found in groundwater well data. The research must be conducted in order to create individual vulnerable maps for each pollutant.

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