

Threat Severity of the Seawater Intrusion in Güzelyurt Aquifer

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ABSTRACT

Groundwater is a dependable and easily treatable natural water resource crucial for civilizations with limited freshwater access. Overexerting pressure on these types of water resources might result in groundwater depletion and undesired chemical contaminants. Güzelyurt (Morphou) Aquifer has been suffering from depletion as well as Sodium Chloride (NaCl) contamination for more than 40 years due to the over-extraction of groundwater to supply the high demand. The necessity of a study focused on the degree of threat caused by the seawater intrusion phenomenon emerges after a huge change in the water balance within the study area originated in the form of the Water Supply Project (WSP), where 75 MCM freshwater is transferred to TRNC from Turkey annually. Initially, the water head contours and NaCl iso-chloride maps of the last 40 years were drawn. Additionally, these maps are used in the determination of seasonal saturated aquifer volume as well as seasonal average NaCl concentration. The aim of this study is to assess the trends of the seasonal time series generated using the maps computed, followed by a statistical model generation in order to forecast the year where the quality degradation and water table depletion will diminish or return to their ‘natural state’ using the existing datasets with significant trends. An additional evaluation criterion for the threat severity was the seawater intrusion velocity calculated using the salt balance equation. Out of the three time series with significant trends, only the wet season average NaCl concentration time series was suitable for forecasting using the developed statistical model. Using this time series, a reasonable recovery of the NaCl content of the groundwater resource was detected in 2029. Finally, the annual rate of seawater volume infiltration from 1980 to 2001 was

calculated as 5.57 m/year, whereas the 2001 - 2019 period was -3.46 m/year suggesting the dilution rate of groundwater concentration.

Keywords: Seawater Intrusion, Salt Balance Equation, Mann-Kendall's Test, ARIMA Modeling, Coastal Aquifer Management, Güzelyurt Aquifer.

ÖZ

Yeraltı suyu, su erişimi sınırlı olan medeniyetler için yüksek önem teşkil eden güvenilir ve kolayca arıtılabilir bir doğal su kaynağıdır. Bu tür su kaynaklarının üzerinde aşırı baskı uygulanması, yeraltı suyunun tükenmesine ve istenmeyen kimyasal kirleticilerin görülmesine neden olabilir. Güzelyurt (Morphou) Akiferi, yüksek talebi karşılamak için yeraltı suyu çekiminin aşırı olması nedeniyle 40 yıldan fazla bir süredir tükenmenin yanı sıra Sodyum Klorür (NaCl) kontaminasyonundan muzdariptir. Deniz suyu girişi olgusunun neden olduğu tehdidin derecesine odaklanan bir çalışmanın gerekliliği, çalışma alanı içindeki su döngüsünde meydana gelen büyük bir değişimin yani her yıl 75 MCM tatlı suyun Türkiye'den KKTC'ye transfer edildiği Su Temini Projesi'nin tamamlanmasının ardından ortaya çıkmıştır. İlk olarak, son 40 yılın su tablası konturları ve NaCl eşel seviye haritaları çizilmiştir. Ek olarak, bu haritalar doymuş akifer hacminin ve ortalama NaCl konsantrasyonunun belirlenmesinde kullanılmıştır. Bu çalışmanın amacı, anlamlı trendlere sahip mevcut veri kümeleri kullanılarak kalite bozulmasının azalacağı ve su seviyesinin iyileşmeye başlayacağı veya 'doğal durumuna' döneceği yılı tahmin etmek için istatistiksel bir model oluşturulması ve haritalar kullanılarak oluşturulmuş olan mevsimsel zaman serilerinin eğilimlerinin değerlendirilmesidir. Tehdit şiddet seviyesinin değerlendirilmesi için kullanılan diğer bir kriter ise tuz dengesi denklemi kullanılarak hesaplanmış olan deniz suyu giriş hızıdır. Anlamlı trendlere sahip üç zaman serisinden sadece yağışlı mevsim ortalama NaCl konsantrasyon zaman serisi, tahmin yürütmek için geliştirilen istatistiksel modelin kullanımı için uygun görülmüştür. Sadece ıslak mevsim ortalama NaCl konsantrasyon zaman serisi, istatistiksel model kullanımı ile tahmin yürütmek için kullanılmıştır. Bu zaman serisi kullanılarak, yeraltı suyu kaynağının NaCl

içeriğinin makul bir şekilde geri kazanılmasının 2029 yılı olduğu belirlenmiştir. Son olarak, 1980-2001 yılları arasında deniz suyu hacminin yıllık azalma oranının 5,57 m/yıl olduğu hesaplanırken 2001 - 2019 döneminde yıllık azama oranının -3,46 m/yıl olduğu belirlenmiş ve bu negatif değerin yeraltı suyu konsantrasyonunun seyrelme oranını belirttiği kanaatine varılmıştır.

Anahtar Kelimeler: Deniz Suyu Girişimi, Tuzluluk Dengesi Denklemi, Mann-Kendall Testi, ARIMA Modellemesi, Kıyı Akiferi Yönetimi, Güzelyurt Akiferi.

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LIST OF SYMBOLS AND ABBREVIATIONS

$A_{(t+\Delta t)}$	Horizontal Cross-section Area of Saturated Aquifer at $t + \Delta t$
A_t	Horizontal Cross-section Area of Saturated Aquifer at t
B	Sen's Constant
C	Seawater NaCl Concentration
C	Constant
$C_{(t+\Delta t)}$	Groundwater NaCl Concentration at $t + \Delta t$
C_t	Groundwater NaCl Concentration at t .
C_t	Average NaCl Concentration at t
C_α	Coefficient Defined by Z Statistic, S Statistic, and α
D	Integrated Component of an ARIMA Model
D	Difference between Paired Ranks
DF_{CV}	Dickey-Fuller Critical Value
DW	Durbin-Watson Statistic
et	Sequence of Independent Normal Random Variables
$f(t_i)$	Monotonic Function
g	Number of Tied Groups
h^-	Average Saturated Aquifer Thickness
H_0	Null Hypothesis
H_1	Alternative Hypothesis
hf	Freshwater Head
m	Gradient

M1	Rank Given to the Q(i) within a Given Time Series Based On C_{α}
M2	Rank Given to the Q(i) within a Given Time Series Based On C_{α}
n	Number of Data
N	Number of Q(i) Estimates
p	Autoregressive Component of an ARIMA Model
P_A	Freshwater Pressure
P_B	Salt-water Pressure
Q	Moving Average Component of an ARIMA Model
Q(i)	Sen's Slope
r_d	dth Lag Sample Autocorrelation.
S	S Statistic
se	Standard Error
r_k	Spearman's Rank Correlation Coefficient
T	Time
t_i	Time Period
T_s	T Statistic
$V_{(t+\Delta t)}$	Saturated Aquifer Volume at $t + \Delta t$
V_s	Seawater Volume entering into the Aquifer
V_t	Saturated Aquifer Volume at t.
WM1	Weighted Mean 1
WM2	Weighted Mean 2
WM3	Weighted Mean 3
x_j	Seasonal Values in Year j

x_k	Seasonal Value in Year k
Y_t	Observations at t
z	Depth of Interface
Z	Z Statistic
$Z_{1-\alpha/2}$ ($-Z_{1-\alpha/2}$)	Z Statistic at Critical Zone
α	Probability of Rejecting H_0
β_1	a Constant obtained by MLE
γ_f	Freshwater Specific Weight
γ_s	Salt-water Specific Weight
δ	Constant Obtained by MLE
ε_i	Residual
θ	Constant Obtained by MLE
φ	Constant Obtained by MLE
ϕ	Coefficient of C_t
ϕ_{dd}	dth Lag Sample Partial Autocorrelation.
ACF	Autocorrelation Function
AIC	Akaike Information Criterion
ARIMA	Autoregressive Integrated Moving Average
DEM	Digital Elevation Model
DF	Dickey-Fuller Test
DSASC	Dry Season Average Salt Concentration
DSI	Devlet Su İşleri
KKTC	Kuzey Kıbrıs Türk Cumhuriyeti
LLF	Log-Likelihood Function
MAD	Mean Absolute Deviation

MAE	Mean Absolute Error
MAICE	Minimum Akaike Information Criterion Estimation
MAPE	Maximum Absolute Percentage Error
MCM	Million Cubic Meters
MLE	Maximum Likelihood Estimation
MTA	The General Directorate of Mineral Research and Exploration
NaCl	Sodium Chloride
ND	Normally Distributed
NND	Not Normally Distributed
PACF	Partial Autocorrelation Function
RMSE	Root Mean Squared Error
SAV	Saturated Aquifer Volume
SID	Su İşleri Dairesi
SRCC	Spearman's Rank Correlation Coefficient
SV	Seawater Volume
TDS	Totally Dissolved Solids
TRNC	Turkish Republic of Northern Cyprus
UNDP	United Nations Development Program
VAR	Variance
WSASC	Wet Season Average Salt Concentration
WSP	Water Supply Project
WSSAV	Wet Season Saturated Aquifer Volume

Chapter 1

INTRODUCTION

Hydrogeology is the science that deals with the occurrence, distribution, movement, consumption, conservation, and chemistry of groundwater (Freeze and Cherry, 1979). The subject also encompasses the development and management of the water within the rocks of the Earth's crust. In today's world, groundwater is one of the most important water resources for a civilization with limited access to freshwater. This type of natural resource is reliable and easy to treat as it is not significantly contaminated to begin with. However, there are cases where this reliable resource is heavily contaminated due to poor management. Even though the study of hydrogeology has been longstanding, poor management doesn't always come from a lack of knowledge. It comes from the lack of alternatives. An example is seen in Güzelyurt (Morphou) Coastal Aquifer. This research aims to contribute to the existing knowledge on the topic of the seawater contamination problem by determining the severity of the threat faced by the Güzelyurt Coastal Aquifer. Thus, this chapter will provide an introduction to the study by first discussing the background and context, followed by a definition of the research problem, aims, objectives, significance, and limitations of the study.

1.1 Earth's Water Resources

Earth's water resources are distributed throughout the planet in different forms and locations. These include air, surface, oceans, and groundwater. 97% of the water body available on Earth is seawater (Shiklomanov, 1998). The rest of the water is considered to be freshwater and approximately 30% of Earth's freshwater is considered to be

groundwater (Shiklomanov, 1998). The remaining 68.7% of the water remains in a solid state within glaciers and ice, whereas the rest of the freshwater is mostly on the surface stored in lakes, rivers... etc as presented in Figure 1 (Shiklomanov, 1998). Generally, groundwater can be identified as a renewable resource as it is considered to be a part of the hydrological cycle.

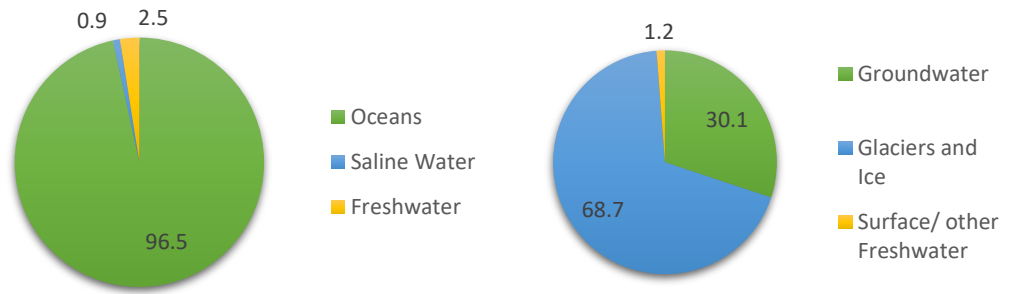


Figure 1: World's Freshwater Resources (Shiklomanov, 1998)

1.2 Climate of Güzelyurt Region

The climate of the island is a typical Mediterranean climate and is classified to be a semi-arid climate. In other words, it is hot and dry in the summers, whereas winters are generally mild with low to intermediate precipitation. Temperature and Rainfall datasets were provided by Meteorological Department of TRNC, 2011-2021 period was used to produce the following meteorological values. The station used to obtain these values is located 48.4 m above msl at 35°11N and 32°59E (Payab and Türker, 2018). According to the data available, July is considered to be the hottest month with the maximum average monthly temperature of 33.6°C -36.6°C. On the other hand, minimum average monthly temperature values around 3°C – 6.5°C are to be expected to be observed during the coldest month, January. The observed precipitation is seen on the island from October to March. This period is considered to be the wet season, whereas the April-September period is considered to be the dry season. Average

temperature in dry and wet seasons are 23.8°C and 14.1°C, respectively. Average Annual Rainfall of the last 10 years in this region vary from 163 mm to 463 mm which were observed in 2015-2016 and 2012-2013, respectively. 94% of this rainfall occurs during the wet season with an average of 295 mm. The rest of the 6% rainfall, which is observed during the dry season usually falls in April or September, average rainfall of the last 10 years in dry season was calculated as 35.7 mm. Average Annual Rainfall observed from 2011 to 2021 is 312.8 mm. The climate is similar throughout all the regions with minimal differences which is a result of the elevation difference caused by Kyrenia and Troodos Mountains. Compared to the total precipitation in millimeters, rainy days are less frequent than expected. This means that the duration where rain is falling is intense. Evaporation and evapotranspiration are higher during the dry season and lower during the wet season proportional to temperature. Approximately, 80% of the precipitation is lost to evapotranspiration (Ergil, 2000). Much like every other country with a Mediterranean climate, Cyprus also suffers from ephemeral streams and decreasing surface water storage.

1.3 Aquifer Water Budget

Even though groundwater is considered to be a naturally renewable water resource, the water budget of the aquifer must be balanced. In other words, simply the sum of the water which goes into the groundwater storage must be equal to the amount of water that is taken out from the aquifer. This balance can be maintained with good monitoring and management skills. The maximum amount of water to be extracted from an aquifer can be defined as the safe yield capacity of the aquifer. Once the extraction of the water is above the safe yield capacity, the water storage within an aquifer starts to deplete. The missing water within the budget is replaced by the system. In coastal aquifers, the replacement is mainly by seawater. The mix of seawater and

freshwater generates a saline groundwater body that contaminates the easily treatable groundwater. This process is known as seawater intrusion and it is a serious contamination problem threatening one of the largest aquifers in Cyprus, which is the Güzelyurt Coastal Aquifer.

1.4 Water Scarcity in Cyprus

When there is less of something, it will become more precious. Especially if this something is essential for all cellular organisms. In this small Mediterranean island, water is a commodity with an incredibly high value. The ideal water resources of a developed community can include;

- Surface water
- Wastewater
- Groundwater
- Seawater

These above-mentioned main four categories can all be found on the island, and treatment methods for all four are currently being used. Seawater and surface water treatment of massive scales to support the water requirement of the community was not an option. The drainage system and rainfall collection methods are not as sufficient as it needs to be to support large scale rainwater collection for treatment. As for seawater, the process of constructing and running a desalination plant is an expensive one. However, the seawater treatment methods have become less expensive over the years and is a decent option today for a large-scale water supply solution as the country is surrounded by the sea with an excess of seawater as a resource. However, the rich and easily treatable groundwater resources were used until the Water Supply Project

(WSP) was completed to supply the necessary municipal and drinking water needs of Famagusta, Nicosia and Güzelyurt as well as irrigation needs of Güzelyurt Area.

The water scarcity problem started in the early 1960s (Ergil, 2000). As the alternative water resources were not well utilized, the groundwater resources have been abused by over-extraction. Unfortunately, some of the coastal aquifers have experienced salination. Water Scarcity in TRNC is a product of;

1. Unrestricted water extraction
2. Increasing population
3. Water resources contamination
4. Salinization of coastal aquifers
5. Underutilized alternatives of the groundwater resources

1.5 A Brief History of Groundwater Resources in Cyprus

The early reports suggest that the springs were used to supply water for domestic and irrigational use (UNDP, 1970). Afterwards, aqueducts and numerous wells were used until the seventeenth and eighteenth centuries when chains of wells were constructed. Four main aquifers that were used for the water supply in Northern part of Cyprus. These are Famagusta Coastal Aquifer, Girne Aquifer, Yeşilköy Aquifer, and Güzelyurt Coastal Aquifer. Since the 1960s, Famagusta Coastal Aquifer is out of use due to high saltwater contamination, where citrus fruit cultivation was carried out until the 1960s (Gozen and Turkman, 2008). The rainfall received by Girne Karstic Aquifer receives the highest precipitation among the three, but most of the precipitation is lost to the sea in a short period due to its topography. This region has a balance between the annual extraction and the safe yield capacity and is replenished by around 10 MCM annually (Elkiran and Ergil, 2006). In the early 1920s, Güzelyurt Coastal Aquifer

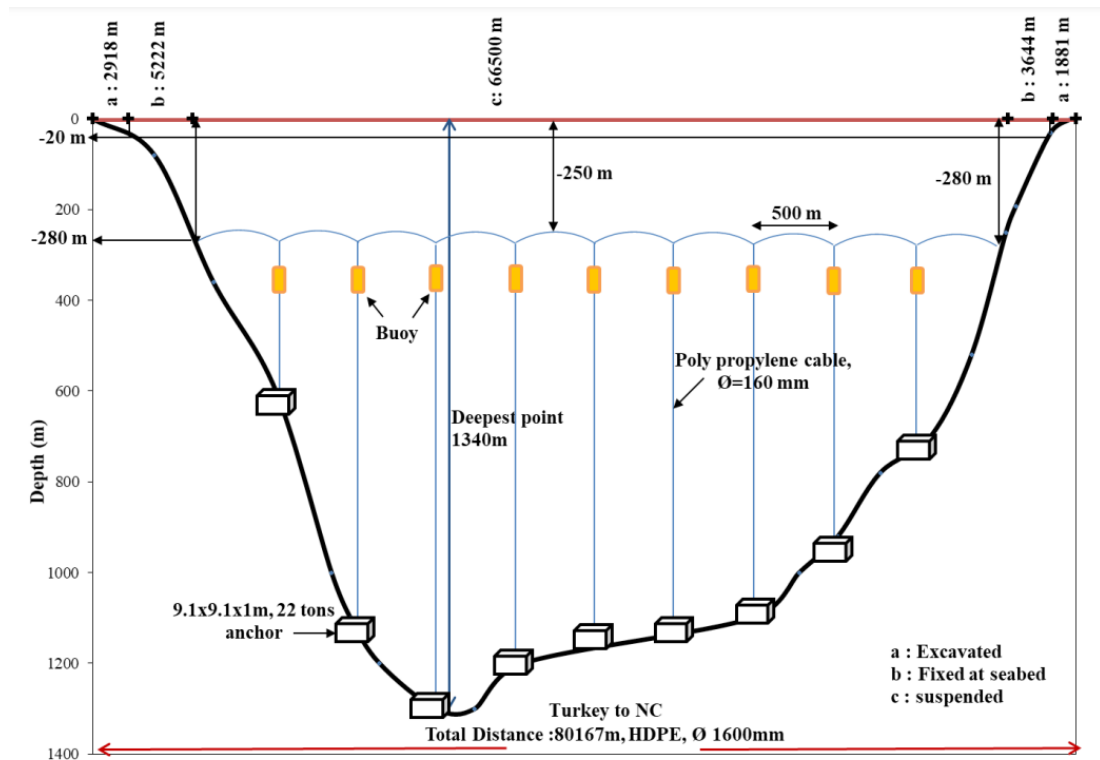
which is the main aquifer focused on this study was discovered by Beely Thompson(UNDP, 1970). This aquifer was found to have a sufficiently thick and wide extent allowing it to be classed as a first-class aquifer along with aquifers based around southeastern Mesaria and Akrotiri Peninsula which is located below Limassol (UNDP, 1970). The aquifer with the largest water body in TRNC. is the Güzelyurt Aquifer (Ergil, 2000). The area located south of Troodos mountains was found to have a surplus of groundwater. Whereas, Eastern Mesaria has insufficient groundwater to fulfill its agricultural potential (UNDP, 1970).

The first observations of seawater intrusion in Güzelyurt Aquifer were made in the 1960s (UNDP, 1970). Various reports suggested that serious aquifer salination could have been prevented by taking appropriate measures by 1970(UNDP, 1970). The earlier research predicted that uncontrolled seawater intrusion might become a source of demineralization, thus artificial recharge experiments must be made to refill the over-pumped aquifers. However, the intrusion was not controlled and thus the salinity (NaCl) levels rose significantly above 1000 ppm along the coast by 1977, more than 3000 ppm by 1987, and the 400 ppm boundary, being the accepted non-saline level, has significantly moved inland by 1997(Ergil, 2000). Furthermore, the water levels continued decreasing by more than 40 m below mean sea level (msl) by 1977 (Ergil, 2000). The economy of the TRNC community revolves around agricultural production and because of the salination and the higher pumping cost resulting from the lower water table in the aquifer, the annual cost of the production process has increased.

1.6 Water Supply Project (WSP)

The most recent attempt to solve the water scarcity problem in TRNC was the implementation of the water master plan prepared by the State Hydraulic Works (DSI)

of Turkey. The strategy involved the transfer of approximately 75 MCM of water by the construction of an underwater pipeline 250 m deep and 80 km long in the Mediterranean Sea from Alaköprü Dam located in Anamur, Turkey to Geçitköy Dam located on the coast of Kyrenia, North Cyprus as detailed in Figure 2 (Gungor, 2016). The project has been completed in 2016 and it is expected to have a durability of at least 50 years (Gungor, 2016). The management plan suggested that the water usage will be approximately 51% for drinking and 49% for irrigational purposes (DSI, 2003). However, the reality is a much different story from the theoretical management strategy. There have been intervals in the water delivery and there has been a period where the water in the Geçitköy Dam was almost depleted in 2020 (TGRT Haber TV, 2020). Additionally, there have been cases where the pipeline needed maintenance due to damaged pipes within the system. Regardless of the disadvantages, WSP is a unique solution strategy providing a much-needed opportunity to relieve some stress from the aquifer which has been under high stress for almost 60 years and implement an artificial recharge scenario to raise the depleted water table and improve the groundwater chemistry by making use of the excess available water. Aquifer recharge carries high importance, in addition to the solution provided to the water scarcity problem by the WSP (Yildiz and Cakmak, 2014).



1.7 Definition of the Problem

seawater intrusion (Ergil, 2000; Fanta, 2015; Demir, 2018). According to Demir, Fanta and Ergil, the drop in the water quality is most visible along the coast but effects of the contamination can be observed within the inner part of the aquifer as well. The quality and the quantity of water the aquifer has to provide have decreased significantly. This provides a threat to the economy of TRNC as the lack of quality water will result in decreased and inefficient crop production.

In 2016, the TRNC Water Supply Project was completed successfully. As of 2017, the TRNC community had 75 MCM of freshwater transported from Turkey to Cyprus yearly. The water available from this project is only used for municipal purposes. The main issue with the TRNC community right now is the proper management of water resources. In context, over-extraction of groundwater and less effective utilization of the freshwater is a result of poor water management. Previously, several strategies have been utilized to minimize water usage and maximize the recharge, However, the TRNC water supply project is the best opportunity for a long-term aquifer rehabilitation scenario (Gökçekuş, 2014). As a result, a detailed water management plan must be revised and put into action.

The latest research paper on the Güzelyurt Coastal Aquifer was written by C. Demir in 2017 before the TRNC water supply project was completed. This paper provided numerical models and predicted the state of the aquifer in different recharge scenarios. The research aims to observe the aquifer state and threat severity of the seawater intrusion.

1.8 Research Aims, Objectives & Questions

Given the lack of research regarding the Güzelyurt Aquifer's contamination situation after the water supply project's completion, this study aims to analyze the threat severity of the seawater intrusion phenomenon faced within the Güzelyurt Coastal Aquifer and provide the relevant management strategies to utilize the freshwater effectively. To achieve this goal, water table contours for dry and wet seasons were correlated as well as the sodium chloride (NaCl) iso-chloride lines of the equivalent seasons. Furthermore, the water table contour maps were used to calculate the variation of the total saturated volume of water within the aquifer, where the iso-chloride lines were used to determine the variation of the average NaCl concentration in ppm. After the estimation of an initial aquifer NaCl concentration and NaCl concentration of the seawater, the amount of seawater infiltrating the aquifer can be determined using the modified salt balance concentration equation.

The water table contour maps which will be used to determine the missing components of the salt balance concentration equation are correlated using SURFER Golden Software, Kriging data gridding method. To do so, 132 wells with consistent measurements of the 810 existing boreholes were used for each season, where the maximum amount of data was used where available since due to several reasons not always the same wells were measured. These borehole locations are presented in Figure 3. After the determination of every missing component, the balance equation was formed and the missing seawater volume entering the aquifer was computed. As a consequence, the seawater intrusion volume, the velocity, and the acceleration rate was determined.

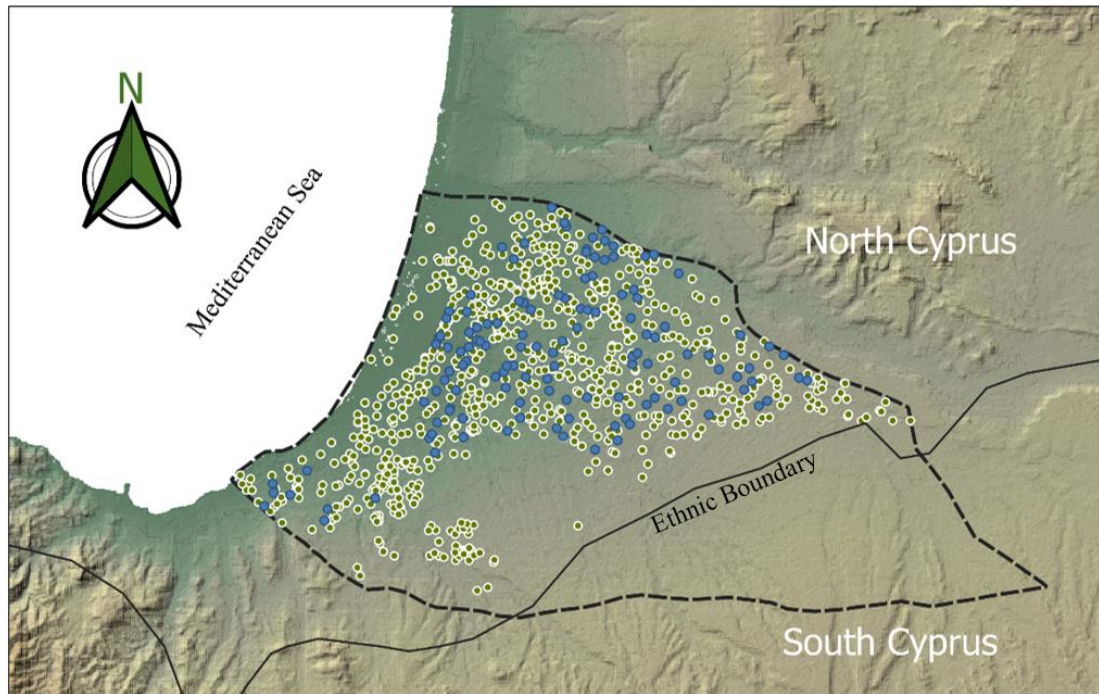


Figure 3: Areal Distribution of All the Wells Available within the Datasets used

In addition, after the establishment of the series using the obtained components of the salt balance equation, normality tests were done to select an appropriate trend analysis and statistical forecasting methodology for each separate time series. After the validation of the selected methods and models, each time series are subjected to trend analysis and forecasting as another objective of this study. As a result, an answer to the following research questions can be given by determining the research objectives;

- What is the updated water table depletion and quality reduction scenario?
- On which location does the seawater intrusion have the most significant effect?
- How much time is required to prevent further seawater intrusion on the groundwater body based on a trend analysis of the past 40 years?
- What is the up-to-date intrusion velocity?
- How can water resources management be improved?
- What are the suggested management strategies for minimizing the intrusion and recharging the aquifer?

Therefore, the four main objectives of this research are drawing water table contours and NaCl iso-chloride maps, calculating seawater intrusion by using salt balance equation, assessing the trends of the time series obtained from the maps by using appropriate time series analysis, and establishing and running an appropriate model for statistical forecasting.

1.9 Significance of the Study

This study will contribute to the body of knowledge on the specific coastal aquifer which is the focus of the study by implementing a modified version of a pre-existing solution strategy to the same study area after the environmental conditions have been altered. Additionally, the topic of hydrogeological water resources management will be expanded upon as the study will enroll a unique scenario of water transportation and usage unlikely to be seen at any other place on earth. The rapidly and significantly changing trends of the water balance equation components open up an interesting gap in the existing knowledge based on the aquifer's hydrology. Additionally, rather than a numerical approach, a statistical approach was used which was not used before for this study area. Thus, the study will help to address the current shortage of research in this area and provide real-world value to the particular departments of the TRNC government in operating the largest hydrogeological water resource on the island.

1.10 Research Limitations

Every research has its limitations, especially the ones with no budget and tight time constraints. One limitation of this study is the scope. The water budget equation can be expanded upon and different methods can be used to calculate the necessary components. Assumptions on the components of the hydrological cycle, the groundwater movement within the aquifer itself, calculation strategies for components like effective precipitation, evaporation, and evapotranspiration... etc. all depend on

the availability of the data and the budget to obtain the necessary data for the selected methodology.

Resource limitations of the project start with a time constraint of 1.5 years. In addition, the project's budget is zero. It is important to mention that the groundwater level datasets and salinity (NaCl) datasets obtained from the Geology and Mining Department did not match with the data obtained from Water Works Office (SID) as the gathered data observed. Thus, a process of elimination and combination between the two datasets was conducted. As a result, the reliability of the data used for gridding the maps was decreased. Furthermore, a total of 9 seasonal data was missing from the chemical analysis dataset, thus 2 different methods were used and the results were compared to fill the gaps in the missing data. Finally, even though the data was still present, the number of measurements taken from the boreholes in recent years was lower than the available borehole measurements in the previous years. This difference in the number of available borehole data resulted in shifts in the topographic contour lines, aquifer base contour map, and the water table contour maps of different periods.

The offered management strategies involve the WSP. Thus the management strategies cannot be applied to other water depletion or contamination scenarios in other parts of the world because the WSP is a unique scenario and most of the isolated islands do not get the opportunity to utilize a significant amount of water received from a nearby country. The management strategies may not be as generalizable. On the other hand, the salt balance concentration equation can be used in any other seawater intrusion scenario to determine the intrusion velocity, acceleration, and volume of the threat with an appropriate trend analysis.

Finally, as only 2/3 of the Güzelyurt Aquifer is located in TRNC and the rest is located in South Cyprus, the study only utilizes data available within the borders of TRNC. This effects the water table contour maps and NaCl iso-chloride maps constructed, in addition to the time series obtained using these maps.

1.11 Structural Outline

The research study starts with a brief review of the study area and the definition of its problems after a background of the field. The introduction chapter establishes the aims, objectives, importance, and limitations of the study. The following chapter is a literature review covering groundwater, salination mechanisms, hydrological cycle. Finally, literature on the previous studies and the attempted management strategies is reviewed.

The following chapter covers the key characteristics of the study area such as catchments, hydrogeology, dams, agriculture, and topography. After that, the research strategy will be determined, and the data analysis process will be defined in the methodology chapter. Theoretical framework and mathematical equations behind the Kriging process, salt balance equation, Mann-Kendall's Test, Sen's Slope Estimator, and ARIMA Modelling will be described. Furthermore, the research approach will be justified, research design and limitations will be discussed. The findings from all the tests are shown in the Results chapter. Furthermore, the results obtained will be used to commentate on the state of the aquifer and an appropriate set of mitigation strategies will be provided. Finally, recommendations for further study will be made. The final chapter will cover the study as a whole.

Chapter 2

LITERATURE REVIEW

2.1 Groundwater

In addition to groundwater having a decent quality before treatment, as a water resource groundwater is one of the most dependable among the alternatives (Freeze and Cherry, 1979). The groundwater body which is the focus of this study is stationed in Güzelyurt Plains based on the westernmost coast of the TRNC. The main usage of groundwater in this region is for agricultural purposes. Groundwater usage for irrigation is easy to control as the hydrological cycle is simplified. Maximizing crop production by effective groundwater usage is manageable in these types of scenarios.

Groundwater is always available even during dry periods. In general, groundwater is cleaner than surface water. This is because generally, water from the ground is less likely to be polluted. When groundwater is being recharged, the small voids above the aquifer apply a natural filtration process purifying the groundwater from all pathogenic bacteria after 15 meters of traveling (Todd and Mays, 2004). Additionally, groundwater can be accessed through wells where it is needed. On the other hand, where water transmission is through fissures, natural filtration does not remove the pathogenic bacteria (Todd and Mays, 2004). In communities where groundwater is highly utilized, the energy required to extract the water from boreholes must always be taken into consideration.

The mismanagement of water resources is the main reason behind the water scarcity problem in Cyprus. Water is a very limited and precious commodity. The increase in the scale of this problem is because the island is dependent on water both socially and economically (Gozen and Turkman, 2008). The scarcity problem is a serious constraint in front of the development of this developing country as most of the water resources are being directed into irrigation.

Aquifer salination is not a problem that humanity came across yesterday. This issue has existed long ago and even caused another aquifer of the community to be contaminated beyond use (Gozen and Turkman, 2008). Famagusta aquifer has been facing this problem since 1958 (Gozen and Turkman, 2008). In retrospect, the TRNC community was expected to realize the consequences of the problem and develop a better management plan to stop the same situation from happening again. The time it took the Turkish Cypriots to react and resolve the problem was a little later than expected. As a result, the annual pumping costs and water quality has dropped significantly due to low water head contours and increased NaCl contamination levels (Ergil, 2000).

2.2 Water Cycle

The water cycle process monitors the journey of water as it travels within Earth's atmosphere as it goes through different states as a result of a complex system (Günyaktı and Gürer, 2020). The main components of this system are;

- **Infiltration/Percolation:** Water flowing through the surface transfers underground and becomes a part of the groundwater storage or travels underneath the ground until it reaches the ocean (USGS, 2022).
- **Runoff:** Water traveling through the surface.

- Plant Uptake: Groundwater moves into plants.
- Evaporation/Evapotranspiration: The change in water state gradually happening from liquid to gas as it transfers from oceans, lakes, and rivers into the atmosphere is called evaporation (USGS, 2022). Evapotranspiration is water evaporating from plants to the atmosphere (USGS, 2022).
- Condensation: The gradual change in the state of water from gas to liquid within the atmosphere.
- Precipitation: Water falling back from the atmosphere to the surface. Precipitation can occur as rain, snow, sleet, or hail.

As represented in Figure 4, the main components of the water cycle related to the water budget of the groundwater body are evapotranspiration, precipitation, and infiltration. In addition, the water budget of an existing water body has other components which are the result of human actions rather than a natural system.

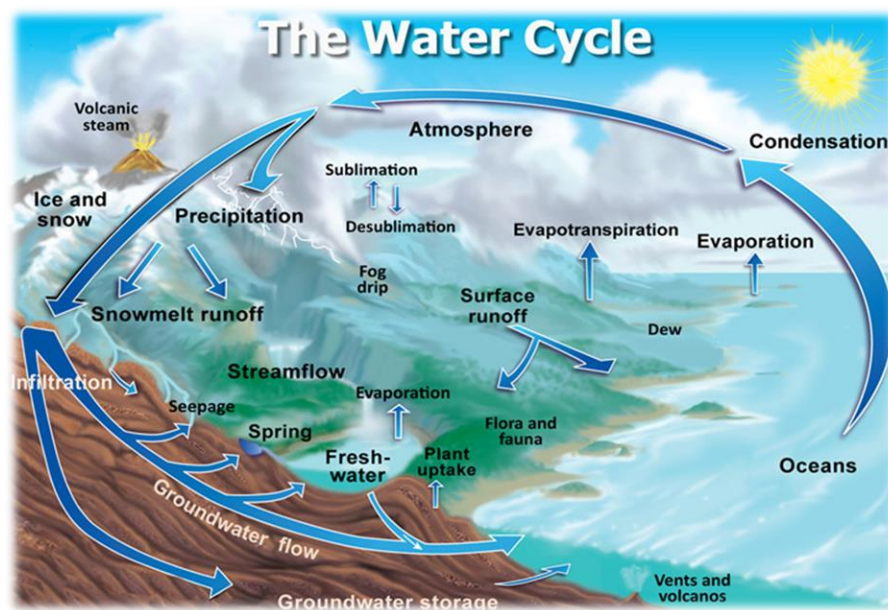


Figure 4: A Diagram of the Water Cycle showing Evaporation, Condensation, Precipitation, and more (USGS, 2022)

2.3 Aquifer Salination

Salts are common in all groundwater resources. The salination phenomenon is the displacement of fresh water by saline water. Depending on the environment, source, and movement of the groundwater, salts can be observed in different types and concentrations. In particular, the highest recorded Totally Dissolved Solids (TDS) content can be up to 300,000 mg/l in brines (Todd and Mays, 2004). On the other hand, salt concentrations less than 25 mg/l can be seen in quartzite springs (Todd and Mays, 2004).

The salinity level of the groundwater is generally measured as TDS in mg/l as detailed in Table 1. However, measurements can also be stated as the Chloride Content in mg/l or ppm. Where; 1 mg/l for TDS is 0.556 mg/l for Chloride Content. This study will use Chloride Content as NaCl being the main source of chemical pollution in this groundwater body.

Table 1: Water Salinity Classification

Water Type	Salinity (Chloride Content, mg/l)	Salinity (NaCl, ppm)
Fresh Water	0 - 556	0 – 1,000
Brackish Water	556 – 5,556	1,000 – 10,000
Saline Water	5,556 – 55,556	10,000 – 100,000
Brine	>55,556	> 100,000

(Freeze and Cherry, 1979)

Generally, fresh groundwater participates more actively in the hydrological cycle, thus freshwater is mostly present in shallower domains in the geological layer sequence (Cheng, Ouazar and Bear, 1999). As a result, fresh groundwater gets recharged more actively. As opposed to fresh water, a significant percentage of the saline groundwater is in a more stagnant state (Cheng, Ouazar and Bear, 1999). The majority of the saline

groundwater resides deeper within the strata (Cheng, Ouazar and Bear, 1999). As the participation in the water cycle is less cogent, saline water might have already been there for the majority of the aquifer's life span, resulting in a continuous dissolution of the geological strata and enriching the mineral content of the groundwater body (Cheng, Ouazar and Bear, 1999). As a result, the salinity level of the groundwater resource tends to increase as depth increases.

2.4 Salination Categories

Table 2 presents the water salination categories and mechanisms. The origins of groundwater salination are either Marine or Terrestrial (van Weert, van der Gun and Reckman, 2009). Firstly, Marine origin refers to seawater intrusion via different mechanisms. The typical NaCl concentration of seawater is 35000 ppm in Mediterranean (van Weert, van der Gun and Reckman, 2009). Whereas, naturally occurring groundwater generally has less than 400 ppm NaCl concentration (Ergil, 2000). The major difference between the relative NaCl concentrations results in a rapid increase in concentration levels.

In TRNC, Famagusta and Güzelyurt Aquifers can be categorized as A4.. The interaction between the sea and the coastal aquifer is a dynamic equilibrium that continues throughout the shoreline (van Weert, van der Gun and Reckman, 2009). Lateral seawater intrusion can be affected by surface water bodies reaching the sea, the route of surface water goes through inland estuaries and rivers to reach the outlet (van Weert, van der Gun and Reckman, 2009). Additionally, fresh groundwater resources being depleted for human use results in a decrease in the water head of the groundwater resource. In case of a negative water balance, the aquifer might not get enough replenishment. This can disturb the dynamic equilibrium by causing an up-

coning effect of the deep saline groundwater (Cheng, Ouazar and Bear, 1999). Thus, an inland movement of the fresh/saline groundwater interface is observed. Furthermore, a decrease in the rivers or estuarine flow might result in increased seawater intrusion. This can be seen in cases where the upward streamflow is prevented from discharging into the sea. The rapidity of this intrusion category depends on the hydraulic pressures and transmissivity of the aquifer (van Weert, van der Gun and Reckman, 2009).

Table 2: Saline Water Categories

Origin of the Class	Salination Mechanism	Environmental Conditions
A0 Marine Origin	A1 Connate Saline Water	Off-Shore Coastal Zone
	A2 Marine Transgression Intrusion	Off-Shore Coastal Zone
	A3 Intrusion by a Recent Flooding of the Sea	On-Shore Coastal Zone
	A4 Lateral Seawater Intrusion	On-Shore Coastal Zone
	A5 Intruded Seawater Sprays	On-Shore Coastal Zone
	A6 Mixture of A2 and A3	Off and On-Shore Coastal Zone
	A7 Mixture of A1, A2 and A3.	Off and On-Shore Coastal Zone
B0 Natural Terrestrial Origin	B1 Produced by Evaporation	Shallow Water Table in Arid Climate
	B2 Dissolution of subsurface salts	Salt Tectonics, Regional Halite, dissolvable formations
	B3 Salt filtering membrane effects	Thick sedimentary basins with semi-permeable layers
	B4 products of igneous activity	Regions with igneous activity
	B5 Mixture of B1 and B2	Shallow Water Table, Arid Climate, and Dissolvable formations
C0 Anthropogenic Terrestrial Origin	C1 Irrigation – Concentrated residual water	Arid, Semi-Arid zones, Shallow Depth
	C2 Anthropogenically Polluted groundwater	Anywhere, Particularly consumptive urban communities.
D0 Mixed Origin	A mix of A, B, or C-class mineralized groundwater	Anywhere

with freshwater or another
saline groundwater type.

(van Weert, van der Gun and Reckman, 2009)

The second class is natural or man-made terrestrial salination. Salination resulting from soluble materials in the geologic strata ie. B2 is very common. In fact, the thesis written by Gökçekuş suggests that some of the salination problem faced in Güzelyurt Aquifer can be categorized as B2 in addition to A4 (Gökçekuş, 1990).

2.5 Seawater Intrusion

Salt-freshwater issues are among the most significant practical issues with groundwater quality, particularly salt-water intrusion in coastal areas. The determination of the variation in the quality of the groundwater is generally necessary to solve this type of problem, thus it is important to look into how the chloride amount changes over time and space in the pertinent flow field. Since groundwater moves very slowly, it could take several years after pollution first began for the contaminated water to appear in a well. For the same reason, it could take a long time to clean up contaminated aquifers once the pollution's source has been effectively managed.

The flow of saltwater into freshwater aquifers caused by groundwater development is known as the saltwater intrusion phenomenon (van Weert, van der Gun and Reckman, 2009). The phenomenon is particularly a problem seen in freshwater aquifers which are hydraulically connected to seawater in coastal areas. Hydraulic gradients encourage the flow of seawater toward the pumped well or wells when significant amounts of freshwater are extracted from these aquifers, i.e., above the safe yield of the aquifer (Ergil, 2000). Since this issue impacts coastal regions all over the world, it has become increasingly important in recent decades.

Salinity in irrigation water might have a negative impact on agriculture, lowering yields and harming crops with low salt tolerance (Ergil, 2000). Even in certain instances, environmental factors can need a switch to more salt-tolerant crops.

Based on total dissolved solids or chlorine ion content, the mixing zone limitations are the area between 1% and 95% seawater content. In general, the mixing zone thickness is less than the aquifer thickness and can be regarded as a sharp transition for practical and mathematical reasons (Ergil, 2000).

Assuming that the freshwater, interface, and underlying salt water are in hydrostatic equilibrium is the easiest method to model a freshwater lens (Todd and Mays, 2004). Badon Ghyben in Holland and Herzberg (1901) in Northern Germany separately made the first quantitative studies of the salt-water depth in coastal porous aquifers (Drabbe and Badon Ghijben, 1889; Herzberg, 1901; Houben, 2018; Post, 2018a). They lead to a hydrostatic method that employs the equilibrium of two immiscible stationary fluids of different densities in a U-tube. The water pressure must be equal on both sides at any given point of the sharp interface shown in Figure 5 and this pressure is determined by multiplying the water depth by the specific weight of the water (Houben, 2018; Post, 2018b).

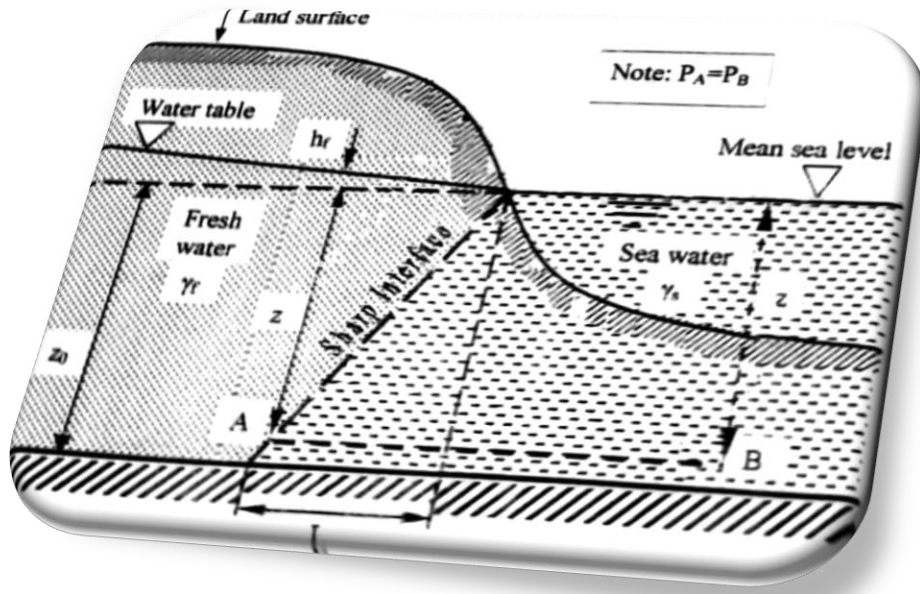


Figure 5: The Badon Ghyben-Herzberg Principle: a Fresh-Salt Interface in an Unconfined Coastal Aquifer (Todd and Mays, 2004)

Point A's freshwater pressure (P_A) and Point B's saltwater pressure (P_B) are;

$$P_A = (h_f + z)\gamma_f \quad (2.1)$$

and

$$P_B = z\gamma_s \quad (2.2)$$

respectively. After that, the hydrostatic equilibrium can be used to generate the equation below to obtain z .

$$z\gamma_s = (h_f + z)\gamma_f \quad (2.3)$$

$$z = \frac{\gamma_f}{\gamma_s - \gamma_f} h_f \quad (2.4)$$

where;

h_f : the freshwater head (above msl) (m)

z : the depth of the interface (below msl) (m)

γ_f : the freshwater specific weight $\cong 9810 \text{ (N/m}^3\text{)}$

γ_s : the salt-water specific weight $\cong 10055 \text{ (N/m}^3\text{)}$ (can range from $10006 \text{ (N/m}^3\text{)}$ to $10110 \text{ (N/m}^3\text{)}$ depending on the temperature and salinity content.).

Equation (2.4), together with its underlying assumptions, is referred to as the Badon-Ghyben-Herzberg relationship (Todd and Mays, 2004). According to this equation, there will be around 40 times as much freshwater in the lens below sea level as there is above (Todd and Mays, 2004).

In actuality, there is some mixing occurring in the contact between the incompatible fresh and salt water, mostly through microscopic and macroscopic dispersion (Ergil, 2000). After that, freshwater and saltwater are both drawn in the direction of the sea. A little landward saltwater flow in equilibrium with the freshwater flow within a coastal groundwater aquifer should be maintained to preserve the salt balance as indicated schematically in Figure 6.

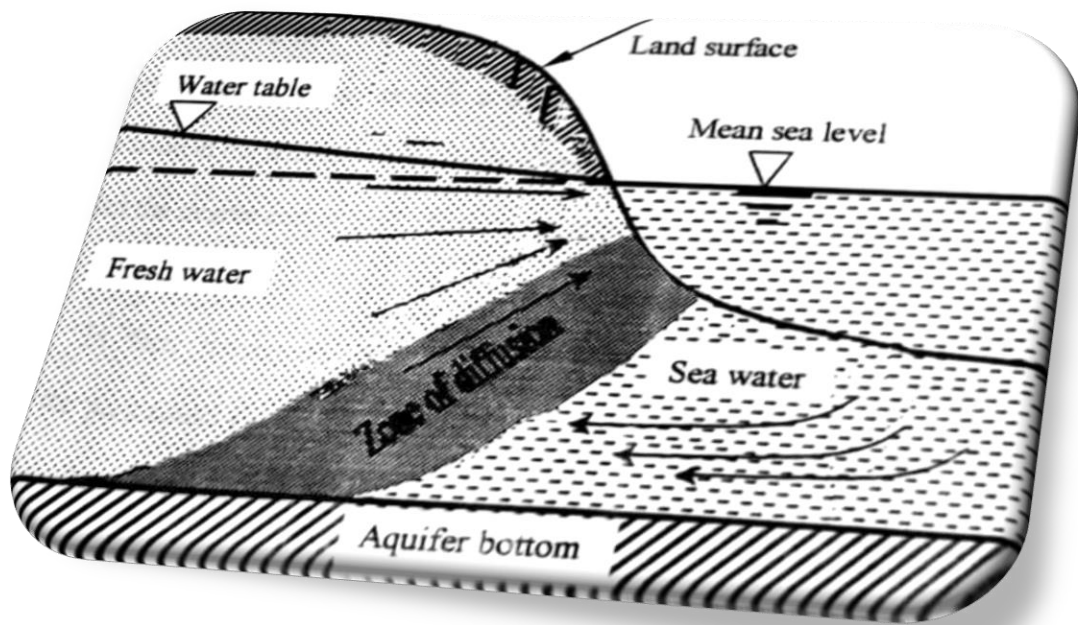


Figure 6: Zone of Diffusion in an Unconfined Aquifer (Todd and Mays, 2004)

The Ghyben-Herzberg hydrostatic technique explained previously for immiscible fluids is not applicable since the water table at the coast is lower than the mean sea level (Todd and Mays, 2004).

It is necessary to take into account the dynamic approach that takes into account a zone of transition between fresh and saltwater with gradually increasing chloride content from fresh to saltwater (where the density and viscosity terms become important) (Bond and Bredehoeft, 1987). This causes chemical advection, dispersion, and diffusion (Wu et al., 1993). An imaginary band is therefore considered to represent the mixing zone of varied thickness, with its top and lower border levels being 1 and 95% sea-water concentration, respectively, depending on the aquifer's hydrodynamic parameters (van Weert, van der Gun and Reckman, 2009).

In most flow systems where advection and dispersion take place, diffusion—which is the spreading of a solute due to molecular diffusion in response to a concentration gradient—occurs as a second-order mechanism. While advection takes into account the amount of solute as a result of groundwater flow and is the most significant phenomenon that moves the solute away from the source, dispersion is the mixing of fluids due to the impacts of unresolved heterogeneities in permeability distribution (Unesco, 1987; Xue *et al.*, 1993). As a result, it is believed that the saltwater will progressively mix with the freshwater, resulting in a range of saltwater concentrations from that found in the medium to that found in the sea (Ghassemi, Jakeman and Thomas, 1989).

Since freshwater and seawater are miscible fluids, the band-like zone of transition is mostly created by hydrodynamic dispersion. The area where the groundwater level is below zero in relation to the mean sea level is almost exactly where the sea-water intrusion area is developing. Even if the discharge rates are not extremely high, the interface will still advance at a slower pace and so it will never halt, even while the rise in flow rate exacerbates the seawater intrusion close to the high discharge pumping zones (assuming the wells are in use). The water head elevation contours in this location don't accurately depict the direction of the intrusion's flow. A broad zone of transition between saltwater and freshwater extends over the research region.

2.6 Previous Studies

Güzelyurt Aquifer has been the subject of numerous field investigations since the late 1960s. A UNDP report on Cyprus's mineral and water resources was published in 1970. Additionally, an island-wide hydrogeological map was drawn and published by the Government of Cyprus Geological Survey Department (UNDP, 1970).

Furthermore, the DSI of Turkey later produced reports on the hydrology of the Güzelyurt region as well as the aquifer situation in 1975 and 1976 (DSI, 1975 and 1976). These studies have largely established the region's geology and hydraulic properties. The General Directorate of Mineral Research and Exploration (MTA) of Turkey also carried out hydrogeological field studies on the Güzelyurt Aquifer in the late 1990s. Due to the Güzelyurt Aquifer's depletion and salinization, MTA has dug about 20 boreholes nearby to identify new water sources to satisfy the region's growing water demand. This investigation showed that seawater had intruded 8.5 km from the shore to the inland; as a result, it was required to halt further pumping well drilling in the area and maintain water use levels considerably below the predicted replacement amounts (MTA, 1997).

One of the most important research in the Turkish Cypriot water resources community is Ergil's (2000) research. It was referred to as the sole investigation of the salinization of the Güzelyurt Aquifer for a long time until recently. In this work, the water budget of the aquifer was evaluated using a reverse approach that roughly calculates the water balance from the salinity of the groundwater and the available water head distribution. Because of the data's ambiguous chronological and spatial foundation, the author was forced to employ this kind of broad method. A volumetric water balance approach that incorporates salt balance equations has been used to calculate the aquifer's continuous water usage. Moreover, groundwater head and salt concentration contour maps using the kriging technique have been created using the data on water level and salinity concentration collected throughout the 20 years between 1977 and 1997. These led to an estimation of the unknown component of the aquifer's water budget. It is estimated that 8.5 MCM/year of groundwater extraction is done by the Southern Part of the Güzelyurt Aquifer (Ergil, 2000). Additionally, it was discovered that between 1977

and 1997, almost 24 MCM of seawater had migrated 12 km inland (Ergil, 2000). In addition, the total annual irrigational water demand of the Güzelyurt was determined as 60 MCM by taking into account the type of planting on the aquifer (Ergil, 2000). The first half of the methodology used in this study is identical to Ergil's research.

Ergil's study from 2000 has served as a standard for all subsequent academic research endeavors. As a result, it carries a high significance for the Güzelyurt Aquifer because it highlights the necessity for sustainable water management to prevent additional aquifer degradation. While numerical modeling is frequently used to predict groundwater elevation and water budget, the methodology used in this study is very different from that type of methodology. Through the use of simulations, numerical techniques aid in the understanding and prediction of the behavior of the aquifer system. As a result, the Middle East Technical University and the Geology and Mining Department of Northern Cyprus launched several modeling initiatives in response to the demand for such fundamental modeling tools. As a pioneering effort in this direction, Fanta (2015) created a conceptual model of the Güzelyurt Aquifer. In the research conducted by Fanta, hydrogeological maps and the topographic map transformed into a digital elevation model (DEM) were evaluated with the goal of more precisely determining the geographic distribution of the aquifers using modern technologies (2015). The assessments performed in this study revealed that both the new and the old datasets have the potential to be employed in the generation of the numerical simulation model of the aquifer (Fanta, 2015).

The most recent study on Güzelyurt Aquifer was Demir's research written in 2018 and published in 2022 (Demir, 2018; Demir *et al.*, 2022). A simulation of the hydraulic behavior of the aquifer under artificial recharge and different stress scenarios was

created. Detailed 3-D numerical models of the aquifer were constructed with the inclusion of managed artificial research scenarios. After calibration and validation, the constructed numerical model was used to simulate three distinct controlled aquifer recharge scenarios, to determine if it would be feasible to return water levels to their "natural state" within an acceptable amount of time. In all cases, it took between 11 and 14 years for the groundwater depression zone to reasonably recover. The models, however, demonstrated that the aquifer had reached its "natural condition" in 48–73 years (Demir, 2018).

2.6.1 Statistical Analysis in Groundwater Time Series

In the Karnal district of Haryana, a study was conducted to determine the trends in pre- and post-monsoon groundwater levels using the Mann-Kendall test and Sen's slope estimator, as well as for time series modeling of groundwater levels to anticipate the pre- and post-monsoon water levels (Patle *et al.*, 2015). It was determined that the ARIMA (0, 1, 2) was the best model for predicting and modeling time series (Patle *et al.*, 2015). According to the findings, the pre- and post-monsoon groundwater levels in 2050 would be 12.97 m and 12.00 m lower than the water level that was measured in 2010 and would be 29.95 m and 28.14 m below the surface of the earth, respectively (Patle *et al.*, 2015). Pre- and post-monsoon groundwater levels in the district would typically fall at rates of 0.32 and 0.30 m/yr, respectively (Patle *et al.*, 2015). This study follows a similar trajectory to this research in trend analysis and statistical modelling aspects. The research adapted the approach to groundwater levels successfully and forecasted using the ARIMA model.

2.6.2 Drought Events in Güzelyurt

Two consecutive studies were published by Payab in 2018 and 2020 regarding the temporal spatial characteristics of drought events in northern part of Cyprus. The first

study aimed to use Standardized Precipitation Index (SPI) to investigate and identify the drought events, their duration and severity (Payab and Türker, 2018). The findings of this study suggests that there has been a drought period from 1983 to 1988 which was considered to be between moderate and severe drought (Payab and Türker, 2018). In addition, the following study investigated the temporal and geographic effects of drought on irrigation water demand of citrus and pomegranate, and available groundwater (Payab, Banihabib and Türker, 2020). The results of this study suggested that irrigation water demand of crops increased by an average of 12% for different drought scenarios (Payab, Banihabib and Türker, 2020). Finally, when the correlation between SPI and change in groundwater level anomalies were studied, a positive correlation was seen between one year lagged SPI and change in groundwater anomalies (Payab, Banihabib and Türker, 2020). This suggests that the effect of drought gets visible after roughly one year (Payab, Banihabib and Türker, 2020).

2.7 Implemented Management Strategies

Ever since the start of the problem, alternative management strategies have been suggested. There have been two attempts to improve the water budget of the aquifer. The first one was the TRNC Water Master Plan implemented by DSI in 2003. The most recent management strategy attempted was the implementation of the WSP (DSI, 2003). The second Master Plan was prepared after the completion of WSP in 2016. The Ministry of Agriculture and Natural Resources of TRNC released the 2017 TRNC Agriculture Master Plan where water management plans were included in this document (KKTC Tarım ve Doğal Kaynaklar Bakanlığı, 2017).

With regard to population growth, there are no published official strategies, however, the approach taken by the government shows that there is a demand for population

growth, especially among university students in urban areas. The increase in universities and enrolled students are prominent in the country. Figure 7 shows that yearly enrolled students in the universities have nearly doubled. Not only this enhances the economy of TRNC but also enhance drinking and municipal water demand.

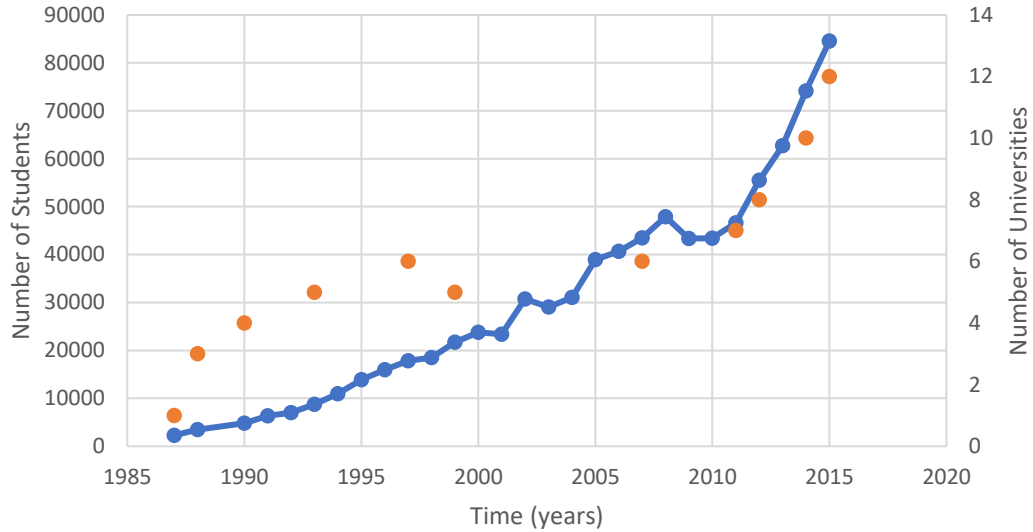


Figure 7: Number of Students and Number of Universities between 1985-2015 (KKTC Tarım ve Doğal Kaynaklar Bakanlığı, 2017).

A vegetation pattern plan and recommendation project were funded and published by the government of TRNC in 2016. Local agricultural recommendations were included in addition to general recommendations on different plant types to maximize production efficiency, quality, and quantity. The plan recommended an increase in citrus fruit production up to 42,500 donums compared to the 37,846 donums relying on the freshwater from WSP (KKTC Tarım ve Doğal Kaynaklar Bakanlığı, 2017). This becomes more obvious as the water demand for the amount recommended is 38.3 MCM which is the amount of water directed for irrigation from WSP. However, the recommendation was not fulfilled, it was reversed and the plantation coverage for citrus fruits has decreased.

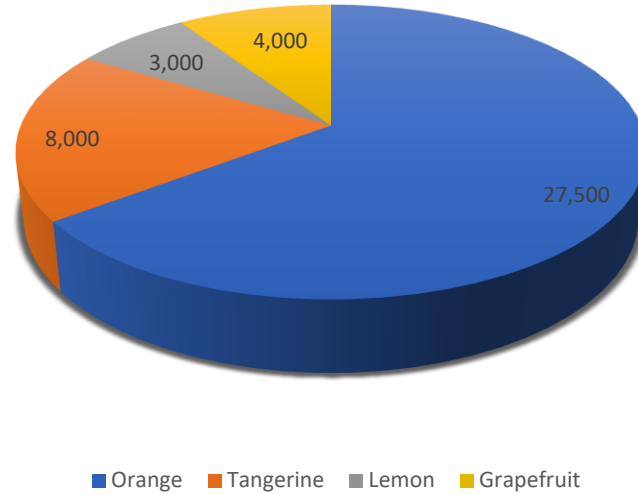


Figure 8: Recommended Type and Amount of Citrus Plant Production in Güzelyurt Area in donums (KKTC Tarım ve Doğal Kaynaklar Bakanlığı, 2017)

Additionally, TRNC Master Plan suggested that groundwater usage will be stopped with no further extraction from Güzelyurt Aquifer (KKTC Tarım ve Doğal Kaynaklar Bakanlığı, 2017). With regards to the management of freshwater from the WSP, the planned usage suggested that 38 MCM of the freshwater was to be allocated for drinking/municipal purposes, whereas 37 MCM was to be allocated for irrigational purposes (Demir, 2018).

Master Plan published in 2017 released that there are 2342 farmers in the citrus fruit sector (KKTC Tarım ve Doğal Kaynaklar Bakanlığı, 2017). There are 107 farmers with plantation area coverage exceeding 40 donums (KKTC Tarım ve Doğal Kaynaklar Bakanlığı, 2017). Most of the farmers are working with a plantation area of 15 donums or less. Around 25% of TRNC's economy revolves around the exportation of agricultural products with 16% of this 25 being citrus fruit exports, taking the number one spot (KKTC Tarım ve Doğal Kaynaklar Bakanlığı, 2017). This demonstrates the importance of irrigated agriculture in the economy.

Chapter 3

STUDY AREA AND DATA

3.1 Definition of the Study Area

The Güzelyurt Aquifer study area is situated in Moprhau Plain, close to Northern Cyprus's west coast (Figure 9). According to a report by Gokmenoglu, the Güzelyurt Plain has a drainage area of 900 km² and a total surface area of 415 km² (Gökmenoğlu *et al.*, 2002). About two-thirds of the aquifer area is located within the borders of the TRNC, while the remaining one-third is within the borders of South Cyprus (SC) (Gökmenoğlu *et al.*, 2002). A large portion of the drainage area is situated in the southern SC borders. Approximately 373 km² of the Güzelyurt Plain's drainage area, which is divided into 6 sub-basins, is located inside TRNC's borders. Shuttle Data Topographic Mission (SRTM), Hydrobasins, Open Street Map (OSM), and Natural Earth were used with appropriate DEMs to delineate the watershed and its sub-basins. Using the delineated catchment, the area of the watershed was calculated as 1171 km². Determination of the aquifer boundary was done regarding Ergil's research and the hydrogeology of the area given by the Cyprus Geological Survey Department (Ergil, 2000). The estimated area within the aquifer is 254 km², of which 180 km² is within the boundaries of TRNC and 75 km² is within South Cyprus as detailed in Figure 9.

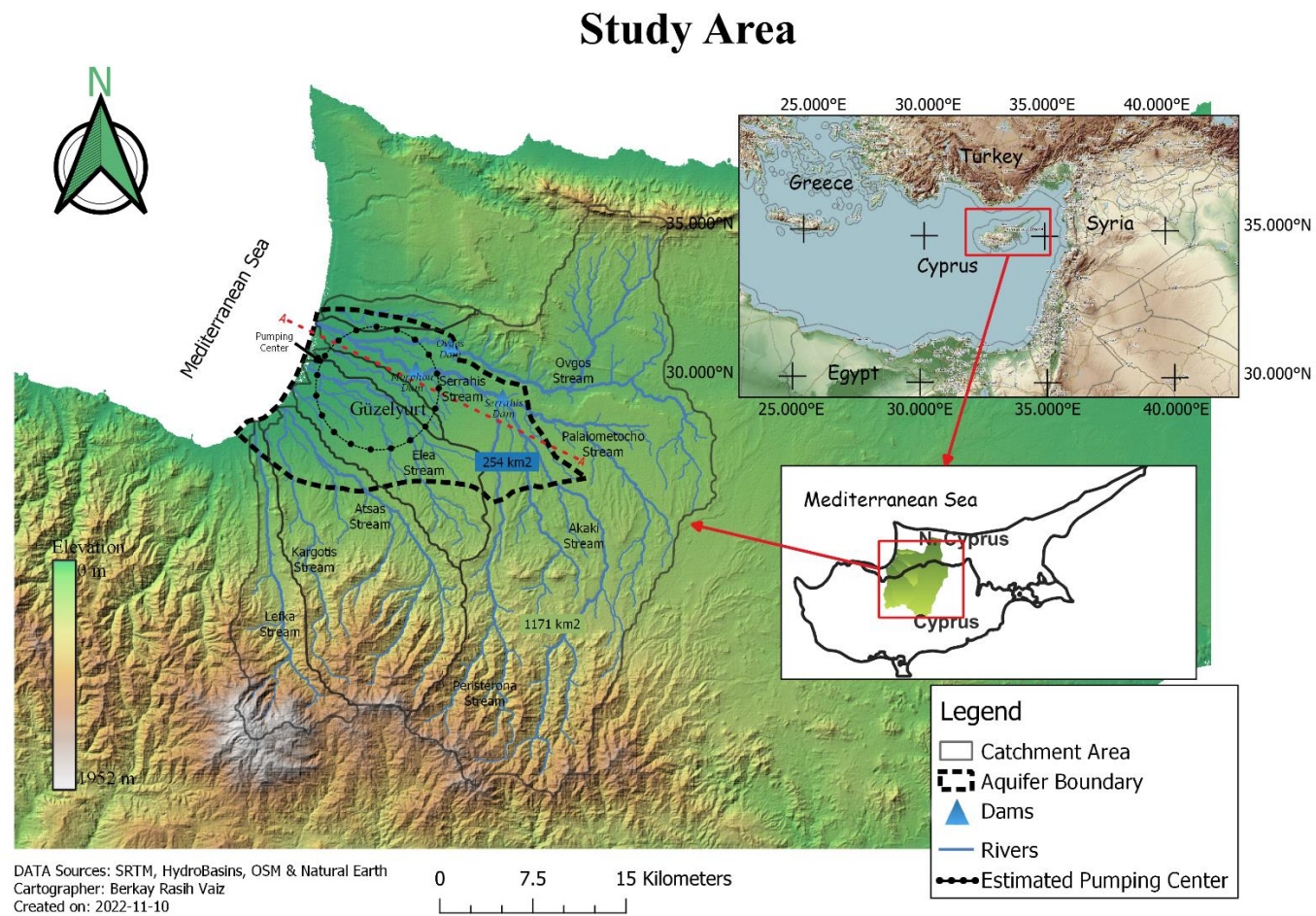


Figure 9: Güzelyurt Aquifer and its Catchment, A-A Cross-Section, Physical Boundaries, Surface Areas, and Sub-Basins

The urbanization in the area is mainly in the form of a town located at the center of the study site. Ever since 1950, more than 2400 wells have been dug and 810 currently active pumping wells within use, cover the majority of the aquifer (Ergil, 2000). Güzelyurt area is known for its massive citrus fruit production capacity covering approximately 52 km² of the total land in the study area which is decreasing annually due to several reasons such as export constraints, high labour cost, and low fertilizing subsidy.

The position of the A-A cross-section used to produce slices of the water table contours is shown in Figure 9. This cross-section was selected because it is perpendicular to the coastline. In addition, the cross-section covers the area where most groundwater depletion is observed and most of the irrigated land (i.e. groundwater extraction) is located. After a point, the A-A cross-section covers the aquifer area located in South Cyprus.

3.2 Agriculture in Cyprus

As mentioned earlier, agriculture carries economical importance to TRNC. The total land among the borders of TRNC is approximately 9250 km² and from this surface area around 900 km² is cultivated land (Fanta, 2015) (KKTC Tarım ve Doğal Kaynaklar Bakanlığı, 2017). The dry and irrigated portions of this land are observed to be 92% and 8%, respectively (KKTC Tarım ve Doğal Kaynaklar Bakanlığı, 2017). The area that this study is interested in is the irrigated land. In TRNC, 70% of the irrigated agricultural terrain is located in the Güzelyurt Area (KKTC Tarım ve Doğal Kaynaklar Bakanlığı, 2017). The fruit types and the amount of land used by the type are shown in Figure 10. 75% of the agricultural production revolves around citrus

fruits. In addition, grapes, fruit-bearing vegetables, and tuber crops follow up in a smaller scale of production.

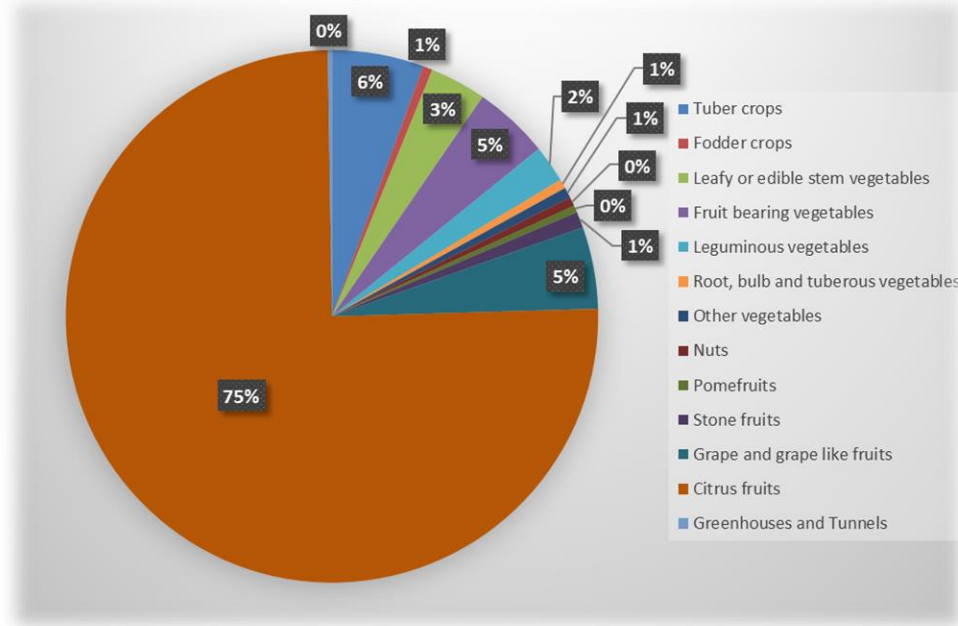


Figure 10: Distribution of Irrigated Land in Güzelyurt Area (KKTC Tarım ve Doğal Kaynaklar Bakanlığı, 2017)

Citrus trees require frequent irrigation especially in the summer months from 15 May to 15 September in Mediterranean Climates. It is considered to be the time zone where the irrigational needs peak. Generally, the irrigational demand for these trees is 800-1000 mm/year (Levy, 1998). Assuming 900 mm/year is used and considering the crop production in 2016, 31.8 MCM water is necessary for the irrigation of 35.2 km² of fully grown citrus trees present in the study area. Figure 11 defines the annual citrus production of TRNC. The value used in the example above is a result of an optimistic scenario and a byproduct of a positive management strategy. Knowing that the citrus plant is not the only type of plant demanding irrigation, It is normal to see high values.

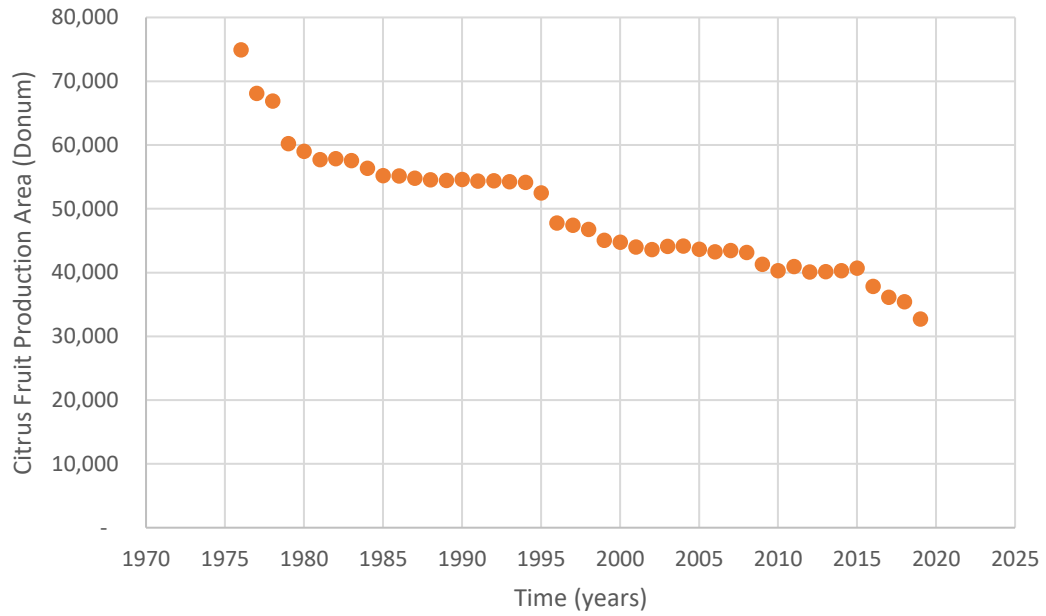


Figure 11: Yearly Citrus Fruit Production in TRNC (KKTC Tarım ve Doğal Kaynaklar Bakanlığı, 2017)

3.3 Dams & Surface Water

Infiltration of water from precipitation and seasonal runoff through rivers and ephemeral streams originating from Troodos and Latmos mountains is the main source of recharge. The water trapped as snow in the Troodos Mountains begins to melt in the spring, but the snow storage is all melted by the time summer arrives. Rivers remain dry for the majority of the year. The majority of runoff created by precipitation and snowmelt occurs in the winter. The flow rates of the streams significantly fall after March when the majority of the runoff from melted snow disappears (Ergil, 2000). Catchments and streams delineated are shown in Figure 12, Figure 13, Figure 14, and Figure 15. Movement of surface water is done throughout these streams towards the ocean. The majority of the surface area of these catchments is located in Southern Cyprus. However, they are mostly dry due to the artificial lakes and the dams constructed over them in South Cyprus (Demir, 2018).

Ovgos Dam and Güzelyurt Dam are Earthfill dams constructed by the Water Development Department of South Cyprus in 1964 and 1962, respectively (Water Development Department, 2009). Ovgos Dam had a capacity of 147.000 m³ with a reservoir surface coverage of 260.000 m² and it is used for irrigation and recharge (Water Development Department, 2009). Whereas, Güzelyurt (Morphou) Dam had a capacity of 387.000 m³ with a reservoir surface coverage of 480.000 m² (Water Development Department, 2009). Masari (Şahinler) was also constructed by the Water Development Department of South Cyprus in 1973 with the purpose of recharge. Masari Dam had a capacity of 278.000 m³ with a reservoir surface coverage of 620.000 m². Güzelyurt and Masari Dams both get charged by the Serrachis river (Water Development Department, 2009).

The aquifer water demand cannot be satisfied by the three dams. Therefore, a derivation channel was built between 1983 and 1994 to increase the volume of water stored in the Güzelyurt Dam, preventing nearby streams from losing water to the sea, and increasing the amount of water infiltrating the aquifer by lengthening the time it took for the water to flow into the dam. The Güzelyurt Dam has a capacity of 8 MCM, which stores the winter flows of the Lefke, Camlik, and Maden streams (Demir, 2018). However, a significant portion of the water evaporates on the way to the Dam as a result of channel siltation. Consequently, the amount of water transported to the Dam is much less than the demand (DSI, 2003).

3.4 Catchments in Güzelyurt Aquifer

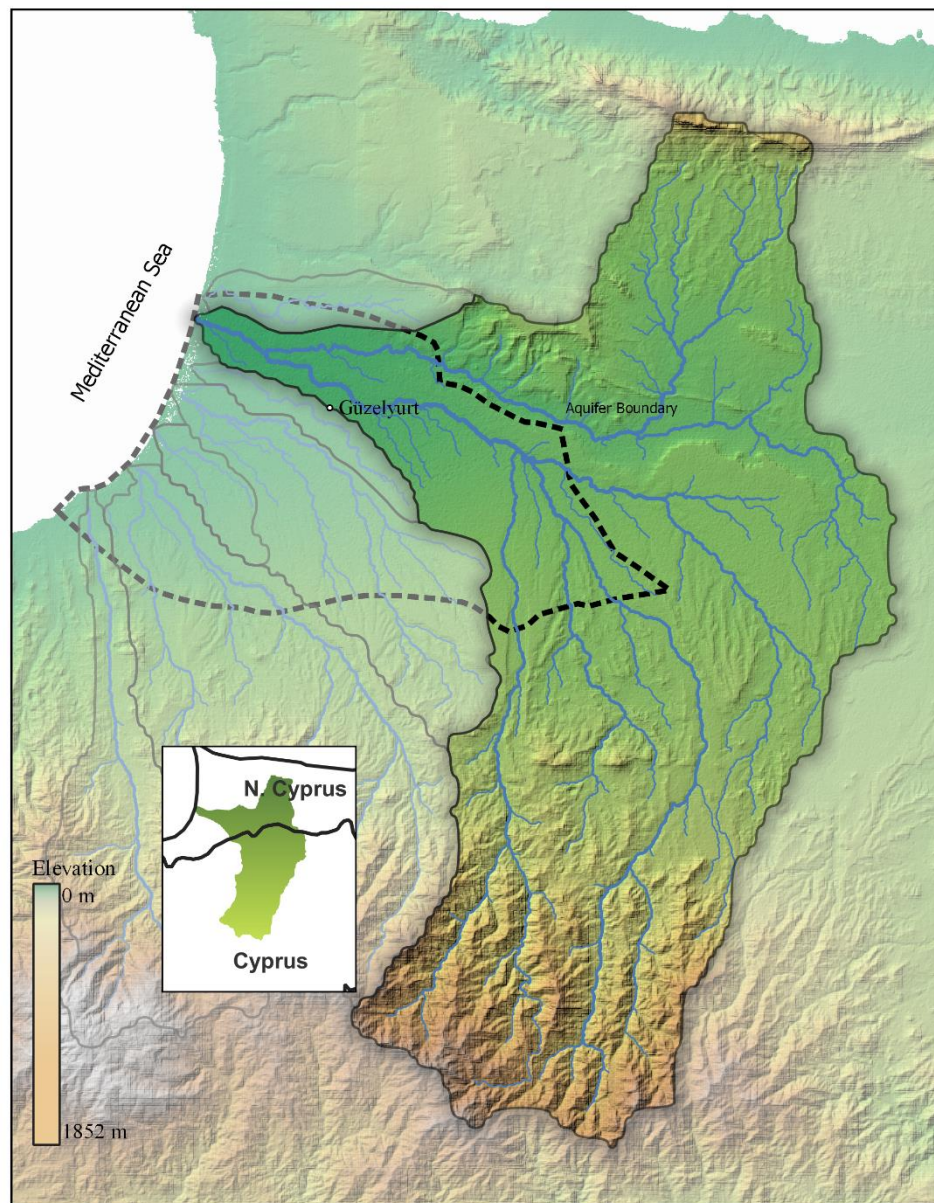
The catchment within the study area was delineated by using the Strahler method with the help of QGIS and the online hydrological database HydroBasins. The delineated catchments were presented in 4 different figures as shown below. Stream network obtained using Strahler order consists of mostly ephemeral streams. Moreover,

groundwater recharge is mostly related to the surface drainage of the rainfall and irrigation patterns. Thus, an accurate representation of the catchments and stream network is necessary to observe and comment on aquifer recharge. The stream network shown in Figure 12, Figure 13, Figure 14, and Figure 15 suggests that a large portion of the recharge is a result of the precipitation falling on Troodos mountains and a smaller percentage of the rainfall resulting in the recharge is directed to the area located directly above the aquifer from Latmos mountains. The surface area covered by catchments 1, 2, 3, and 4 is 705 km², 114 km², 235 km², and 97 km², respectively.

In addition to the rainfall in the wet season, the water stored as snow in the Troodos mountains melts and infiltrates the aquifer after the winter through catchments 1 and 3 having partial catchment areas within the Troodos Mountains. The snow storage depletes during spring and summer where most of the melting occurs in the spring season. The rivers and streams shown in the following figures are dry most of the year, especially after March when most of the snow has melted, and significantly lower runoff rates are observed. Furthermore, runoff occurs mostly during winter as an aftermath of rainfall.

As shown in the locator maps on catchments 1, 2, and 3, most of the basin area is located in the southern part of the island. Some of the rivers are blocked by dams constructed by the Republic of Cyprus, denying a large amount of water the aquifer depends on. Dry streams are observed in Northern Cyprus because of these dams.

Morphou Catchments



DATA Sources: SRTM, HydroBasins, OSM & Natural Earth
 Cartographer: Berkay Rasih Vaiz
 Created on: 2022-03-20

0 5 10 km



□ Catchment Area — Strahler Order 3
 Channels — Strahler Order 4
 — Strahler Order 1 — Strahler Order 5
 — Strahler Order 2

Figure 12: Delineated Catchment 1 in the Güzelyurt Area

Morphou Catchments

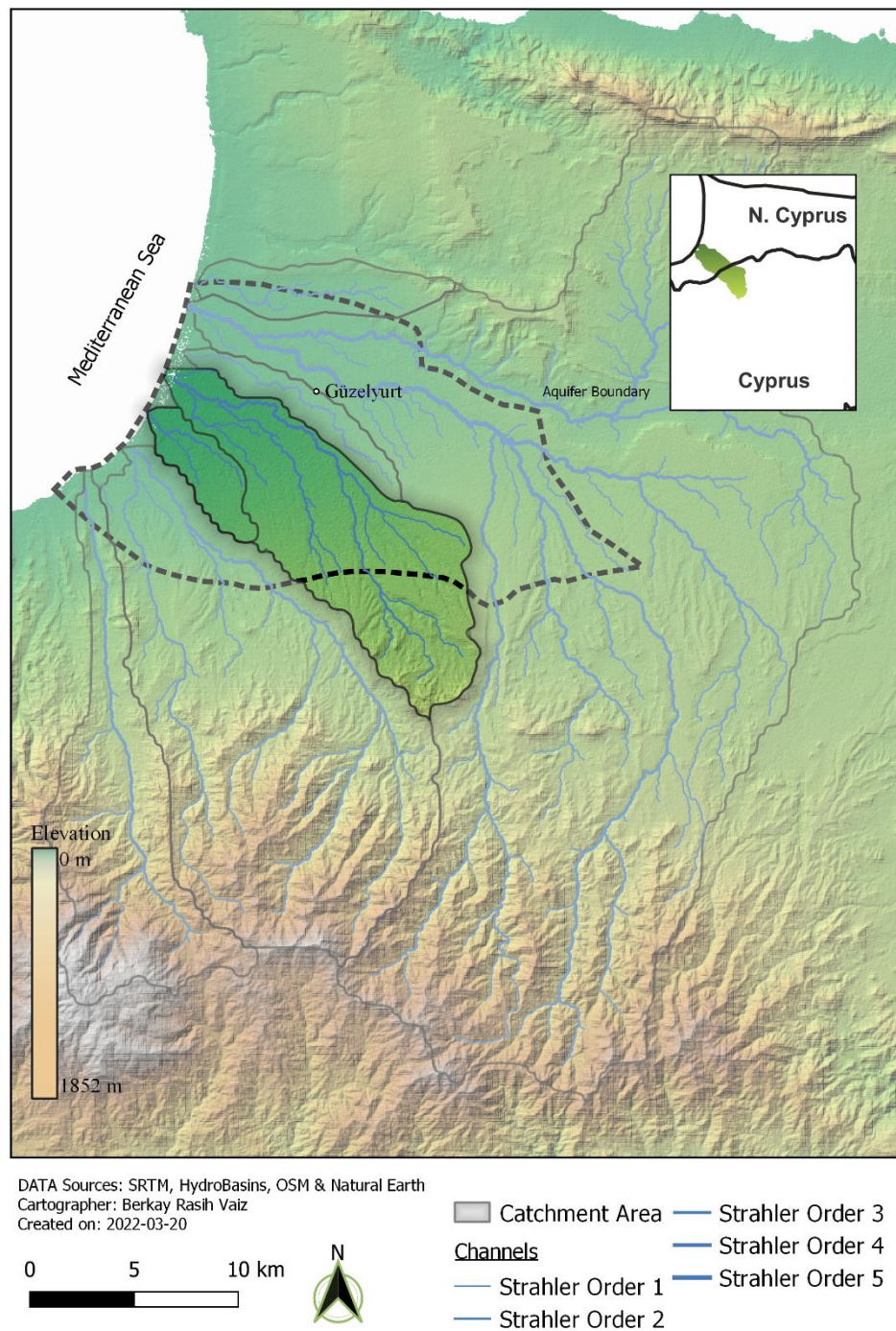


Figure 13: Delineated Catchment 2 in the Güzelyurt Area

Morphou Catchments

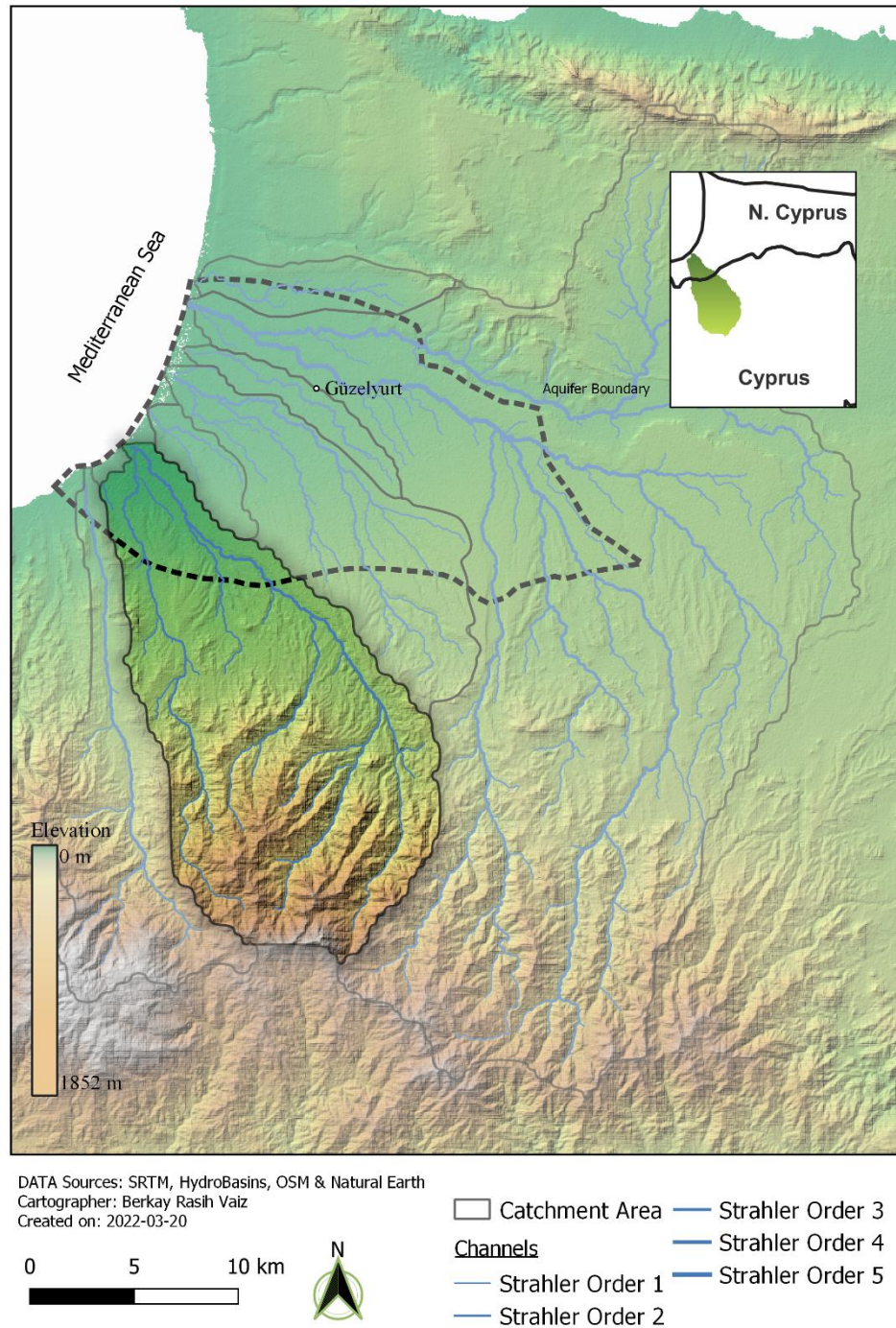


Figure 14: Delineated Catchment 3 in the Güzelyurt Area

Morphou Catchments

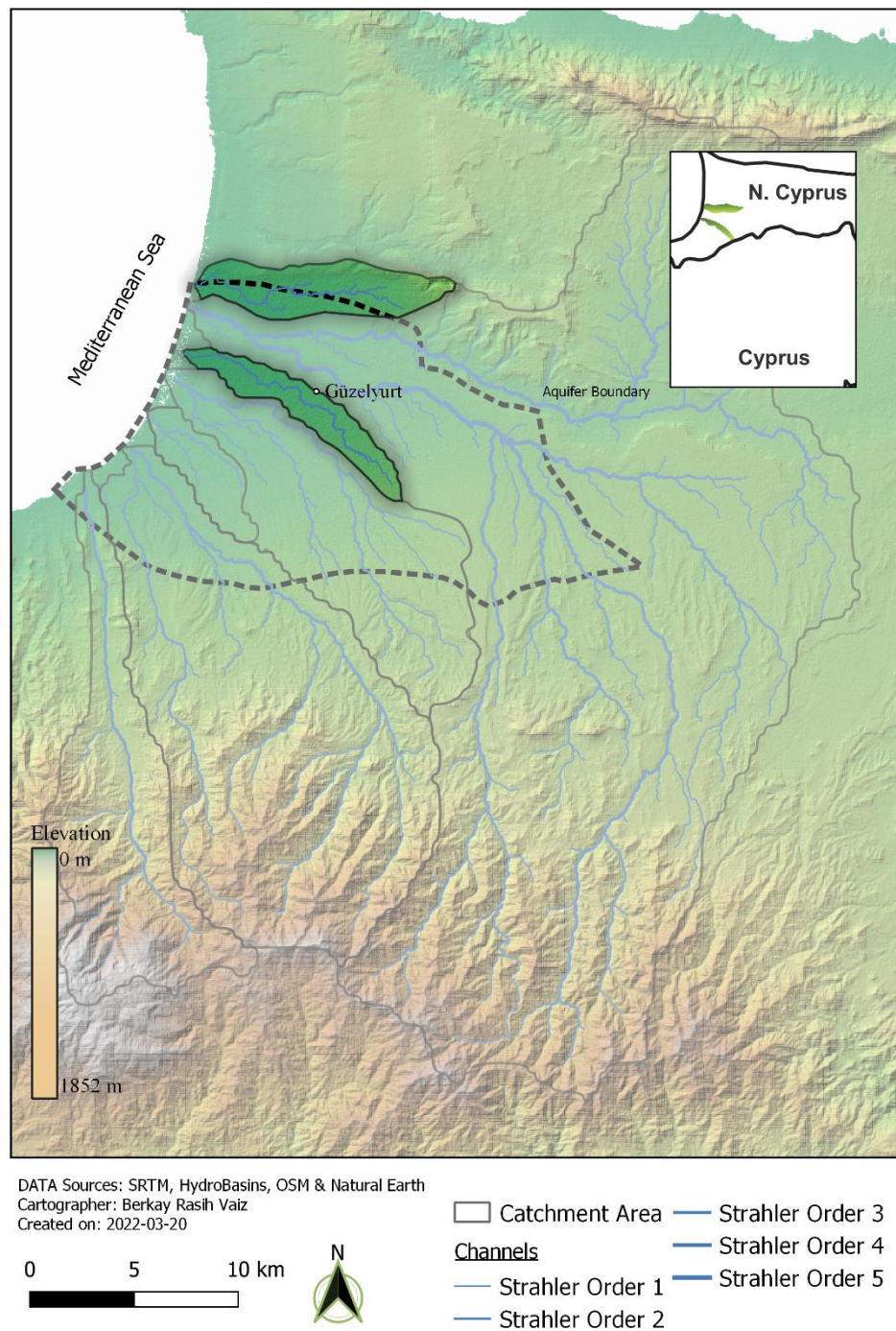


Figure 15: Delineated Catchment 4 in the Güzelyurt Area

3.5 Hydrogeology of the Güzelyurt Aquifer

The hydrogeology of the study area mostly consists of alluvial deposits, Pleistocene sand, gravel, silt deposits, karstic limestone, dolomite gypsum, and chalk (UNDP, 1970). The base of the aquifer is formed by clay and mildly undulating Pliocene marl, making it an impervious layer. The majority of the area is covered by shallow unconfined coastal alluvial deposits. The area defined in this region also includes riverbeds in Figure 16. Alluvial aquifers are made of sand gravel, clay, and silt (Todd and Mays, 2004). Aquifers composed of alluvial deposits are known to have high storage capacity and transmissivity (Todd and Mays, 2004). Throughout the aquifer, vertical and lateral variations can be observed. Partially impermeable or semi-permeable zones exist within the study area, consisting of the same materials as the base. In opposition, most of the materials forming the aquifer, hold strong water-holding capacity such as limestone, sandstone, and conglomerate-containing materials (UNDP, 1970). Terrestrial/Marine Fanglomerates and Terrace formations comprise the second-largest plan view shown in Figure 16. The water-holding capacity of the Fanglomerates is also high. Approximately 10% of the study area is composed of a confined region. This region was plotted by Cyprus Geological Survey Department in 1970 (UNDP, 1970). It is fully located in Southern Cyprus; thus, the water head elevations are not known. To summarize, Güzelyurt Aquifer is an unconfined, unfractured groundwater body with high water storage capacity and mostly high permeability and transmissivity. The coastline was measured to be 14 km. The zone which is in direct contact with the sea is composed mostly of sand, gravel, and pebbles. This layer is underlain by a layer of marl and sandstone, making the region susceptible to erosion. In the determination of the aquifer boundary, the thin areas extending with

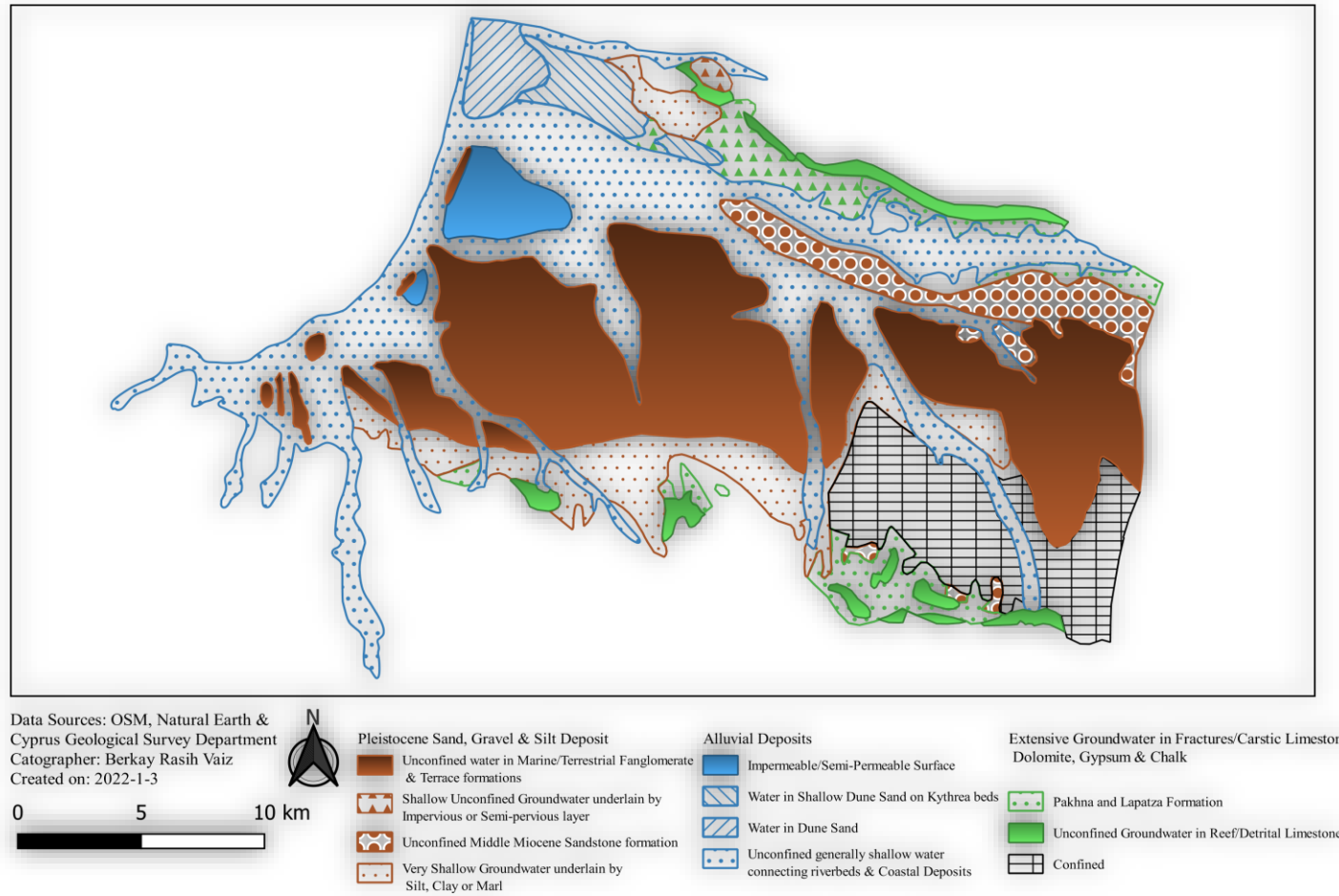


Figure 16: Hydrogeological Map of the Study Area (UNDP, 1970)

rivers, regions with very shallow groundwater bodies, and the confined aquifer area were all excluded. Forming a smooth shape similar to the shape of the aquifer defined in the previous studies. Based on definitions given in Table 2, Güzelyurt Aquifer is categorized as, A4, groundwater originating from laterally intruded seawater.

Aquifer thickness varies from 45 m where its base is around 50 m above msl, to 100 m where the land meets the sea along the coast. The deepest point of the aquifer base is around 104 m below msl. Correspondingly, the thicker side is completely below the mean sea level as shown in Figure 17.

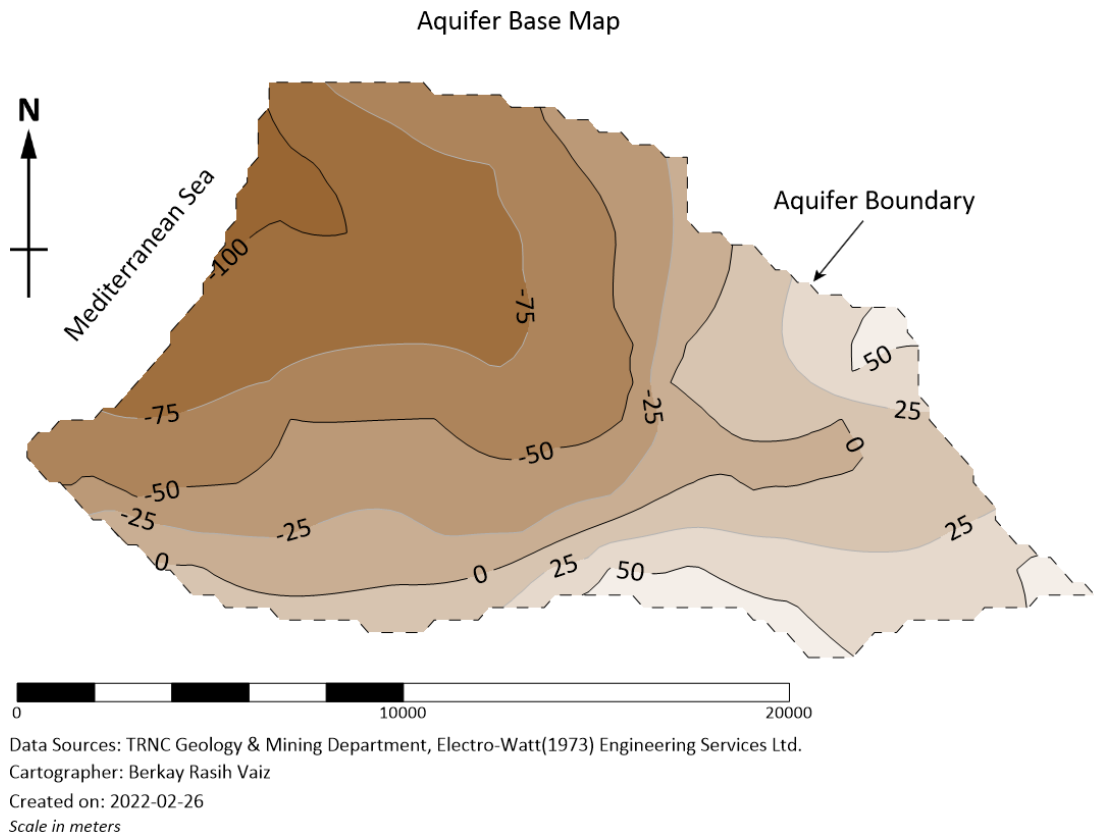


Figure 17: Estimated Güzelyurt Aquifer Base Contours in meters above msl

Along the coastline, the aquifer is 100 meters thick. There are locations, particularly in the far east, with only a depth of 45 m below the topographic elevation because its

bottom contours are inclined steeper than the slope of the topographic contours above it (earth surface). The aquifer's lowest point is about 35 meters above sea level. Where the height of the aquifer bottom is below or above mean sea level, there is a clear distinction. Regarding saltwater intrusion, the elevation of the aquifer bottom is crucial because, under the most pessimistic scenario, if an abrupt incursion of saltwater is assumed, the progression of the salt wedge can be halted before this limit (Bouwer, 1978; Bear, 1979). Another noteworthy point is that well locations and distribution almost exactly match the parts of the aquifer whose beds are below mean sea level over the agricultural area. The aquifer in this area is thick enough to be used. This complicates matters further since along the shore, seawater seeps in and contaminates the aquifer as a result of the water being drawn primarily for irrigation, which is clearly above the aquifer's safe yield capacity. Due to a lack of relevant data, it is difficult to directly determine the intervening amount.

According to the examination of groundwater samples obtained from the observation wells in the study region, the total NaCl concentration and the water level heads are connected. The average background chloride concentration of natural groundwater is around 270 ppm. Due to the heavily vegetated area and long-term excessive watering, the soil becomes salinized, which impacts the chloride concentration of the precipitated water that infiltrates through the recharge. The regions where the groundwater level has significantly dropped are immediately threatened by the entrance of the sea along a perpendicular distance from the coast. As a result, the interface between saltwater and freshwater intrusion advances landward until a new equilibrium is reached. Local infiltration occurs as a result of the seasonal creeks and semi-perennial rivers in the aquifer region. Therefore, 400 ppm NaCl concentration is

used as a representative index for the overall aquifer quality in the absence of salination from seawater.

3.6 Topography

The study area is located in Güzelyurt Area, and it can be described as a slightly sloping coastal plain (Fanta, 2015). The change in elevation near the coast is minimal so much so that the topography can almost be considered flat. Figure 18 shows a significant increase in the elevation due southeast where Troodos is located. The elevation within the catchment area ranges from mean sea level up to 400 m due southwest of where Troodos mountains are located. Additionally, the average elevation can be observed as 65 m above msl.

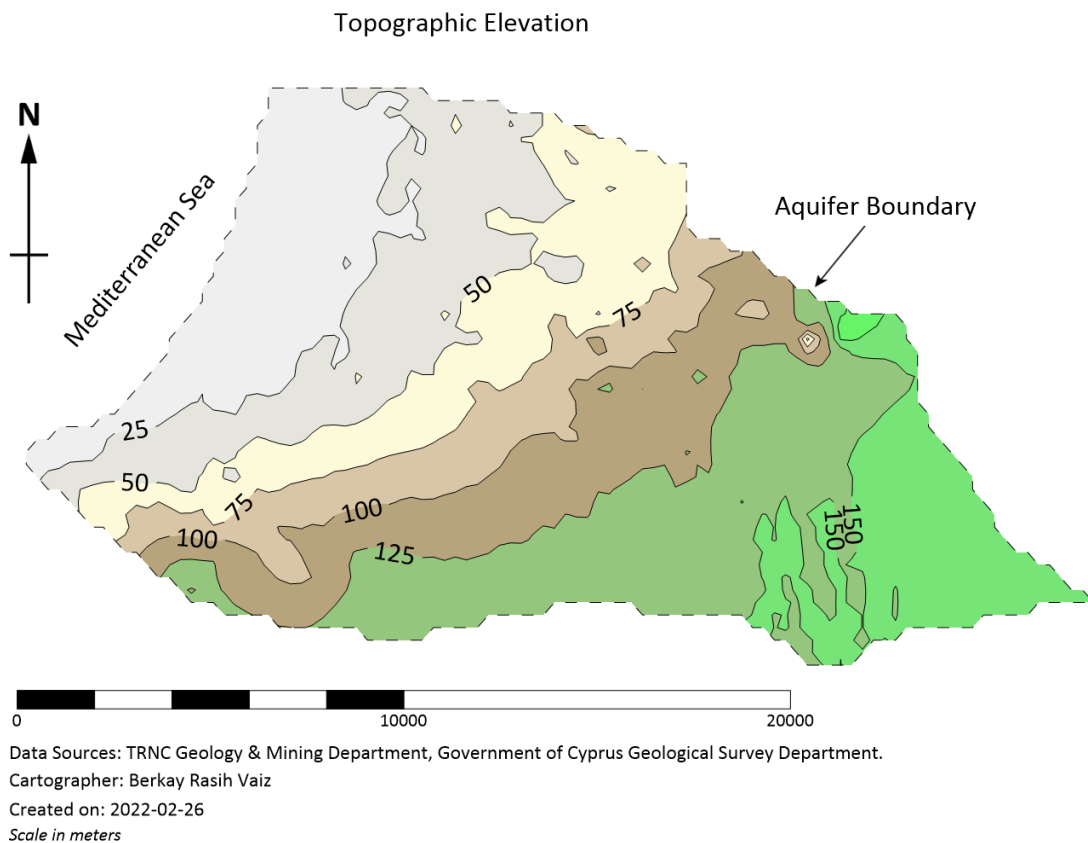


Figure 18: Topographic Elevation within the Aquifer Boundary (Geology & Mining Department TRNC)

3.7 Available Borehole Data

A dataset with a longitudinal time horizon was obtained from two different sources. One of them was TRNC Geology and Mining Department and the other one was obtained from SID. The second dataset was in the possession of the supervisor of this thesis and the dataset was used to produce the results of the Ph.D. thesis of Prof. Dr. Ergil in 1999. The responsibility of measurement and storage of the borehole data was changed after the SID and Geology and Mining Department were separated. Thus, there were small differences between the two datasets from the years 1980-2000 where the range of available data intersects. Since unfortunately, there is no proper official sanction between these two offices to double-check their measured datasets. Appropriately, the datasets were united. While this process was going on 2 cases were observed;

1. One of the datasets has a given value for a borehole, the other one does not.
2. One of the datasets has a given value for a borehole, and so does the other one.

For case 1, the missing borehole value was added to the first dataset. For case 2, an average was taken between the two available values. Covering a lengthier period by combining the two datasets into one. This was repeated for both water quality and quantity datasets. As a result, the available data is to be used in the trend analysis development.

Table 3: Water Table Elevation Statistics of Wet Season Borehole Data for the displayed Water Table Contour Map Years.

Year	Water Table Elevation Statistics			
	Wet Season			
	Minimum	Maximum	Average	Standard Deviation
1980	-41.94	98.79	0.75	28.58
1988	-64.30	95.60	-0.01	32.64
1998	-61.15	96.80	-4.49	34.07
2009	-59.93	85.54	-3.44	33.01
2018	-49.95	107.22	5.28	38.54

Table 4: Water Table Elevation Statistics of Dry Season Borehole Data for the displayed Water Table Contour Map Years.

Year	Water Table Elevation Statistics			
	Dry Season			
	Minimum	Maximum	Average	Standard Deviation
1980	-34.66	98.70	1.11	27.79
1988	-54.17	93.63	4.33	32.24
1998	-52.00	79.70	-5.32	28.44
2008	-52.63	84.16	-1.11	33.15
2018	-49.25	137.80	15.23	46.07

Table 5: NaCl Concentration Statistics of Wet Season Borehole Data for the displayed NaCl Concentration Iso-Chloride Years.

Year	NaCl Concentration Statistics			
	Wet Season			
	Minimum	Maximum	Average	Standard Deviation
1980	94	29543	938	2924
1989	70	20475	907	2263
1998	64	4615	636	726
2008	53	7100	606	921
2018	64	2663	566	608

Table 6: NaCl Concentration Statistics of Dry Season Borehole Data for the displayed NaCl Concentration Iso-Chloride Map Years.

Year	NaCl Concentration Statistics			
	Dry Season			
	Minimum	Maximum	Average	Standard Deviation
1980	57	1420	217	182
1988	76	20475	1141	2788
1998	43	2840	491	555
2007	64	4793	564	723
2019	38	3836	501	681

Table 3, Table 4, Table 5, Table 6 gives more information about the datasets used to produce the presented maps with the available data. Even though the dataset provided by SID extends back to the 1970s, the combined dataset starts from 1980. Additionally, the data is more consistent. Fewer data missing in the dataset provided by the Geology & Mining Department of TRNC. Thus, for trend analysis, forecasting, and estimation of the seawater intrusion, the data available after the 1980s combined dataset was used. Furthermore, data given by Geology & Mining Department extend up to 2020. As a result, the map constructed in 2020 was not taken into consideration during the analysis. Finally, no data is available after 2020 due to covid-19.

3.7.1 Replacing Missing Data

A total of three wet season relevant NaCl concentration data, three dry season water table elevation data, and six wet season NaCl concentration data are missing. The number of readings is insufficient to construct a contour/iso-chloride map. In order to apply statistical analysis to the datasets, the Deterministic Regression Imputation approach was applied to replace the missing volume and concentration values with substitute values. The deterministic model is a model where the outcome is determined by the known relationship between input values (McClave *et al.*, 2014). The approach enhances the correlation in a time series by not considering a random variation within the given regression slope (Schork, 2018). This model is preferred over Stochastic regression imputation because, the number of missing data is not a lot and if the estimation of the substitute value involves a random error, the results can be heteroscedastic or implausible (Schork, 2018). A deterministic model was formed by using the linear regression between six total consecutive seasonal data, the previous three and the posterior three concerning the missing season. The missing value was

substituted by an estimation using the equation of the linear trendline obtained from the graph.

3.7.2 Secondary Datasets

Additionally, three more datasets were obtained. These are monthly rainfall, the average temperature in Güzelyurt Area, land used for agriculture in Güzelyurt area, and the type of crops produced yearly. The first two datasets were obtained from the Department of Meteorology and the other dataset was available online for free provided by the Department of Agriculture.

Chapter 4

METHODOLOGY

The study is focused on the determination of the state of the water quality and quantity within Güzelyurt Coastal Aquifer. This goal is to be achieved by making observations of the water table contours and iso-chloride lines drawn using Golden Software Surfer 2021. Additionally, obtaining seawater intrusion velocity is the other major aim of the study, essential to comment on the threat severity of the salination problem. Lastly, the study aims to complete two final objectives which are trend analysis and forecasting using Mann-Kendall's Test and an appropriate ARIMA model. Thus, this chapter will provide a detailed explanation of the collection, sampling, and analysis strategy of the available data.

4.1 Research Type and Philosophy

The study methodology follows a quantitative approach making use of the data provided by the Geology and Mining Department of the TRNC government. Even though the data is inconsistent and even missing in certain years, the study follows the concept of positivism which is common in many quantitative studies. As a consequence, the study assumes that there is a single reality and the results obtained from the available data show the only single reality existing independently from the observer, suggesting that the trend between the seawater volume entering the system and time produces a radical velocity and acceleration value (Park, Konge and Artino, 2020). In addition, the concept opens up the opportunity for the observer to interpret the truth objectively by using numerical data since the quantitative research is based

on this numerical data. Suggesting that the contour maps and the iso-chloride lines are all relevant regardless of the number of available borehole data used to produce the grid map. Moreover, a deductive approach was made pursuing the established research methodology used by (Ergil, 2000).

4.2 Research Strategy

This thesis studies the seawater intrusion phenomenon within the given context of a coastal aquifer, categorizing the thesis with a case study research strategy. A single case study is being researched as the state of the Famagusta Coastal Aquifer is far beyond recovery and there are no other aquifers in TRNC suffering from an intrusion of this scale. The strategy can be considered to be an example of an embedded case study as not every component of the aquifer water balance was implemented in the methodologies. The reason is that the data for some components such as water volume extracted from the south is not known, moreover, components such as the evapotranspiration volume of the area and the rate of infiltration from the derivation canal can only be determined by vague estimations. Correspondingly, the aquifer water balance equation was abandoned and a modified salt balance concentration equation was used in order to calculate the intrusion velocity and acceleration, making the study an embedded single case study.

4.3 Salt Balance Equation

Groundwater hydrology is a complex subject because not only is the free surface typically unknown, but the boundary condition along the free surface is quadratic in terms of the derivatives of the head and the phenomenon occurring in the unsaturated zone should be taken into consideration for its solution (Freeze and Cherry, 1979). It has only been possible to treat unconfined flow in aquifers with constant coefficients and straightforward boundary conditions. The complexity of the unconfined flow is

simplified in part by the use of Dupuit-Forchheimer assumptions, but the resulting Boussinesq equation is still non-linear, making it impossible to find solutions without the proper simplifications (Bear, 1979; Strack, 1989). The numerical attempt, therefore, requires more in-depth analysis.

Other than the impacts of the available pumps, the base of the aquifer is defined in relation to mean sea level, and the groundwater is moving within the aquifer through gravity drainage. The flow from the unsaturated zone and the gradual change in the fluid's density are insignificant. Because the aquifer is not only heterogeneous and anisotropic but also because the inputs and outputs inside the control volume over the study region are not well defined, hence the methodology adopted in this work uses a single equation that solely takes into account the flow of water within the aquifer.

The inputs and outputs are not clearly defined if the aquifer as a whole is used as the control volume under study. The aquifer has irregular and mixed boundaries, where its saturation thickness fluctuates with time and space and is not only heterogeneous but also anisotropic. The mass balance equation forms the core of the theory. Where;

$$\sum Input\ Mass - \sum Output\ Mass = \sum Change\ in\ Storage\ Mass \quad (4.1)$$

The fluctuation of mass storage inside the considered volume over the selected time period is determined by the difference between total mass inflows and total mass outflows. However, this equation cannot be applied directly as the input and output components are not clearly defined. The approximate amount of seawater that directly enters and contaminates the aquifer within the specified time period is obtained by coupling and simultaneously solving another equation from the chemical balance

equation that considers the variation of the salt concentration to eliminate some of the unknown components.

When the Control Volume is the entire aquifer, the continuity equation in integral form defined through Reynold's Transport Theorem (RTT) is as follows:

$$\frac{\partial}{\partial t} \int_{C.V.} \rho dV + \int_{C.S.} \rho v \cdot dA = 0 \quad (4.2)$$

The first term may be written in finite difference form. Then the previous equation becomes

$$\frac{(\int_{C.V.} \rho dV)_{t+\Delta t} - (\int_{C.V.} \rho dV)_t}{\Delta t} = - \int_{C.S.} \rho v \cdot dA \quad (4.3)$$

$$\left(\int_{C.V.} \rho dV \right)_{t+\Delta t} - \left(\int_{C.V.} \rho dV \right)_t = -\Delta t \int_{C.S.} \rho v \cdot dA \quad (4.4)$$

Since the salt concentration is directly related with the density of saline water within the aquifer the equation can be simplified to be written in terms of salt concentrations.

$$C_{t+\Delta t} \cdot V_{t+\Delta t} - C_t \cdot V_t = C_s \cdot V_s \quad (4.5)$$

where;

$$C_s \cdot V_s = -\Delta t \int_{C.S.} \rho v \cdot dA \quad (4.6)$$

As there is no mass outflow through the Control Surface, hence;

$$\Delta(CV) = C_s \cdot V_s \quad (4.7)$$

and

$$\Delta(CV) = \bar{h} \cdot \Delta(CA) \quad (4.8)$$

Thus the volume of saltwater entering the system can be calculated from;

$$V_s = \frac{\Delta(CV)}{C_s} = \frac{\bar{h} \cdot \Delta(CA)}{C_s} = \frac{\bar{h} \cdot [C_{t+\Delta t} \cdot A_{t+\Delta t} - C_t \cdot A_t]}{C_s} \quad (4.9)$$

where;

C_s : NaCl concentration of the seawater (ppm);

C_t : NaCl concentration of the groundwater at time t (ppm);

$C_{t+\Delta t}$: NaCl concentration of the groundwater at time $t + \Delta t$ (ppm);

V_s : volume of salt (sea) water entering into the aquifer during time interval Δt (m³);

V_t : volume of water in the aquifer at time t (m³);

$V_{t+\Delta t}$: volume of water in the aquifer at time $t + \Delta t$ (m³);

A_t : horizontal cross-section area of water in the aquifer at time t (m²);

$A_{t+\Delta t}$: horizontal cross-section area of water in the aquifer at time $t + \Delta t$ (m²);

$\bar{h}$: average saturated aquifer thickness under consideration (m).

In this region, several wells were continually monitored from 1980 to 2019 at various time periods. There are only 108 results accessible each month. Unfortunately, the wells' regular measuring times were not set, thus readings were typically taken before the start of each irrigation season after it ended, particularly when a particular well was being repaired. Because of this, the collected values for the various reading dates were collated and organized into monthly groups.

4.4 Surfer21

Part of this investigation was conducted using a Windows application named SURFER. This program's version primarily assists users in obtaining the Surface Mappings of the specified places (x, y, z). The X and Y coordinates used are the Easting and Northing coordinates. The project Coordinate Reference System (CRS)

used in the software is ED50 / UTM Zone 36N. (This CRS is based on the static plate-fixed European Datum 1950 (ED50) and a Universal Transverse Mercator (UTM) grid system.) The Easting and Northing data was given in the dataset, where the data was missing or during the combination of two datasets, QGIS software was used to georeference the missing coordinates by overlaying the map with unknown borehole coordinates on a map based on ED50 / UTM Zone 36N. Z coordinates used for groundwater and water quality are water head elevation in meters below msl and NaCl concentration in ppm, respectively. The surface mappings help the users to compute the volumetric changes between the supplied volumes and it enables users to show their results inside the necessary border. Additionally, the software has the capacity to compute the variances inside a given slice.

A vast majority of the methodology involved gridding the contour maps using Surfer21. Kriging was selected from the 13 gridding methods provided by the software to model the groundwater level and NaCl levels. Kriging is a geostatistical gridding method. The chosen approach generates a map based on the optimal prediction of the unknown values from the data observed at known locations, in addition to the interpolated quantity while accounting for the spatial correlation structure of the field-gathered data currently available (Cressie, 1990). The method is used to produce visually appealing maps using irregularly spaced data. The borehole data used are not consistent among the 40-year time frame. The quality and quantity of data taken from a borehole are different for consecutive years. Additionally, no data from the south is available, thus the data used to produce the iso-chloride maps is expected to represent the aquifer characteristics of the southern portion of the aquifer. Considering the heterogeneous and anisotropic nature of the aquifer, the kriging method is found to be sufficient. This method of gridding is also flexible which is important as the number

of available data is different every year. Kriging can be an exact and smooth interpolator as this is desired for this project (Cheeney, 1992). The kriging technique used for iso-chloride maps is restricted to the zone below mean sea level to obtain more accurate results as it is believed that the seawater intrusion does not affect the area above msl.

As the projected representative direction of the sea-water intrusion, a cross-section of the aquifer (A-A) that is approximately perpendicular to the shoreline is taken into consideration. This cross-section is then used with the slice function to observe the variation of the location-based water elevation with respect to time.

Surfer21 is able to calculate the total saturated aquifer volume within its boundary as well as the average variation of NaCl concentration over the region with respect to a representative mean concentration index of 400 ppm. Where 400 ppm refers to the locally accepted concentration limit for the municipal needs.

4.5 Time Series Design

Another aim of this study is to detect the identifiable trends within the given saturated volume and average NaCl concentration time series. The core idea of the time-series design is the usage of historical and periodic data to find out the motivation behind the change in the storage and average concentration by observing the trends of different parameters within the study area. The three main parameters considered were saturated aquifer volume, average NaCl concentration, and precipitation which is mainly in the form of rainfall. A standard trend analysis methodology was used for the set of parameters followed by the Mann-Kendall test which was used for the assessment of evidence for the monotonic trends in non-parametric datasets. After that, Sen's slope

estimator test was used to estimate the true slope of the series. Finally, formulation of an Autoregressive Integrated Moving Average (ARIMA) model applied to forecast future values based on historical data trends. Among many options, Microsoft's Excel is readily available and simple which is appropriate for both trend analysis and the Mann-Kendall test. Therefore, Excel was used for all the analysis of this research.

4.5.1 Linear Trend Estimation

The statistical technique called time series regression uses the response history and the transfer of dynamics from relevant predictors to forecast future behavior. The prediction of the behavior of a dynamic system can be achieved using experimental or observational data. The simple linear regression model adopts the formula;

$$y_t = mt + c \quad (4.10)$$

where t is the time, m is the gradient, and c is the constant. A simple linear trend estimation is used to understand the relationship of the dataset with time. In addition to regressing the full dataset, the moving average for a 5-year and a 2-year period was used to determine the turning points where trends within a shorter period can be identified. Time-Series is a type of research design, where measurements of the same variables are taken at different points in time in order to study the trends and relationships of the variables (Rudestam, 2007). Firstly, trend analysis is performed to make a rough visual observation of the annual changes in saturated volume, precipitation, and NaCl concentration as well as an initial determination of the trend for each individual parameter.

4.5.2 Normality Test

A probability distribution known as a "normal distribution" is symmetric about the mean and indicates that data that are close to the mean are more likely to occur than data that are far from the mean (Chen, 2022). In order to determine the set of tests that

are going to be used for trend analysis and forecasting, the normality of the datasets must be established. Two major categories for tests are parametric and non-parametric tests, where parametric tests assume that data is normally distributed and the populations have equal variances, on the other hand, non-parametric tests have no assumptions and are preferred for smaller sample sizes.

Table 7: Normality Test for Seasonal and Annual Datasets

Dataset	Test		Normality
	Jarque Bera	Doornik Chi-Square	
Rainfall	6.8	18.6	NND
Dry Season	24.6	19.4	NND
Wet Season	3.8	3.86	ND
SWV	2.3	2.9	ND
Dry Season	0.9	0.5	ND
Wet Season	10.3	6.5	NND
NaCl Concentration	325.8	306.8	NND
Dry Season	1386.7	510.9	NND
Wet Season	47.6	60.7	NND

(ND: Normally Distributed, NND: Not Normally Distributed.)

The tests used in Table 7 are Jarque Bera Test, Shapiro Wilk Test, and Doornik Chi-Square. Jarque Bera Test is a goodness-of-fit test to identify whether the sample data have skewness and kurtosis matching a normal distribution (Brys, Hubert and Struyf, 2004). If the score is far from 0, the data is not normally distributed. Additionally, Doornik Chi-Square Test is also a goodness-of-fit test which suggests that the dataset is a Gaussian Distribution if the Score < Critical Value which is 5.9 (Zaiontz, 2014). Results obtained in Table 7 show that three of the datasets are normally distributed and 6 are not normally distributed. As a consequence, non-parametric tests are preferred

throughout this study in order to preserve consistency and obtain more accurate and reliable results consistent with the datasets. As with most unlike parametric tests, the non-parametric test does not make assumptions about the underlying distribution (Glen, 2014). Furthermore, non-parametric tests are more robust (Addisonsoft, 2019). Although parametric tests tend to be more accurate, non-parametric tests can be applied to a broader range of situations (Addisonsoft, 2019). Another reason non-parametric tests were taken into consideration was the ability to evade the problems caused by data skew (Arun Mondal, 2020).

4.5.3 Mann-Kendall's Test

Mann-Kendall's test is the non-parametric test that is used for the trend analysis. The test was formulated by Mann (1945) to detect trends and further developed test statistic distribution by Kendall (1975) for testing non-linear trends and turning points (Arun Mondal, 2020). With the increased public concern over environmental degradation, the usage of the method has increased significantly. Generally, the trend detection studies that use Mann-Kendall's test assume that serially independent data is used in the analyses. The method conducted was used in its basic form. In other words, the data analyzed followed monotonic trends, no seasonal changes were analyzed but instead, annual changes in one season were analyzed (Salmi, 2002). The method will be applied using the Excel Template, MAKESENS. The template was developed to determine and estimate the trends in the time series of annual values of atmospheric and precipitation concentrations.

4.5.3.1 Series of Steps

Equation (4.11) shows the model that the analyzed x_i data that must have in order to apply the Mann-Kendall's test for a given t_i period, where $f(t_i)$ and ε_i are

continuously increasing/decreasing monotonic function and residual value, respectively (Salmi, 2002).

$$x_i = f(t_i) + \varepsilon_i \quad (4.11)$$

Broadly, there are two possible outcomes. Either the data shows a trend or it does not. The aim is to test the null hypothesis which suggests that there are no trends, H_0 . To do so, an alternative hypothesis is considered, H_1 , where the observations x_i are randomly ordered in time where there is an increasing or decreasing monotonic trend (Salmi, 2002). The MAKESENS template exploits Z statistics, i.e. normal approximation (Salmi, 2002). In the coding, Z statistics is applied for time series with 10 or more data points (Salmi, 2002). The time period considered in every series is the same which is 40 years. As a result, only normal approximation (Z statistics) was considered. (If there was a time series with a time period shorter than 10 years, S statics would have been considered) (Salmi, 2002).

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (4.12)$$

Equation (4.12) is used to calculate S. In this equation, n , x_j and x_k represent the number of seasonal values studied and the seasonal values in years j and k , where $j > k$, respectively (Salmi, 2002).

$$\text{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases} \quad (4.13)$$

For an n value smaller than 10, the S obtained from equation (4.12) is compared with the S derived by Mann and Kendall. On the other hand, provided that the n value for

the analysis in this study is greater than 10, a normal approximation test is used (Salmi, 2002). Firstly, variance of S (VAR(S)) is calculated by the equation (4.14).

$$\text{VAR}(S) = \frac{1}{18} \left[n(n-1)(2n+5) - \sum_{p=1}^g t_d(t_d-1)(2t_d+5) \right] \quad (4.14)$$

Here t_d , d and g represent the number of data values in the d^{th} group and the number of tied groups, respectively (Salmi, 2002). After that, the Z statistic of the test is calculated using S and VAR(S) (Salmi, 2002).

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{VAR}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{VAR}(S)}} & \text{if } S < 0 \end{cases} \quad (4.15)$$

Either if there is a trend or not is determined by the value of Z. An upward (downward) trend is indicated by a positive (negative) value of Z (Salmi, 2002).

4.5.3.2 Two-Tailed Test

MAKESENS Template uses the two-tailed test for testing the null hypothesis and statistical significance. The test has a two-sided critical area of distribution (Adam, 2019). Moreover, the goal of the method is to test whether a sample has greater than or less than a certain range of values (Adam, 2019). If the sample being tested falls into either of the critical areas, the alternative hypothesis is accepted instead of the null hypothesis (Adam, 2019).

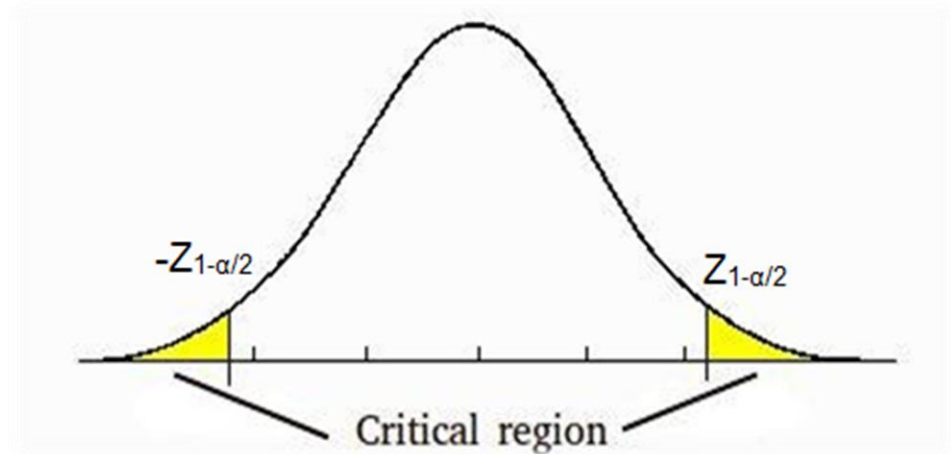


Figure 19: Two-Tailed Test's Critical Regions (Adam, 2019)

The null and alternative hypothesis was defined as H_0 and H_1 (Salmi, 2002). $Z_{1-\alpha/2}$ was obtained from standard normal cumulative distribution tables (Salmi, 2002). The critical region in the case studied is the values larger (smaller) than $Z_{1-\alpha/2}$ ($-Z_{1-\alpha/2}$) (Salmi, 2002). H_0 is rejected when Z is in the critical region and the alternative hypothesis is considered (Salmi, 2002). This process is followed to determine the monotonic trends at a significance level, α (Salmi, 2002). In the template, the two-tailed test is applied for four different values of α . These values of α are;

- 0.001
- 0.01
- 0.05
- 0.1

The α values signify the probability that rejecting H_0 was a mistake, i.e. the probability of x_i values being from a random distribution. For example, $\alpha = 0.05$ means that the probability of the values belonging to a random distribution is 5% and that there is a 5% chance that we have made a mistake by rejecting H_0 (Salmi, 2002). The most reliable significance value is 0.001 and the least reliable one is 0.1. 0.001 shows that

the existence of a monotonic trend is quite probable, whereas 0.1 represents that there is a possibility that the trend does not exist.

4.5.4 Sen's Slope Estimator Test

Where Mann-Kendall's test is about establishing whether there are existing trends or not, Sen's slope estimator test is applied to estimate the true slope of an existing trend (Salmi, 2002). In addition, the method is a non-parametric test and the estimated slope represents change per year (Salmi, 2002).

$$f(t) = Qt + B \quad (4.16)$$

The test can be only applied to data that are in the form of the equation (4.16), where B is a constant and Q is the slope. $f(t)$ is referred to $f(t)$ in the first equation (Salmi, 2002).

4.5.4.1 Series of Steps

Firstly, Q is calculated for every data value pair. This is achieved by using equation (4.17). This process makes the test more reliable as every trend between input pairs is taken and a median of the Q_i values calculated is taken (Salmi, 2002).

$$Q_i = \frac{x_j - x_k}{j - k} \quad (4.17)$$

where $j > k$.

Assuming there are n number of x_j values input, the number of slope (Q_i) estimates, N, is determined by the formulae $N = n(n-1)/2$. The median of the N values of Q_i are taken in order to estimate Sen's slope (Salmi, 2002). Equations (4.18) and (4.19) represent the concept of Sen's Estimator for odd and even N of Q_i values. Finally, the N values of Q_i are ranked from the smallest to the largest and computed by Sen's Estimator (Salmi, 2002).

$$Q = Q_{[(N+1)/2]}, \text{ if } N \text{ is odd} \quad (4.18)$$

$$Q = \frac{1}{2} \left(Q_{[\frac{N}{2}]} + Q_{[\frac{N+2}{2}]} \right), \text{ if } N \text{ is even} \quad (4.19)$$

B in equation (4.16) is obtained by calculating the n values of differences $x_i - Q_i$ (Salmi, 2002). The median of these values gives an estimate of B (Salmi, 2002). A similar procedure is applied for the confidence interval as Q_i (Salmi, 2002).

4.5.4.2 Confidence Interval

In order to determine a range where the true Q_i (and B) would lie, confidence intervals are necessary. By definition, a confidence interval is ‘a range of values for a variable of interest so that this range has a specified probability of including the true value of the variable (Davies, 2009). The confidence interval represents the probability of the test including the true value of the variable depending on the range (Davies, 2009). This probability can be also referred to as confidence level (Davies, 2009). In addition, the endpoints of the confidence interval are called confidence limits, these are represented as max and min in MAKESENS. The most traditional confidence level is 95% (Davies, 2009). In this analysis, 95% confidence level was used.

A non-parametric technique based on normal distribution is applied to estimate the confidence interval (Salmi, 2002). 95% confidence level corresponds to $\alpha = 0.05$. Firstly, the equation (4.20) is computed where $Z_{1-\alpha/2}$ is obtained from standard normal distribution and VAR(S) was defined in the equation (4.14) (Salmi, 2002).

$$C_\alpha = Z_{1-\alpha/2} \sqrt{\text{VAR}(S)} \quad (4.20)$$

Secondly, the equation (4.21) is computed for M_1 and M_2 . The largest M_1^{th} and $(M_2+1)^{\text{th}}$ from the ranked N of slope estimates, Q_i , are $Q_{\min}$ and $Q_{\max}$, respectively (Salmi, 2002). $Q_{\min}$ and $Q_{\max}$ represent the lower and upper confidence limits.

$$M_1 = \frac{(N-C_\alpha)}{2} \ \& \ M_2 = \frac{(N+C_\alpha)}{2} \quad (4.21)$$

4.6 ARIMA Model

One of the most widely used techniques for forecasting and modeling time series data is the ARIMA model (Box *et al.*, 2015). It is expressed as ARIMA, which stands for autoregressive (AR), integrated (I), and moving average (MA) portions (p , d , q). Where p denotes the autoregressive component, d is the integrated component, and q is the moving average component. Additionally, time series representing groundwater levels and quality were employed for modeling and forecasting as functions of time.

4.6.1 Box and Jenkins Method

Box and Jenkin's Method suggest that an ARIMA model must be constructed by using the following steps (Box *et al.*, 2015);

1. Identify Time Series
2. Estimate Parameters
3. Validate
4. Forecast

Check the Stationarity and Seasonality of the Time series by using Dickey-Fuller Test as well as Autocorrelation Function (ACF) and Partial Autocorrelation Function (PACF) (Patle *et al.*, 2015). Estimation of the parameters p and q can also be made using ACF and PACF by detecting the peaks and pits on the chart over confidence intervals (Patle *et al.*, 2015). Whereas, d can be detected by comparing the ACF and PACF chart with a differenced ACF and PACF chart (Patle *et al.*, 2015). Parameters

were obtained by a ready-made Excel package with an excel add-in named NumXL. NumXL is a statistical analysis add-in with the aim of building, validating, ranking, and forecasting. The parameter estimation process is a process of Maximum Likelihood Estimation (MLE) It uses a the built-in excel add-in known as ‘Solver’ as an optimizer to maximize the Log-Likelihood Function (LLF). Validation of the selected ARIMA Model is done by identifying a period ie. 2000-2010 and forecasting the following 10 years using the model. If the R^2 of the simple linear regression is close to 1, the selected model is fit to be used in forecasting future data.

A time series can be represented as;

$$Y_t = Y_1, Y_2, Y_3 \dots Y_t \quad (4.22)$$

where Y_1, Y_2, Y_3 are observations at time $t_1, t_2, t_3 \dots$

AR: This section describes how the current observation and earlier observations are related (Patle *et al.*, 2015). Each observation is solely a consequence of one prior observation if $p = 1$.

$$Y_t = c + \varphi_1 Y_{t-1} + e_t \quad (4.23)$$

where e_t is a random error, c and φ_1 are constants, and Y_t is the observed value at time t . Y_{t-1} is the prior observed value at time $t-1$. If $p > 1$, more observed series values may be added to the right side of the equation.

$$Y_t = c + \varphi_1 Y_{t-1} + \varphi_2 Y_{t-2} \dots \varphi_p Y_{t-p} + e_t \quad (4.24)$$

I: This component of the model chooses whether to directly represent the observed values or to simulate variations between successive observations (Patle *et al.*, 2015). The observations are directly modeled if $d = 0$. The discrepancies between subsequent

observations are modeled if $d = 1$. The differences of the difference are modeled if $d = 2$. In reality, d is rarely greater than 2.

MA: If $q=1$, each observation is a function of just one prior error, i.e. this section of the model identifies the relationship between observation and past q errors (Patle *et al.*, 2015).

$$Y_t = c + \theta_1 e_{t-1} + e_t \quad (4.25)$$

where c is a constant term, e_t stands for the random error at time t and e_{t-1} for the random error that occurred before it at time t minus 1. If $q > 1$, additional errors may be added to the right side of the equation. Time series is analyzed for stationarity and forecast was done assuming normality is not a necessity for the model.

4.6.2 Stationarity of the Time Series

The stationarity concept in time series analysis is key as most of the models, including ARIMA, require the time series to be stationary to be used. In order to call a time series constant, it must have constant mean and standard deviation throughout the given period. Furthermore, there must be no predictable seasonal behaviour present. Determination of the stationarity in a time series can either be done visually by analyzing if any of the above criteria is not met, doing global vs local tests of mean and standard deviation, or implementing by Augmented Dickey-Fuller Test.

4.6.2.1 Dickey-Fuller Test

The original Dickey-Fuller (DF) Test assumes that the time series in question is an AR(1) process, this process can be formulated as Equation (4.26) (Dickey and Fuller, 1979). Where the null hypothesis (H_0) suggests when $\phi_1 = 1$, there are unit roots and the dataset is not stationary. On the contrary, the alternative hypothesis (H_1) suggests that when $\phi_1 < 1$ there are no unit roots thus the dataset is stationary (Dickey and

Fuller, 1979). Making the dataset stationary requires us to subtract y_{t-1} from both sides resulting in the equation below;

$$\Delta Y_t = c + \delta Y_{t-1} + e_t \quad (4.26)$$

where $\delta = \varphi_1 - 1$.

The alternative H_0 and H_1 become $\delta = 0$ and $\delta < 0$, respectively. Using δ , a t statistic can be obtained to compare with the Dickey-Fuller Distribution defined by Dickey and Fuller by using the formula;(Dickey and Fuller, 1979)

$$t_s = \frac{\hat{\delta}}{se(\hat{\delta})} \quad (4.27)$$

Where $\hat{\delta}$ can be derived from δ and se is the standard error of $\hat{\delta}$. Afterwards, t_s is compared to the Dickey-Fuller Distribution's Critical Value (DF_{CV}). When $t_s < DF_{CV}$ H_0 is rejected (Dickey and Fuller, 1979). The hypothesis suggesting the time series has unit roots is rejected, meaning the series is stationary (Nesbitt, 2016). On the contrary, when $t_s > DF_{CV}$ H_0 is not rejected. The evidence needed to call the time series stationary is not provided and the time series cannot be accepted to be stationary (Dickey and Fuller, 1979).

4.6.2.2 Augmented Dickey-Fuller (ADF) Test

Generally, time series models are more complicated than AR(1). The Dickey-Fuller test is augmented with the assumption that the time series is not AR(1) but AR(p) with the formula;(Nesbitt, 2016)

$$Y_t = \mu + \sum_{i=1}^p \varphi_i Y_{t-i} + e_t \quad (4.28)$$

The same step is repeated where Y_{t-1} is subtracted from both sides of the equation;

$$\Delta Y_t = \mu + \delta Y_{t-1} + \sum_{i=1}^p \beta_i Y_{t-i} + e_t \quad (4.29)$$

The null and alternative hypothesis for the ADF test is the same. The formula of the t statistic becomes;

$$t_s = \frac{\hat{\beta}_t}{se(\hat{\beta}_t)} \quad (4.30)$$

The stationarity tests were made to a significance level of 5%. The DF_{CV} values for equations of 4 different regression Models are given in Table 8.

Table 8: ADF Test Scenarios and Conditions for the Scenario, Equation used, and Dickey-Fuller Distribution's Critical Values (Nesbitt, 2016)

Regression Model	Equation	DF _{CV}
No Constant, No Trend	$\Delta Y_t = \delta Y_{t-1} + \sum_{i=1}^p \beta_i Y_{t-i} + e_t$	-1.9
Constant Only	$\Delta Y_t = \mu + \delta Y_{t-1} + \sum_{i=1}^p \beta_i Y_{t-i} + e_t$	-2.9
Constant+ Trend	$\Delta Y_t = \mu + \delta Y_{t-1} + \lambda_1 t + \sum_{i=1}^p \beta_i Y_{t-i} + e_t$	-3.5
Constant+Trend+Trend ²	$\Delta Y_t = \mu + \delta Y_{t-1} + \lambda_1 t + \lambda_2 t^2 + \sum_{i=1}^p \beta_i Y_{t-i} + e_t$	-4.0

(where $\lambda_1 t$ is for Trend and $\lambda_2 t^2$ is for Trend²)

4.6.3 Autocorrelation and Partial Autocorrelation Function

In order to understand what ACF and PACF are, an example was given using the salt concentration dataset.

$$\begin{bmatrix} C_t = \text{Avg Concentration this year} \\ C_{t-1} = \text{Avg Concentration last year} \\ C_{t-2} = \text{Avg Concentration 2 year ago} \end{bmatrix}$$

Several external factors might be involved in the determination of the up-to-date value of C_t such as aquifer water volume, rainfall, evapotranspiration, and water outtake from the system. However, the most intuitive determiner of C_t this year is C_{t-1} . C_{t-2} has an effect on C_{t-1} (RitvikMath, 2019). Additionally, C_{t-1} influences C_t . Not only there is an indirect effect C_{t-2} has on C_t , but also it can have a direct effect on C_t (RitvikMath, 2019). ACF is comprised of a compilation of the correlation between the data within direct and indirect routes. Whereas PACF only considers the direct effect C_{t-2} has on C_t (RitvikMath, 2019).

Usage of both ACF and PACF is necessary as direct effect sometimes has little to no effect on C_t (Green *et al.*, 1995). The importance of PACF surfaces, as ACF can sometimes be deceiving. ACF can be calculated simply by taking the Pearson correlation between a dataset and its lagged version (Green *et al.*, 1995). Calculation of PACF can be described with another example considering salt concentration lagged by 2 years (Green *et al.*, 1995). ϕ_{22} given in the equation below is a coefficient that displays the direct effect C_{t-2} has on C_t . This is considered to be a direct effect as the effect of C_{t-1} is given by ϕ_{21} in the same equation. ϕ_{22} is the PACF for this example.

$$C_t = \phi_{21}C_{t-1} + \phi_{22}C_{t-2} + \varepsilon_t \quad (4.31)$$

The following formulae can be used to calculate ACF and PACF (Box and Jenkins, 1976). Where ACF is:

$$r_d = \frac{\sum_{i=1}^{n-d} (Y_i - \bar{Y})(Y_{i-d} - \bar{Y})}{\sum_{i=1}^n (Y_i - \bar{Y})^2} \quad (4.32)$$

And PACF can be defined as:

$$\hat{\phi}_{11} = r_1 \quad (4.33)$$

$$\hat{\phi}_{22} = (r_2 - r_1^2)/(1 - r_1^2) \quad (4.34)$$

$$\hat{\phi}_{dj} = \hat{\phi}_{d-1,j} - \phi_{dd}\phi_{d-1,d-j} \quad d = 2, j = 1, 2, \dots, d-1 \quad (4.35)$$

$$\hat{\phi}_{dd} = \left(r_d - \sum_{j=1}^{d-1} \phi_{d-1,j} r_{k-j} \right) / \left(1 - \sum_{j=1}^{d-1} \phi_{d-1,j} r_j \right), \quad k = 3 \dots \quad (4.36)$$

Where:

r_d : dth lag sample autocorrelation.

$\hat{\phi}_{dd}$: dth lag sample partial autocorrelation.

$\bar{Y}$: is the average of the n observations.

4.6.4 Akaike Information Criterion

The Akaike Information Criterion (AIC) was selected for model identification. The AIC concept of data modeling, which is free from the individual theory of sampling distributions and other statistical tables, evaluates models by an information quantity (Akaike, 1998). The AIC method for elimination of the tentative models is appropriate as it can be mathematically reconciled with conventional methods and it has a unified approach focused on dealing with advanced problems (Y. Sakamoto, 1988). The AIC score of a model with AR(p) and MA(q) is determined by;

$$AIC(p, q) = N \log (\text{MLE of innovation variance}) + 2(p + q) \quad (4.37)$$

Where MLE is the maximum likelihood estimation. The ARIMA models of different p and q values with the Minimum Akaike Information Criterion Estimate (MAICE) values were selected for further validation to determine the best model for forecasting.

4.6.5 Validation

After the elimination of the models based on MAICE, 2009-2019 was forecasted using the available 1980-2008 data. The model validity was determined based on the following model statistics;

- R^2 : Determines the percentage of the dependent variable's variance that the independent variable can account for statistically in a regression model (CFI, 2022).
- RMSE: Root Mean Squared Error (Ergil, 2021)

$$RMSE = \sqrt{\frac{1}{n} \sum_{t=1}^n (y_t - x_t)^2} \quad (4.38)$$

- MAPE: Mean Absolute Percentage Error (Ergil, 2021)

$$MAPE : \frac{1}{n} \sum_{t=1}^n \left| \frac{y_t - x_t}{x_t} \right| * 100 \quad (4.39)$$

- MAE (MAD): Mean Absolute Error (Deviation) (Ergil, 2021)

$$MAE = \frac{1}{n} \sum_{t=1}^n |y_t - x_t| = \frac{1}{n} \sum_{t=1}^n |e_t| \quad (4.40)$$

The desired outcome from a model is $R^2 > 0.85$ and the model where the rest of the parameters are smallest is preferred.

Chapter 5

RESULTS

To investigate the patterns in water table fluctuation and assess the groundwater potential, it is crucial to study the continuous records of dry and wet seasonal water levels. The variations in groundwater levels between dry and wet periods show the combined impact of groundwater recharge and draft in a region. Additionally, trend analysis of the quality of the water is fundamental to observe the similarities between the trends in water volume and the trends of water quality. For that matter, comments can be made based on the trends and forecast, on whether the table fluctuation is due to recharge or seawater intrusion. Moreover, trend resulting from the fluctuations in the rainfall data is used to predict the effect of nature on the state of the groundwater quality and quantity. To determine the trends in the time series of dry and wet season groundwater levels, the Mann-Kendall test results were used. For predicting, the results of an ARIMA model analysis of time series data were used.

5.1 Durbin Watson Statistic & Spearman Correlation Coefficient

In order to estimate the correlation between the seasonal saturated volume of water available in the aquifer and the seasonal effective precipitation an autocorrelation analysis was made known as the Durbin-Watson (DW) Test. To check for autocorrelation, the Durbin-Watson statistic is often utilized. The Durbin-Watson test has a range of results from 0 to 4 (Durbin and Watson, 1950). A result that is very close to 2 indicates a very low autocorrelation level. Results that are closer to 0 or 4 indicate a stronger positive autocorrelation or a stronger negative autocorrelation,

respectively (Durbin and Watson, 1950). A smooth curve can be drawn using the observations that have positive autocorrelation. A regression line can be added to show that a positive error is followed by another positive error and a negative error is followed by another negative error. Whereas in the case of negative autocorrelation, an increase in a time interval causes a corresponding decline in the lagged interval (Durbin and Watson, 1950). A regression line plot of the observations demonstrates that a positive mistake will be followed by a negative one and vice versa. The Durbin-Watson statistic can be obtained by dividing the sum of the squared difference in residuals by the sum squared of residuals (Durbin and Watson, 1950).

$$DW = \frac{\sum_{t=2}^T \{(e_t - e_{t-1})^2\}}{\sum_{t=1}^T e_t^2} \quad (5.1)$$

Durbin-Watson statistic, which is the result of DW test performed on effective rainfall(mm) and saturated water volume (MCM) was found to be 3.11 (Durbin and Watson, 1950). As 3.11 is greater than 2.5, it is concluded that a significant negative autocorrelation is present. A negative correlation between rainfall and saturated aquifer volume means that an increase/decrease in rainfall corresponds to a decrease/increase in saturated water volume. This means that the difference between the corresponding data for each given dataset move in opposite directions to each other.

In order to understand the natural recharge timing, Spearman's Rank Correlation Coefficient (SRCC) Test was used. The application of this test to the given non-parametric dataset returns the degree and the direction of the linear correlation between the two continuous variables ('Spearman Rank Correlation Coefficient', 2008). Using the formula below, r_k can be calculated. Where a larger/smaller r_k value closer to 1/-1

represents a significant correlation in the positive/negative direction ('Spearman Rank Correlation Coefficient', 2008).

$$r_k = 1 - \frac{6 \sum D^2}{N(N^2 - 1)} \quad (5.2)$$

In Figure 20, A negative correlation can be observed between rainfall and volume when there is no lag with a magnitude of -0.275. A negative correlation with smaller magnitudes can also be seen between the variables when rainfall is lagged by 2 and 4 seasons. Whereas, the peak positive correlation coefficient of 0.282 can be seen at lag-1. Additionally, SRCC calculated by rainfall lagged by 3 and 5 seasons give a positive correlation with minor declines in the magnitude. The conclusion can be drawn from Figure 20 that the effect of rainfall on the saturated water volume is observed after one season.

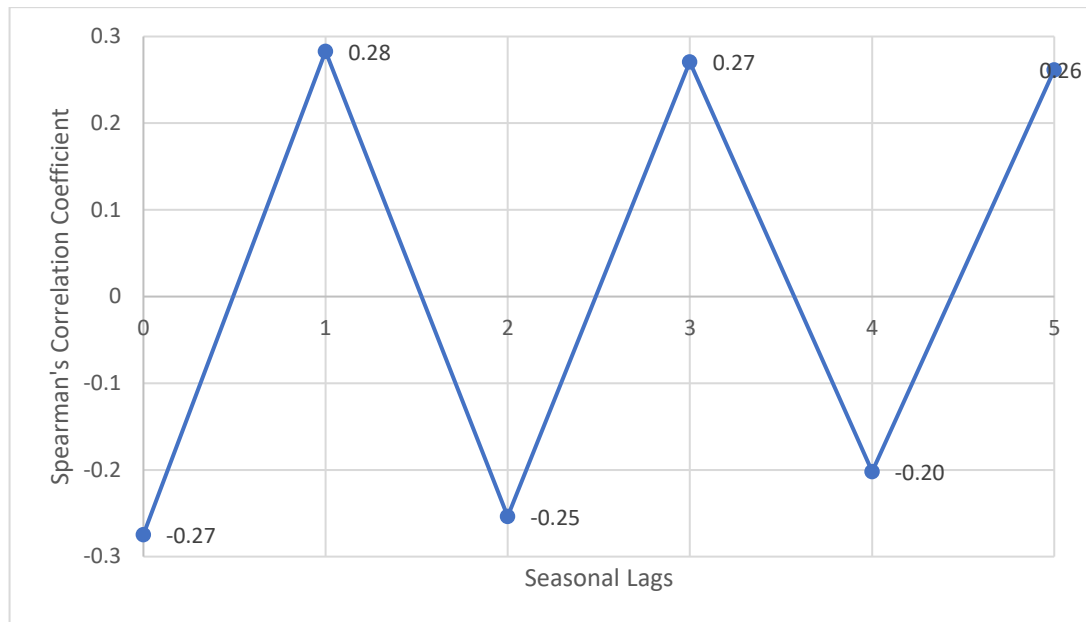
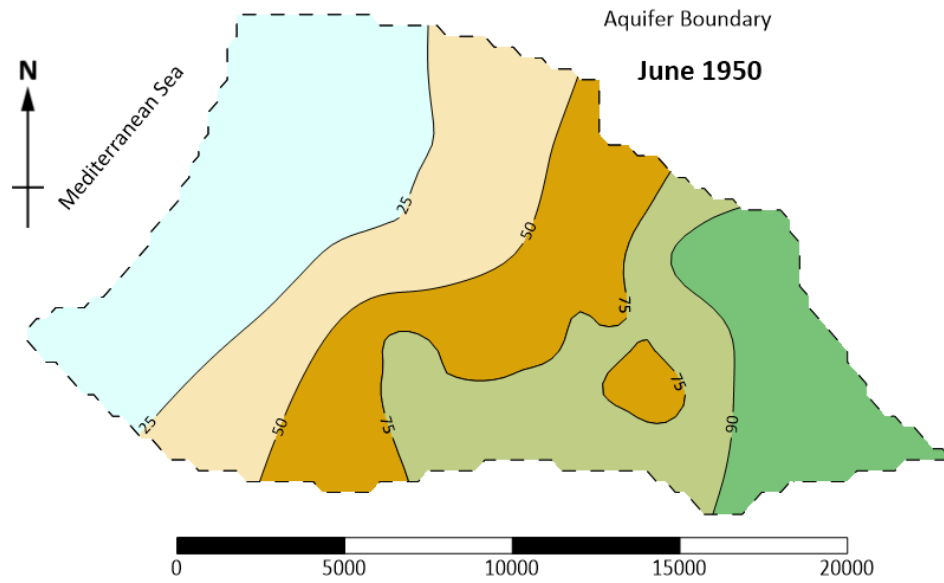


Figure 20: SRCC Test Results for Different Seasonal Lags Performed on Lagged Effective Rainfall (mm) and Saturated Water Volume (MCM).

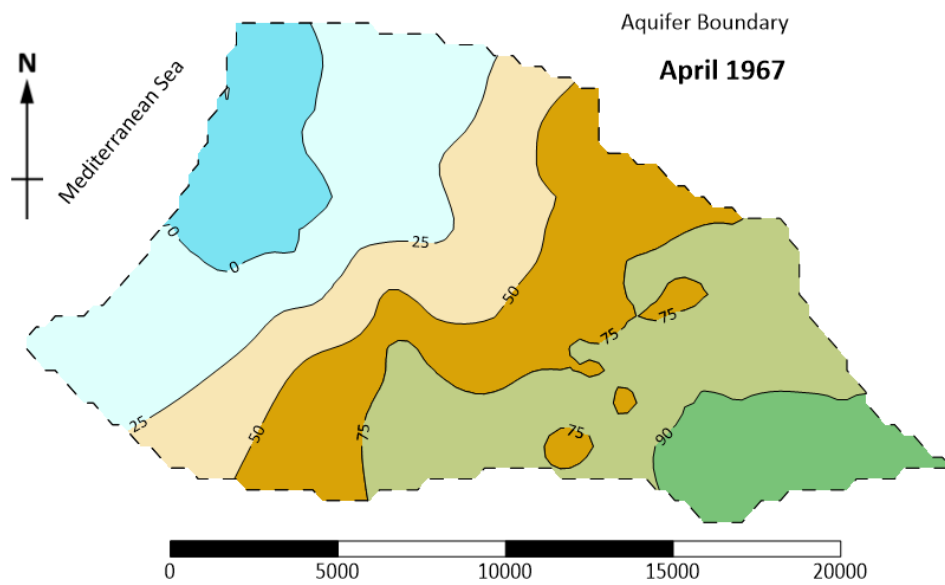
5.2 Groundwater Level Maps

The oldest records of the aquifer groundwater contours date back to 1950. After a long period of no recordings, there is another groundwater level dataset available in 1967. The natural state of the aquifer was shown in Figure 21. Additionally, the water table elevations around the time when seawater intrusion was getting started was shown in Figure 22. Saturated aquifer volume available within the aquifer in 1950 and 1967 are estimated to be 20601 MCM and 19680 MCM, respectively.



Data Sources: TRNC Geology & Mining Department, Government of Cyprus Geological Survey Department.
 Cartographer: Berkay Rasih Vaiz
 Created on: 2022-08-16
 Scale in meters

Figure 21: Water Table Contours of Güzelyurt Aquifer in June 1950 in meters



Data Sources: TRNC Geology & Mining Department, Government of Cyprus Geological Survey Department.
 Cartographer: Berkay Rasih Vaiz
 Created on: 2022-08-16
 Scale in meters

Figure 22: Water Table Contours of Güzelyurt Aquifer in April 1967 in meters

5.2.1 Dry Season Period

The contour maps presented for the dry season starts in 1980. The period between each figure is approximately 10 years. Thus, a decadal depletion of the aquifer groundwater levels is visually presented in the following figures. Additionally, the area affected by the intrusion enlarges with time. Water table elevation pits are most significant in 1998. This is the era where the awareness of the situation was minimum, and the effect of the intrusion was extreme. 2008 mitigates and 2018 shows major improvement in the water table elevations, where the area lower than msl dwindles. Estimated available saturated aquifer volume in the years 1980, 1988, 1998, 2008, and 2018 are 11019 MCM, 10663 MCM, 8467 MCM, 9305 MCM, and 10962 MCM, respectively.

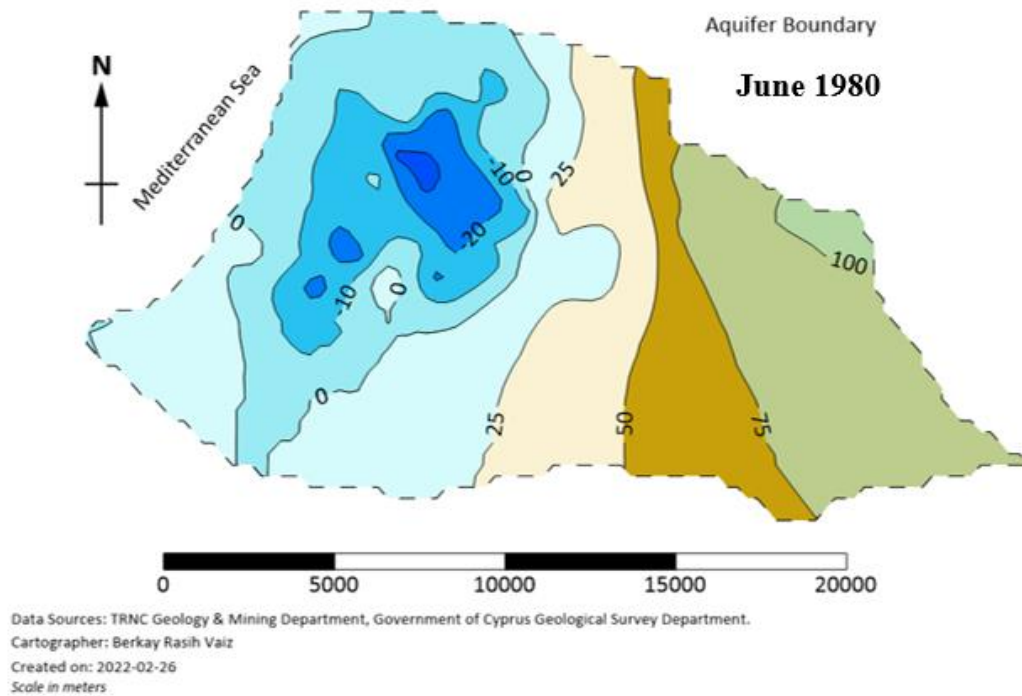


Figure 23: Water Table Contours of Güzelyurt Aquifer in June 1980 in meters

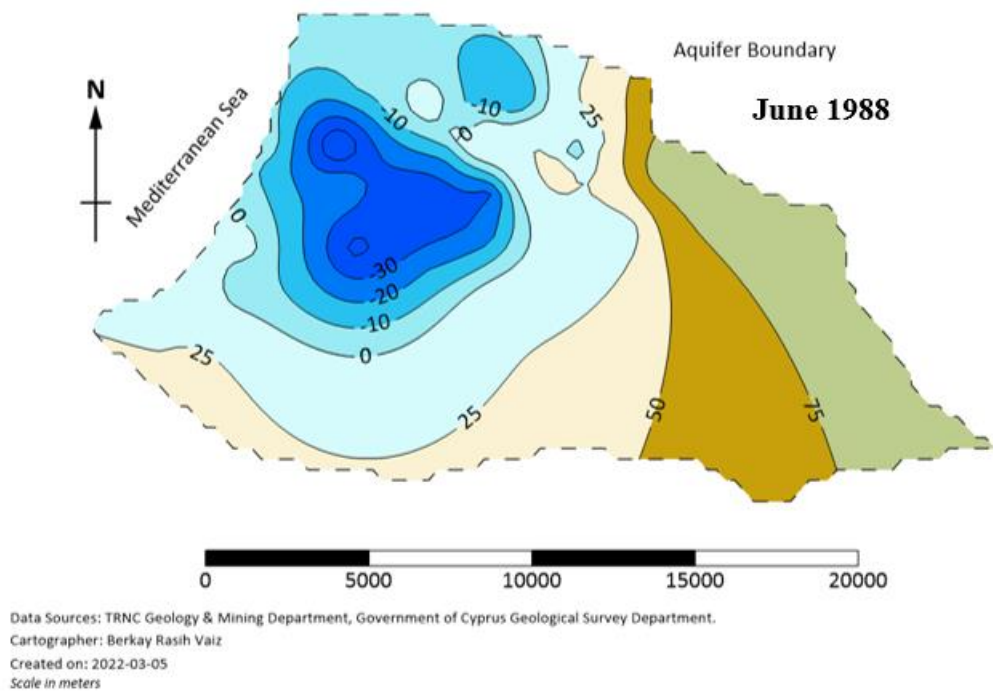


Figure 24: Water Table Contours of Güzelyurt Aquifer in June 1988 in meters

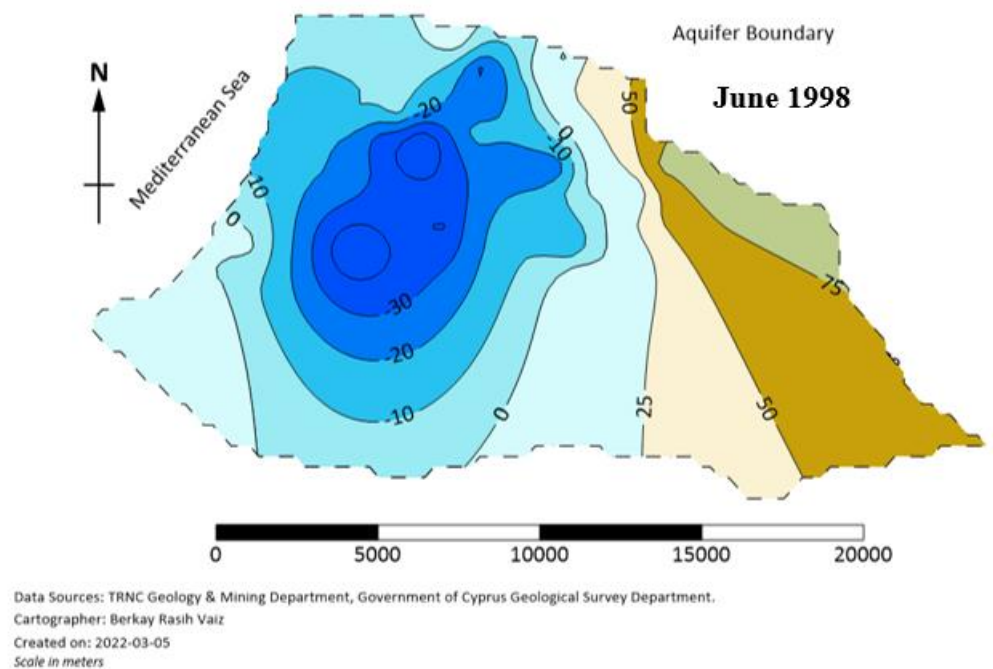


Figure 25: Water Table Contours of Güzelyurt Aquifer in June 1998 in meters

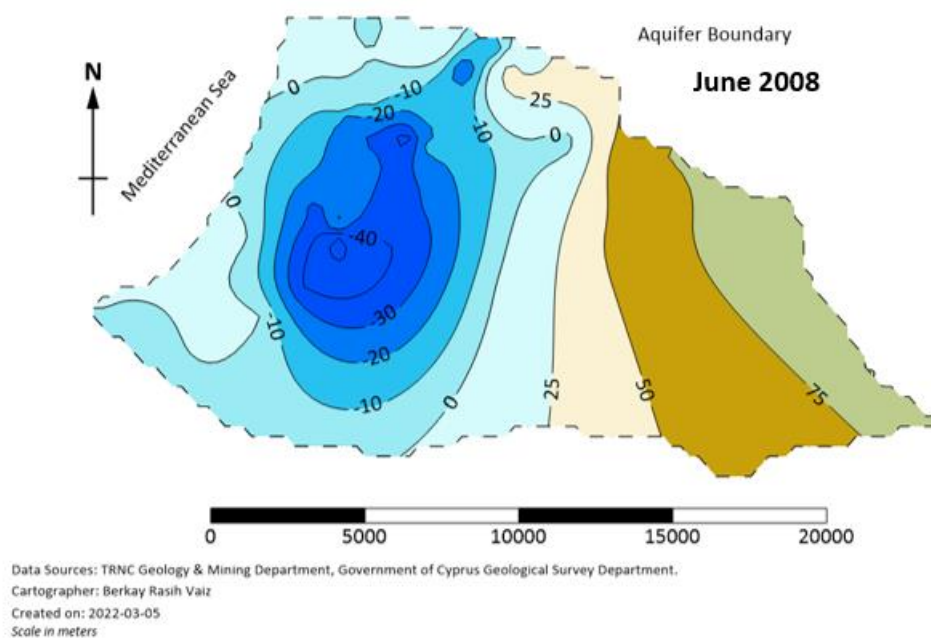


Figure 26: Water Table Contours of Güzelyurt Aquifer in June 2008 in meters

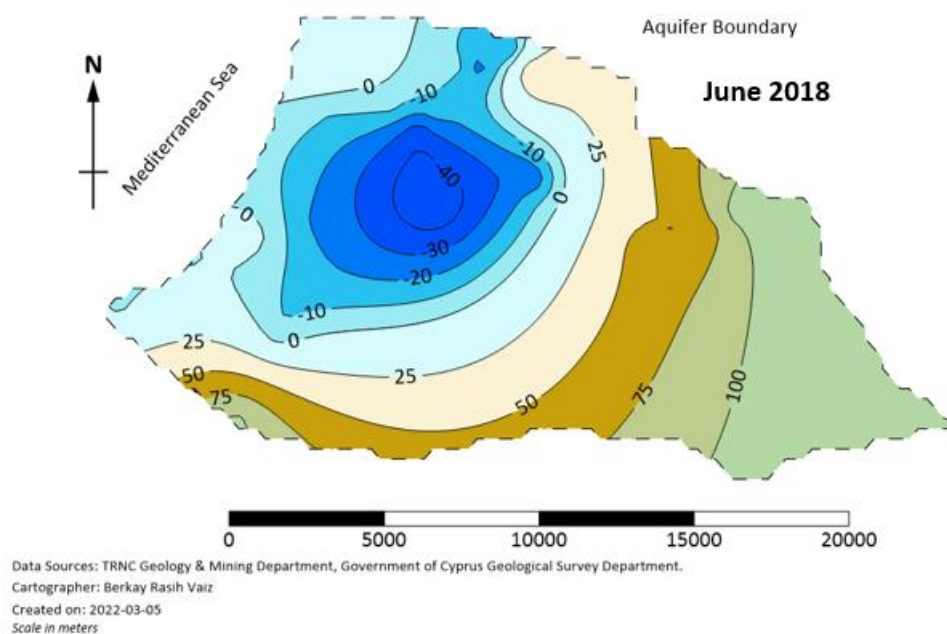


Figure 27: Water Table Contours of Güzelyurt Aquifer in June 2018 in meters

5.2.2 Wet Season Period

A similar presentation was put on for the wet season. The period between each figure is approximately 10 years again. Thus, a visual presentation of a decadal depletion of the aquifer groundwater levels can be seen in the following figures. However, this time an even larger area is affected by the intrusion, and the water table elevation is smaller in general. This can be considered a consequence of the lagged rainfall's effect on the wet season water table. Much like the dry season, the area affected by the intrusion enlarges with time, but this time the dwindling is not clear, in fact, the water table contours represent much worse values with time, especially in the westernmost region of the aquifer, where the values are mostly below msl. Available saturated water volume within the aquifer in 1980, 1988, 1998, 2009, and 2018 are 10027 MCM, 10562 MCM, 10207 MCM, 8961 MCM, and 8793 MCM, respectively.

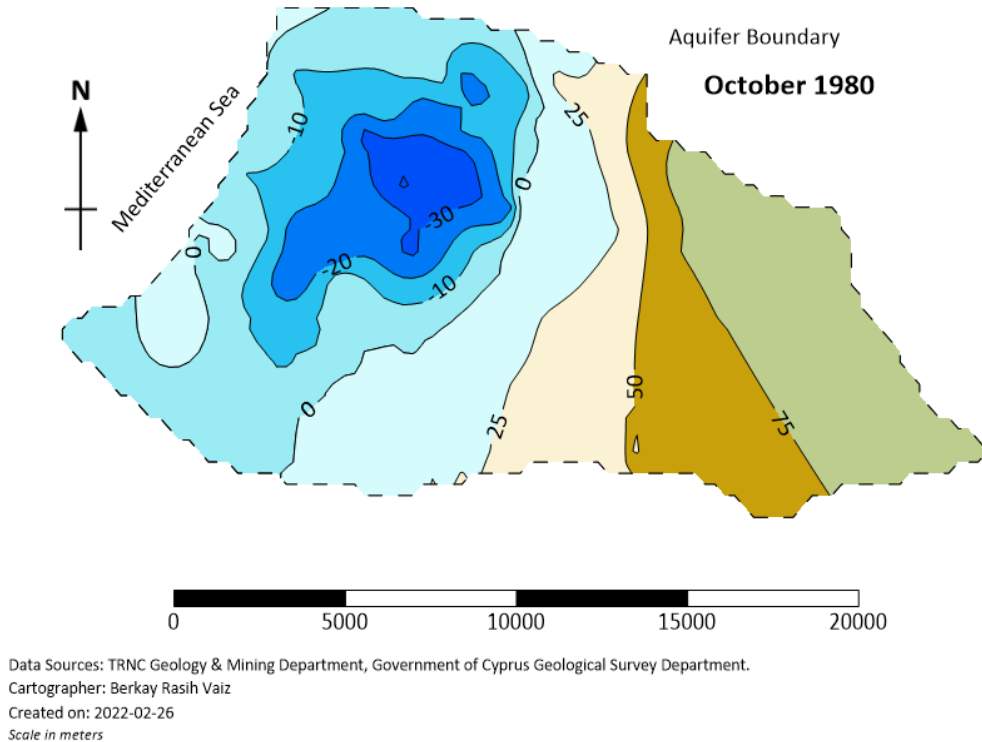
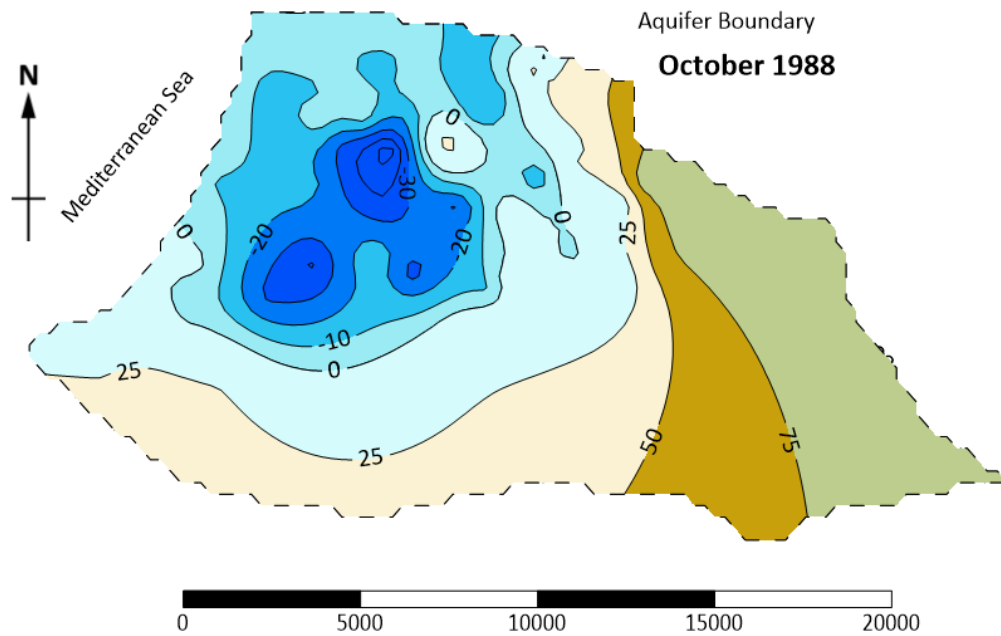
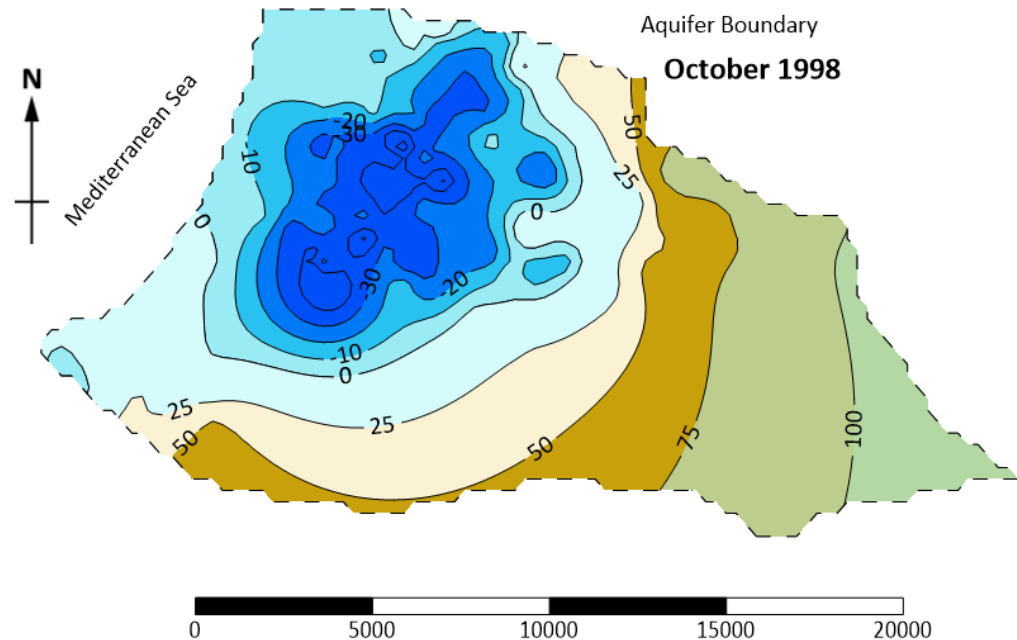


Figure 28: Water Table Contours of Güzelyurt Aquifer in October 1980 in meters.



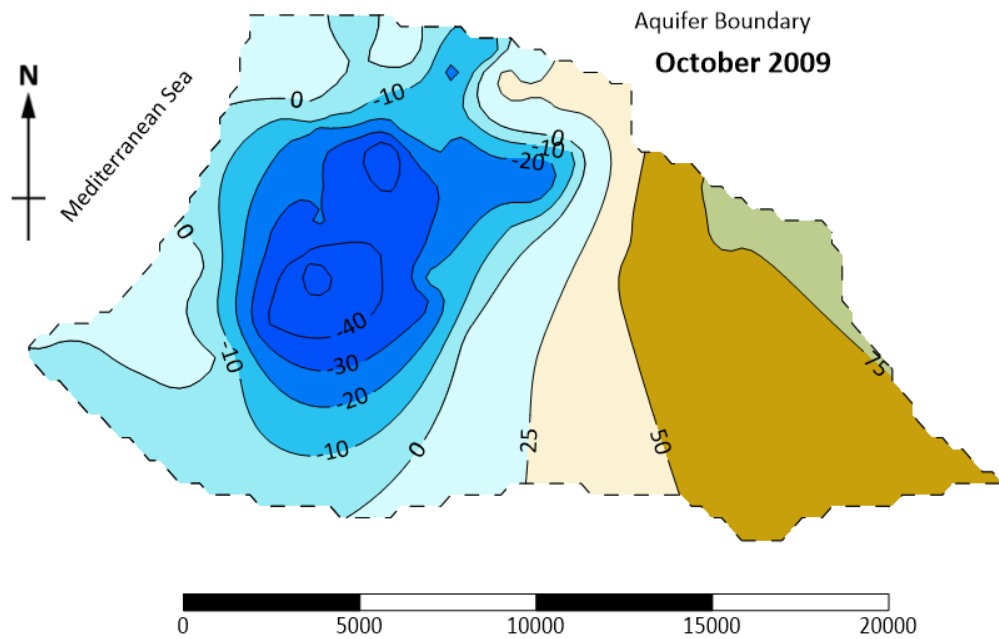
Data Sources: TRNC Geology & Mining Department, Government of Cyprus Geological Survey Department.
 Cartographer: Berkay Rasih Vaiz
 Created on: 2022-03-05
 Scale in meters

Figure 29: Water Table Contours of Güzelyurt Aquifer in October 1988 in meters



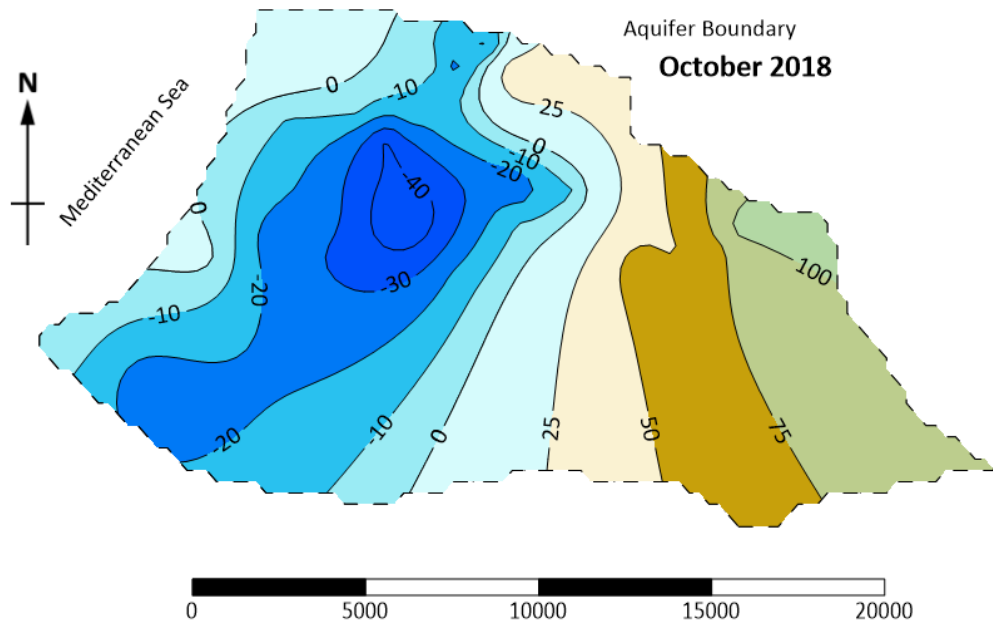
Data Sources: TRNC Geology & Mining Department, Government of Cyprus Geological Survey Department.
 Cartographer: Berkay Rasih Vaiz
 Created on: 2022-03-05
 Scale in meters

Figure 30: Water Table Contours of Güzelyurt Aquifer in October 1998 in meters



Data Sources: TRNC Geology & Mining Department, Government of Cyprus Geological Survey Department.
 Cartographer: Berkay Rasih Vaiz
 Created on: 2022-03-05
 Scale in meters

Figure 31: Water Table Contours of Güzelyurt Aquifer in October 2009 in meters



Data Sources: TRNC Geology & Mining Department, Government of Cyprus Geological Survey Department.
 Cartographer: Berkay Rasih Vaiz
 Created on: 2022-03-05
 Scale in meters

Figure 32: Water Table Contours of Güzelyurt Aquifer in October 2018 in meters

5.2.3 Linear Trendline Forecast

The saturated aquifer volume (SAV) time series calculated from the difference between water table contour maps and the aquifer base map is displayed in Figure 33. Additionally, the 2-year moving average is displayed to identify the turning point where the data has a strong correlation. The dip after 2015 shows that there is a positive correlation following 2015.

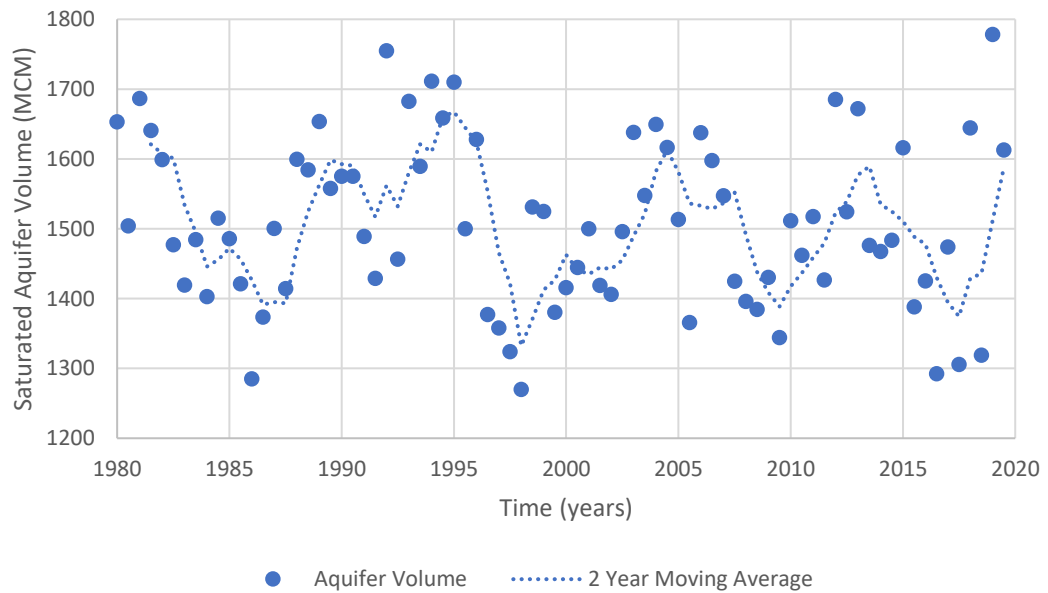


Figure 33: Saturated Aquifer Volume Time Series with a 2-Year Moving Average Trendline in MCM

Using the data between 2015 and 2019 a linear regression trendline equation was obtained in Figure 34. Using the saturated aquifer volume calculated in 1950 and 1967, the time it takes for the aquifer to reach the same saturation level it had in 1950 and 1967 can be calculated using the equation given below.

$$SAV = 18.564t + 1393.4 \quad (5.3)$$

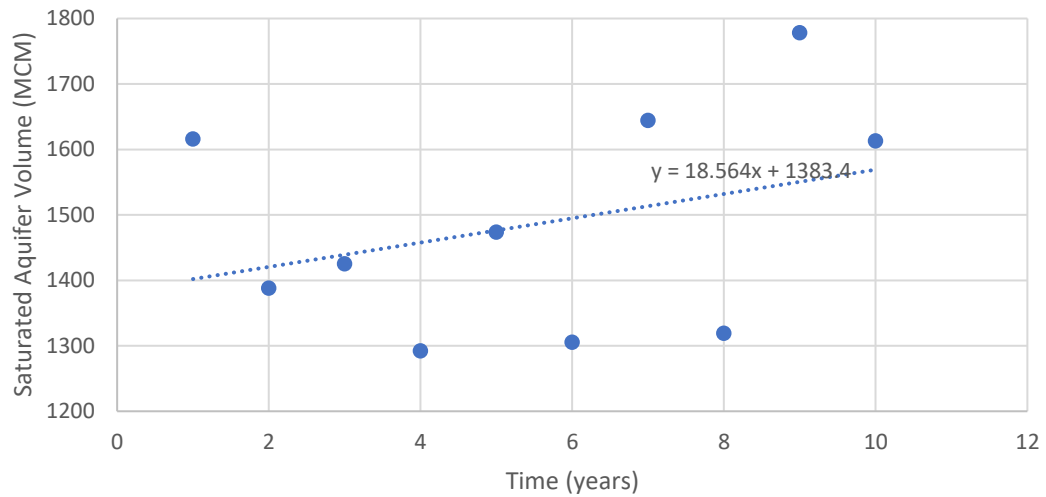


Figure 34: Linear Regression Trendline of Time Series from 2015 to 2019 in MCM

As a consequence, the time it will take for the aquifer to return to a state similar to 1967 when the seawater intrusion was just starting, is 43 years. Furthermore, the time it will take for the aquifer to return to its natural state pre-intrusion is 46 years according to the linear regression trendline between 2015 and 2019.

5.2.4 Water Table Elevation Fluctuations Along the A-A Cross-section

Figure 35 shows the decadal changes in the wet season groundwater elevations along the A-A cross-section shown in Figure 9. Compared to the maximum depletion observed which was in the year 2000, the closer years, 2010 and 2019, depletion observations are similar to 1980 and 1990. However, the cone of depression has much steeper slopes in 2019. Additionally, the water table elevation near the coast follows a straight line at zero for a few meters, displaying the overall improvement in this season. 1976 was only available for the wet season and 1950 and 1967 were only available for the dry seasons. However, they were included in both of the figures to get a better comparison of the depletion severity.

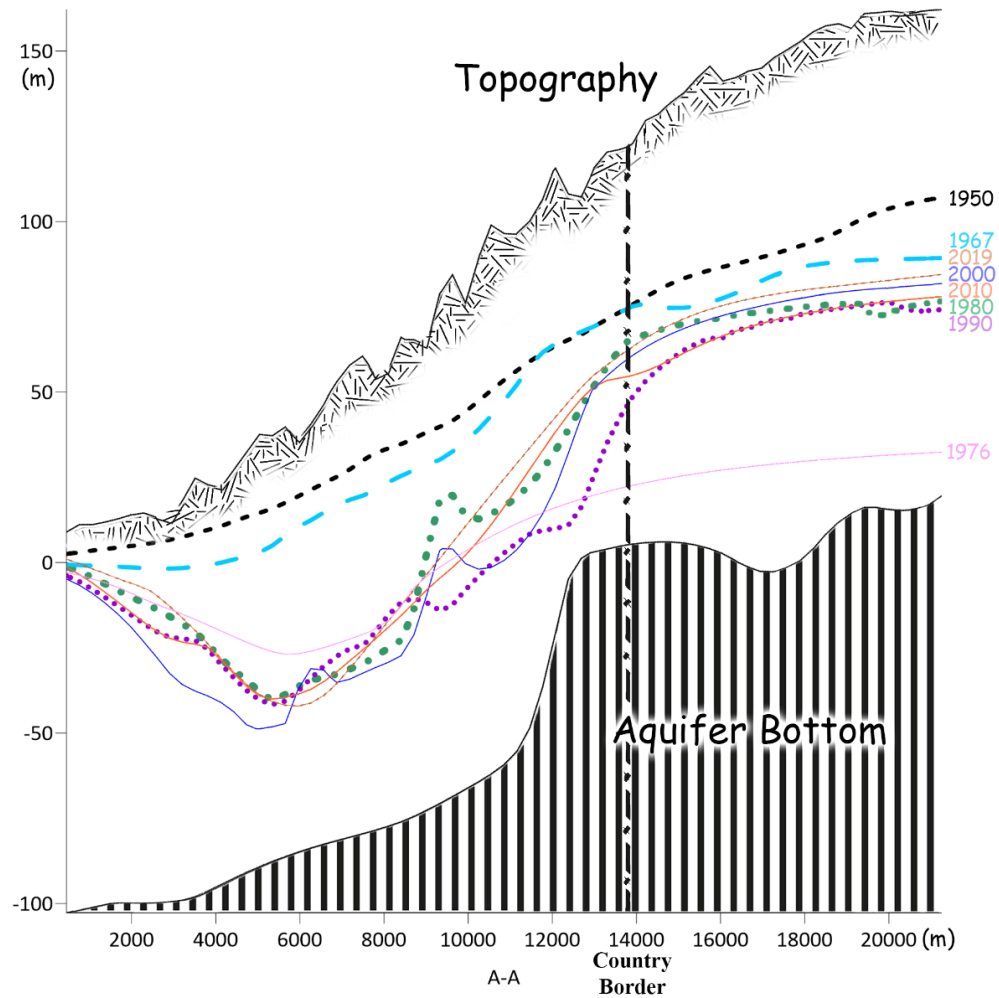


Figure 35: Water Table Elevation Fluctuations in Wet Season along the A-A Cross-Section

Compared to the wet season, the water table elevations are higher in general along the A-A cross-section in dry season. In addition, the improvement in the groundwater depletion problem can be seen as the surface of the cone of depression becomes steeper after 2000 and depth improves slightly. Whereas from 1980 to 2000 the water table becomes deeper. The cone of depression observed in year 2000 is the deepest among them in both seasons. 2019 follows a similar trajectory for both seasons, whereas water table elevations are lower in 2010's dry season.

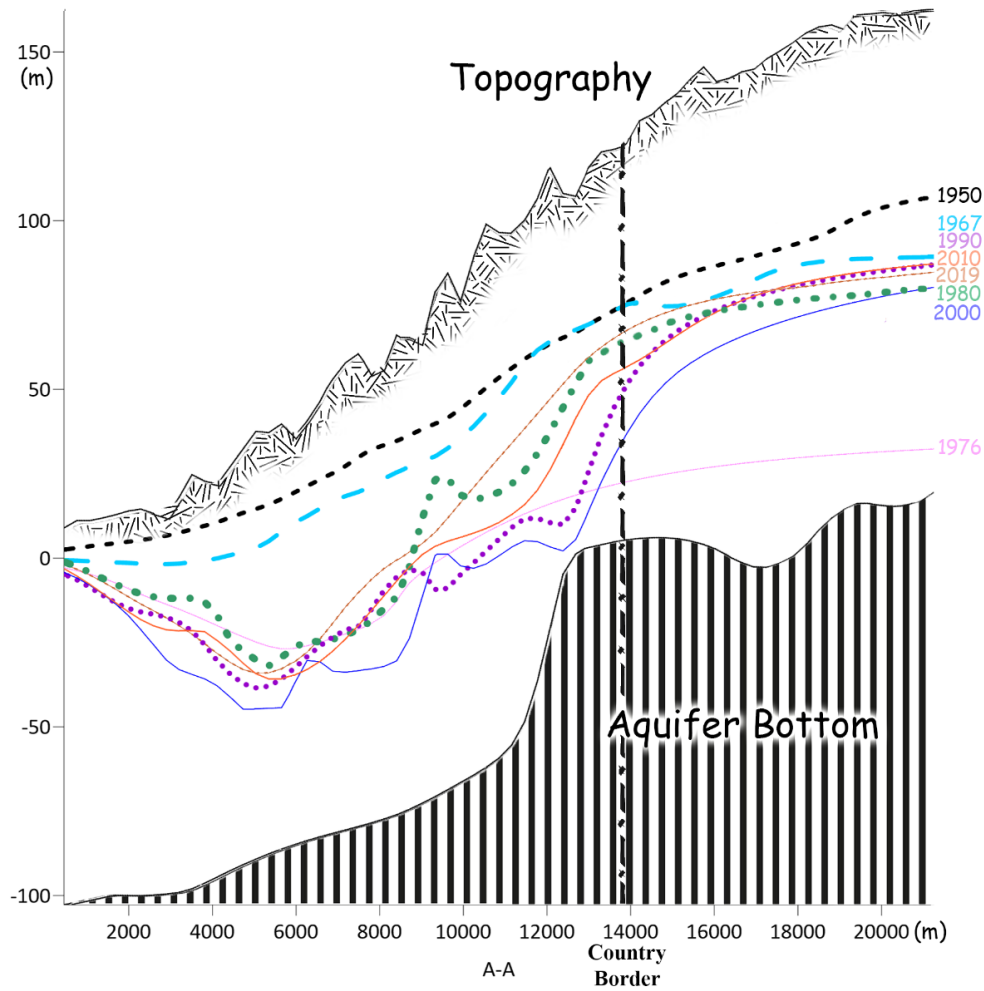


Figure 36: Water Table Elevation Fluctuations in Dry Season along the A-A Cross-Section.

The dotted vertical line shows the border between TRNC and South Cyprus. Borehole information on water table elevations in South Cyprus was not available for this region, the shown water table is a byproduct of the Kriging method.

5.3 Salt Concentration Iso-chloride Maps

Unlike water head elevations, the need for NaCl iso-chloride maps from the 1950s is not necessary as an aquifer unaffected by seawater intrusion phenomena is anticipated to be less than or equal to 400 ppm all throughout the aquifer. Seasonal NaCl concentration iso-chloride maps based on water quality chemical analysis on the specimen taken from different boreholes for dry and wet seasons are computed below.

5.3.1 Dry Season Period

Iso-chloride maps are presented approximately a decade apart for the dry season starting from 1980. The effect of the phenomena on a 10-year basis is visually presented. Area with NaCl concentration higher than 400 ppm is much smaller in 1980. In 1988 area near the coast is faced with a severe rise. In 1998, 2007, and 2019, the salination levels are still high but are not as severe as in 1988. Even though the salination concentration decreases over time, the area near the coast remains salty even in 2019. The average NaCl concentration in the years 1980, 1988, 1998, 2007, and 2019 are 431 ppm, 5930 ppm, 682 ppm, 1151 ppm, and 1416 ppm, respectively.

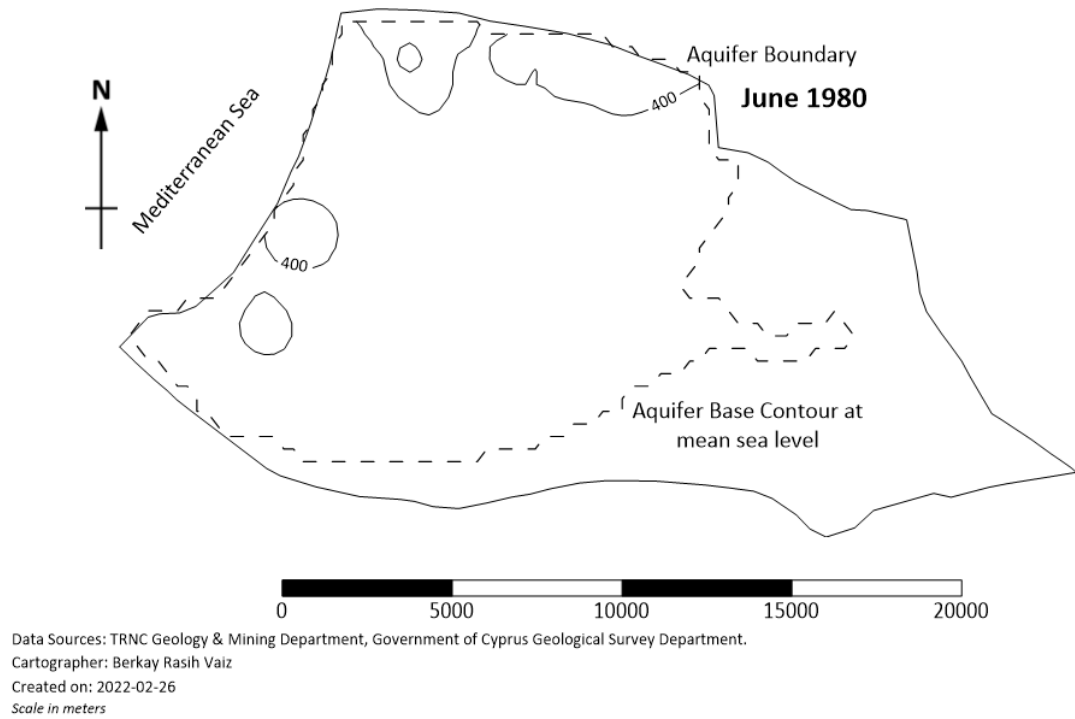


Figure 37: NaCl Iso-Chloride Map of Güzelyurt Aquifer in June 1980 in ppm

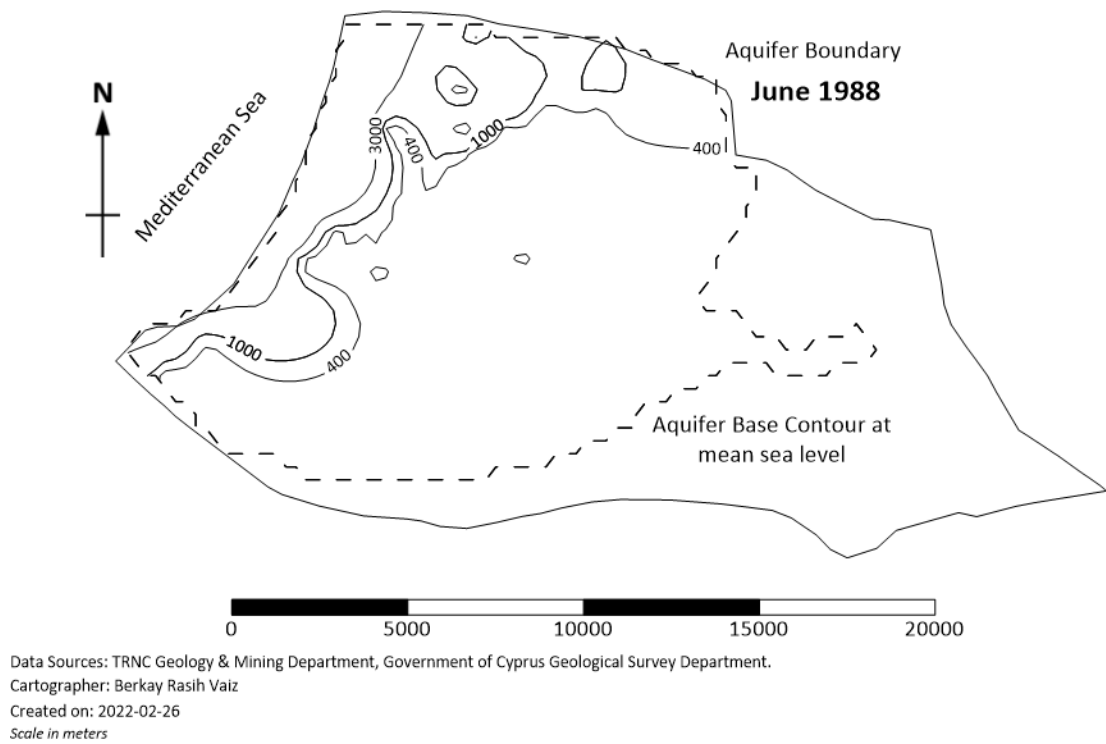


Figure 38: NaCl Iso-Chloride Map of Güzelyurt Aquifer in June 1988 in ppm

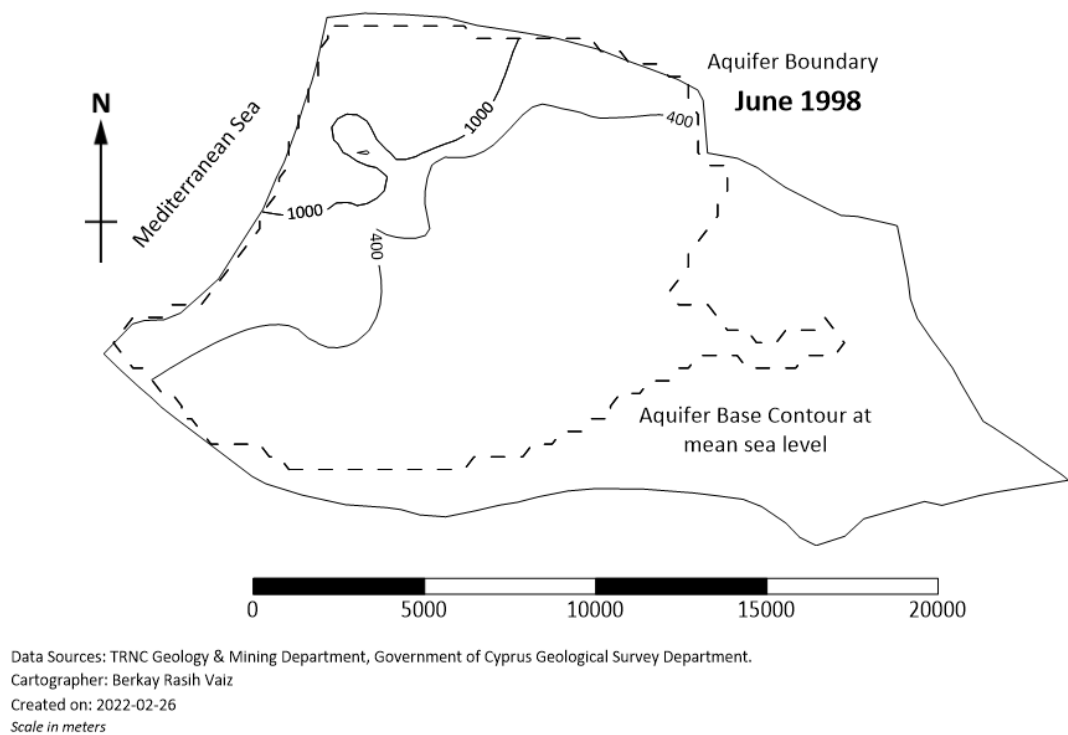
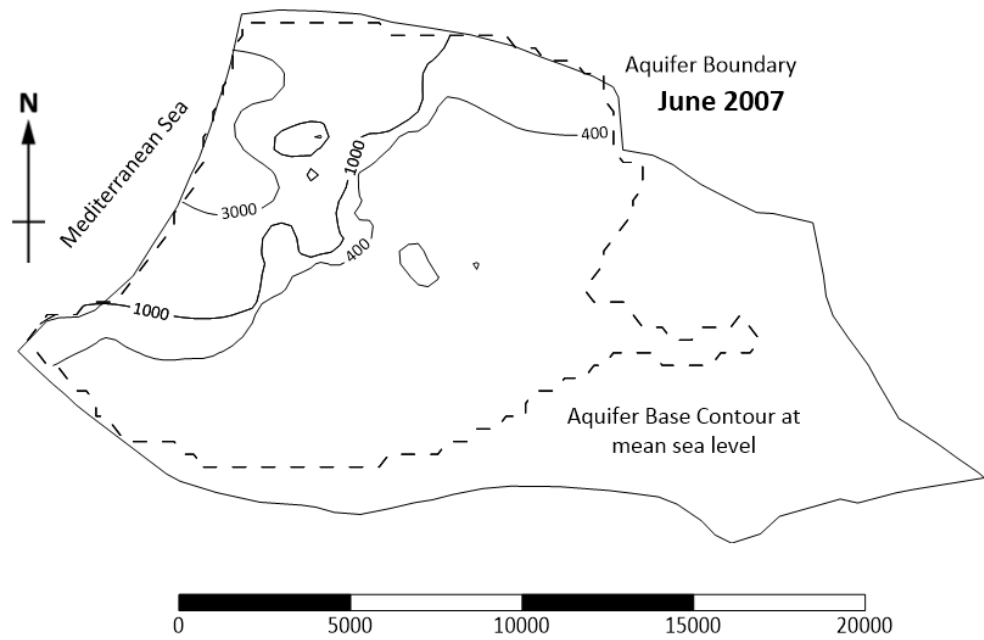


Figure 39: NaCl Iso-Chloride Map of Güzelyurt Aquifer in June 1998 in ppm



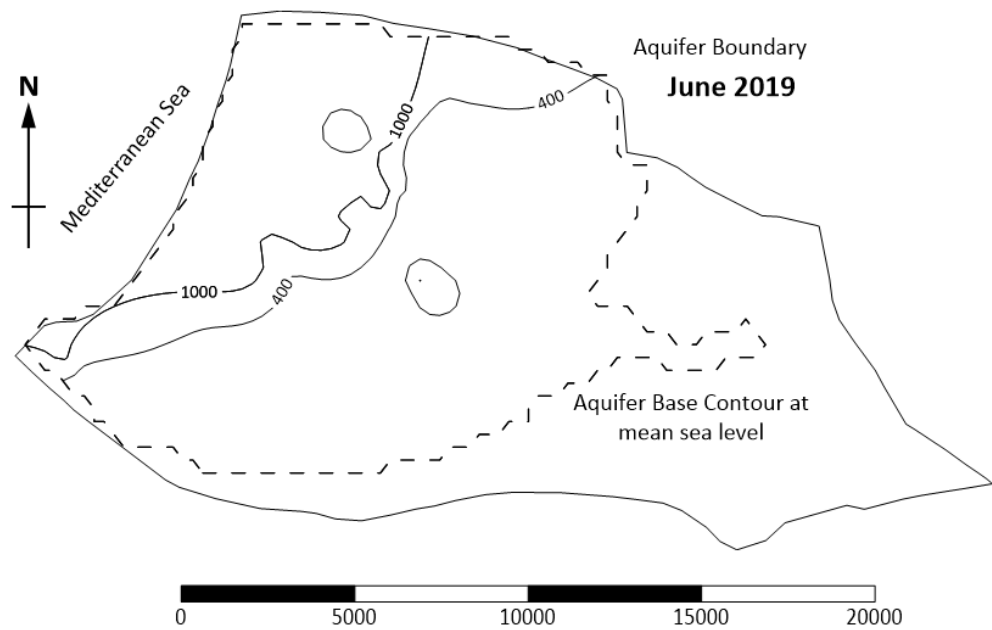
Data Sources: TRNC Geology & Mining Department, Government of Cyprus Geological Survey Department.

Cartographer: Berkay Rasihi Vaiz

Created on: 2022-02-26

Scale in meters

Figure 40: NaCl Iso-Chloride Map of Güzelyurt Aquifer in June 2007 in ppm



Data Sources: TRNC Geology & Mining Department, Government of Cyprus Geological Survey Department.

Cartographer: Berkay Rasihi Vaiz

Created on: 2022-02-26

Scale in meters

Figure 41: NaCl Iso-Chloride Map of Güzelyurt Aquifer in June 2019 in ppm

5.3.2 Wet Season Period

Iso-chloride maps of NaCl for 1980, 1989, 1998, 2008, and 2018 are shown in Figure 42, Figure 43, Figure 44, Figure 45, and Figure 46, respectively. The region near the coastal area is faced with severe salt concentration with a large surface area having NaCl concentration higher than 3000 ppm in 1980 and 1989. In 1998, the peak concentration is much lower but the effect of intrusion is still present. In 2008 and 2018 area above 1000 ppm enlarges compared to 1998. However, there is an observable deterioration in seawater intrusion based on the observed groundwater quality. In general, the extremes of wet seasons are more significant compared to the dry season. The average NaCl concentration in the years 1980, 1989, 1998, 2008, and 2018 are 3692 ppm, 6068 ppm, 855 ppm, 1139 ppm, and 887 ppm, respectively.

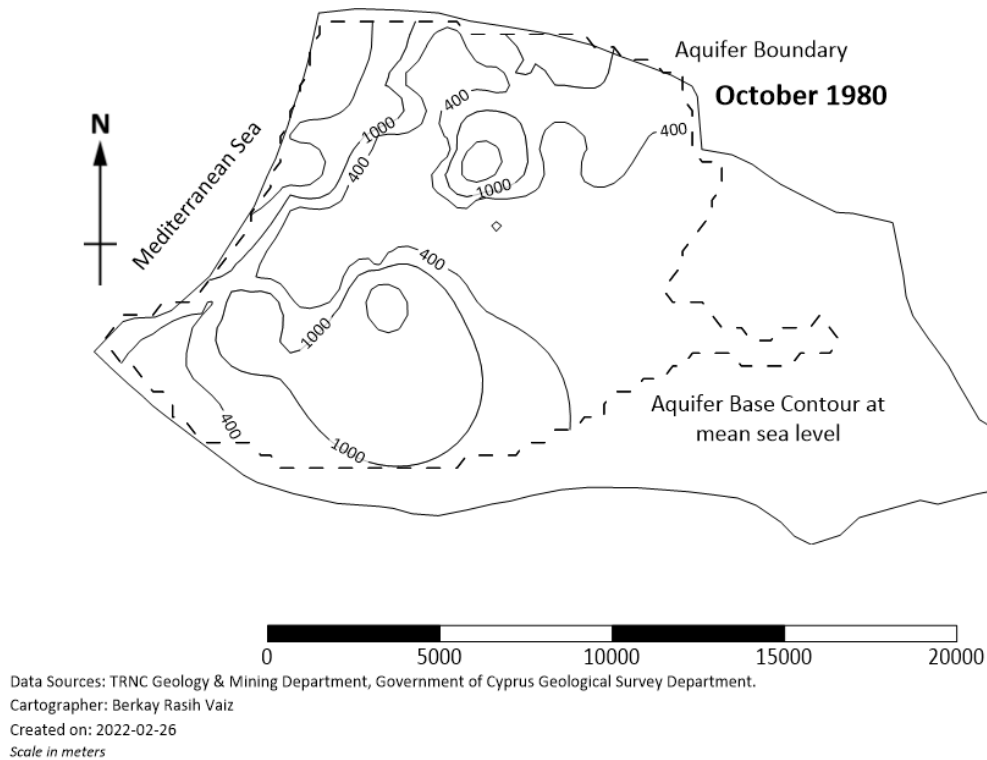
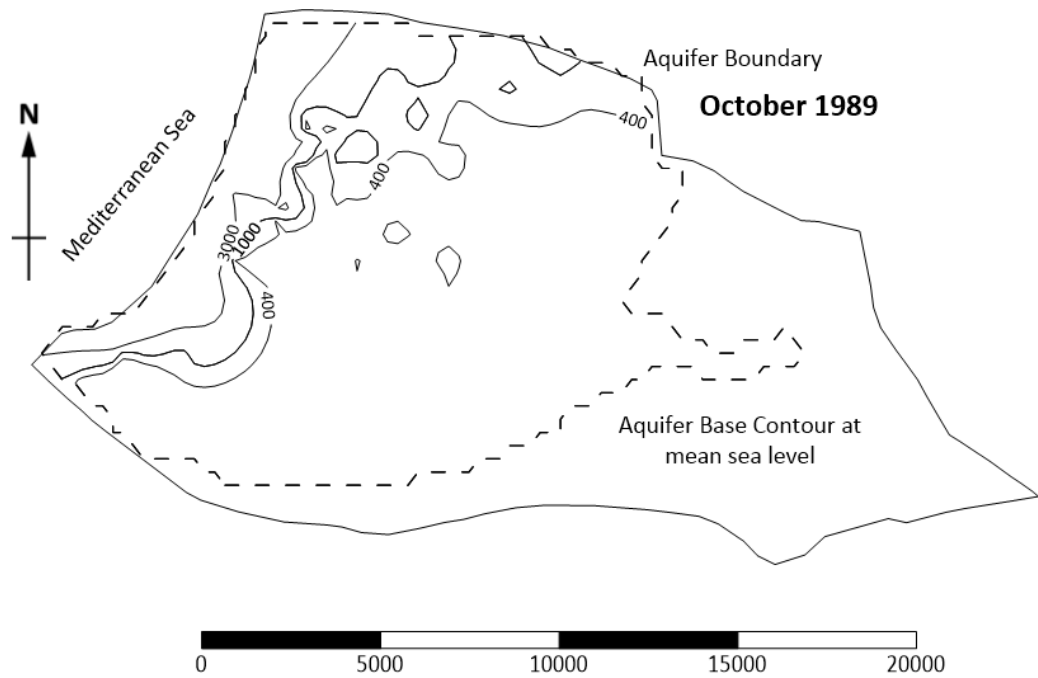
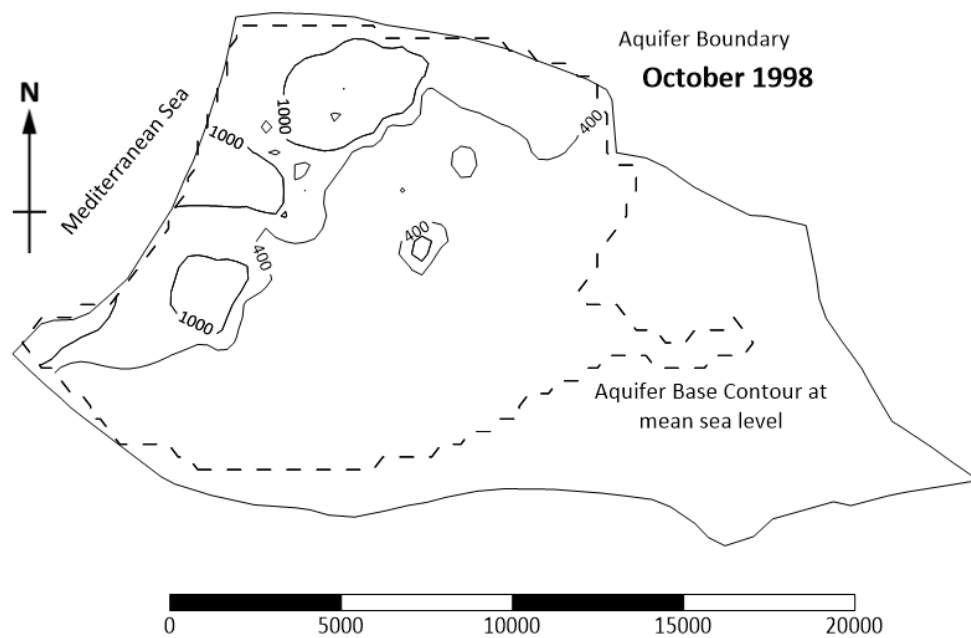


Figure 42: NaCl Iso-Chloride Map of Güzelyurt Aquifer in October 1980 in ppm



Data Sources: TRNC Geology & Mining Department, Government of Cyprus Geological Survey Department.
 Cartographer: Berkay Rasih Vaiz
 Created on: 2022-02-26
 Scale in meters

Figure 43: NaCl Iso-Chloride Map of Güzelyurt Aquifer in October 1989 in ppm



Data Sources: TRNC Geology & Mining Department, Government of Cyprus Geological Survey Department.
 Cartographer: Berkay Rasih Vaiz
 Created on: 2022-02-26
 Scale in meters

Figure 44: NaCl Iso-Chloride Map of Güzelyurt Aquifer in October 1998 in ppm

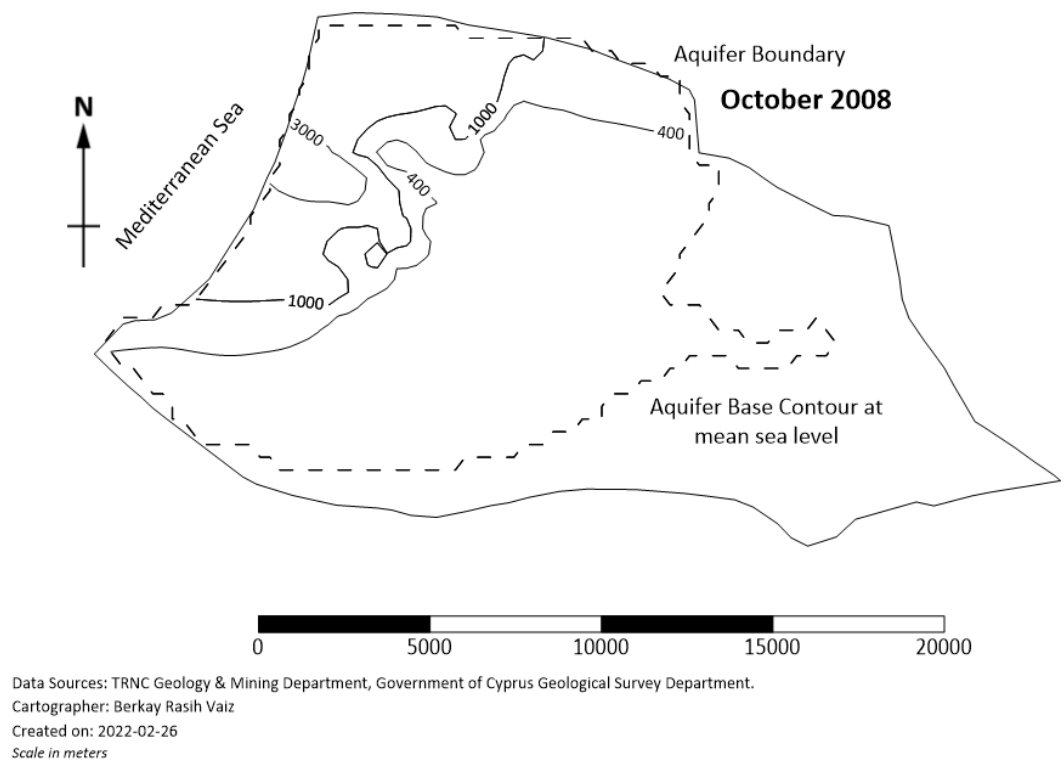


Figure 45: NaCl Iso-Chloride Map of Güzelyurt Aquifer in October 2008 in ppm

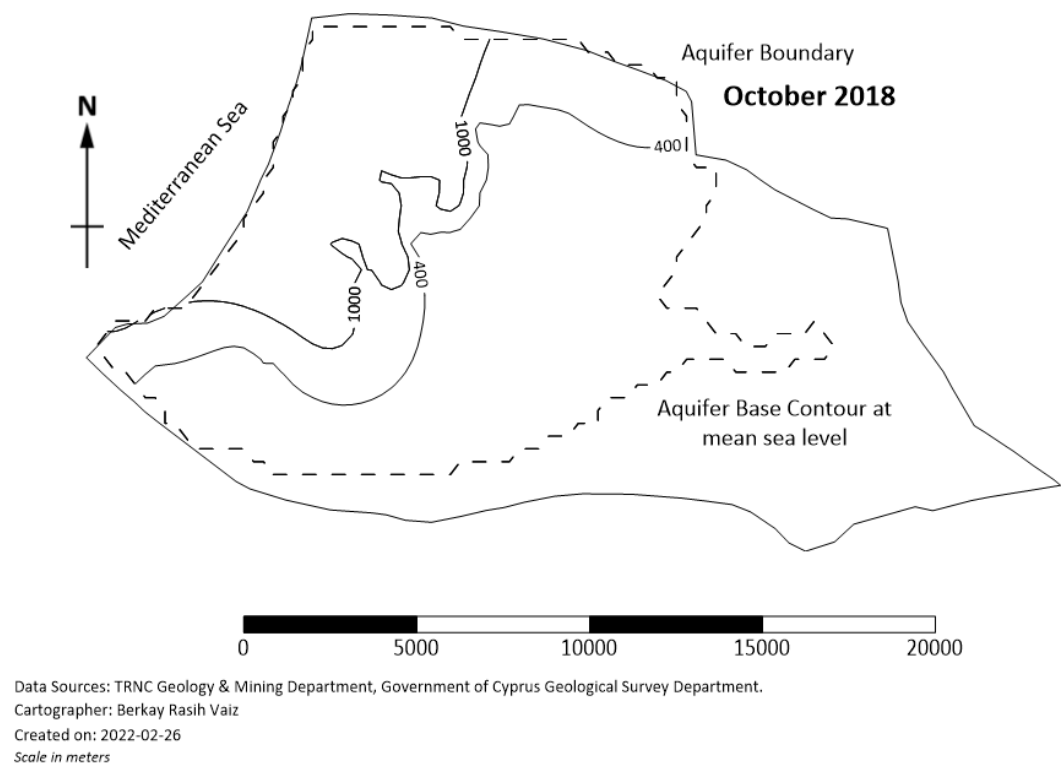


Figure 46: NaCl Iso-Chloride Map of Güzelyurt Aquifer in October 2018 in ppm

5.4 Seawater Intrusion Velocity

The cross-section area of the aquifer in contact with the sea is calculated using the aquifer base contour map's profile along the coastline and the length of the shoreline which is 14 km. The total volume of seawater which has entered and contaminated the aquifer through a cross-section area of 1.27 km² is approximately 10 MCM over 39 years. However, this result was somewhat inconsistent with the result obtained by Ergil(2000) using the same equation, 24 MCM. Thus, an estimation of seawater intrusion volume from 1980 to 2001 was done and the estimated volume was 22 MCM. Considering the differences in datasets and periods used for this study and Ergil's research, the 2 MCM difference is acceptable (Ergil, 2000).

On the other hand, the 10 MCM result obtained from 1980 to 2019 creates confusion. When the data is further studied, the negative values obtained for seawater intrusion volume display the dilution of salinity within the aquifer. In other words, aquifer quality in general is improving with the time series. Consequently, an additional period was studied from 2001 October to 2019 October. The total volume of seawater entering into the system over an 18-year period was calculated as -12 MCM. This does not mean that the seawater was leaving the system, but the amount of freshwater recharging the system compensates for the entering seawater, resulting in the dilution of the average concentration. The average porosity of the aquifer was taken as 15% with reference to previous studies (Ergil, 2000). Using the information calculated above, an estimation of the seawater intrusion velocity yearly approaching the aquifer can be made;

From 1980 October to 2001 October:

$$\frac{22 * 10^6}{21 * 0.15 * 1.27 * 10^6} = 5.57 \text{ m/year}$$

Note that the negative velocity from 2001 October to 2019 October implies the annual net dilution rate of the saturated aquifer volume:

$$\frac{-12 * 10^6}{18 * 0.15 * 1.27 * 10^6} = -3.46 \text{ m/year}$$

From 2001 October to 2019 October:

$$\frac{10 * 10^6}{39 * 0.15 * 1.27 * 10^6} = 1.40 \text{ m/year}$$

Additionally, the seawater intrusion volume time series was shown in Figure 47. The extremes shown represent the significant changes in NaCl concentration, but for every peak, there is a dip. The difference between the wet and the dry season's volume of seawater intrusion gives the yearly volume of saltwater entering the system. The extremes observed from 1980 to 2000 are not observed in the latest two decades, as the recharge process is much slower and steadier than the phenomenon. The minor fluctuations represent the diminishing effect of salination.

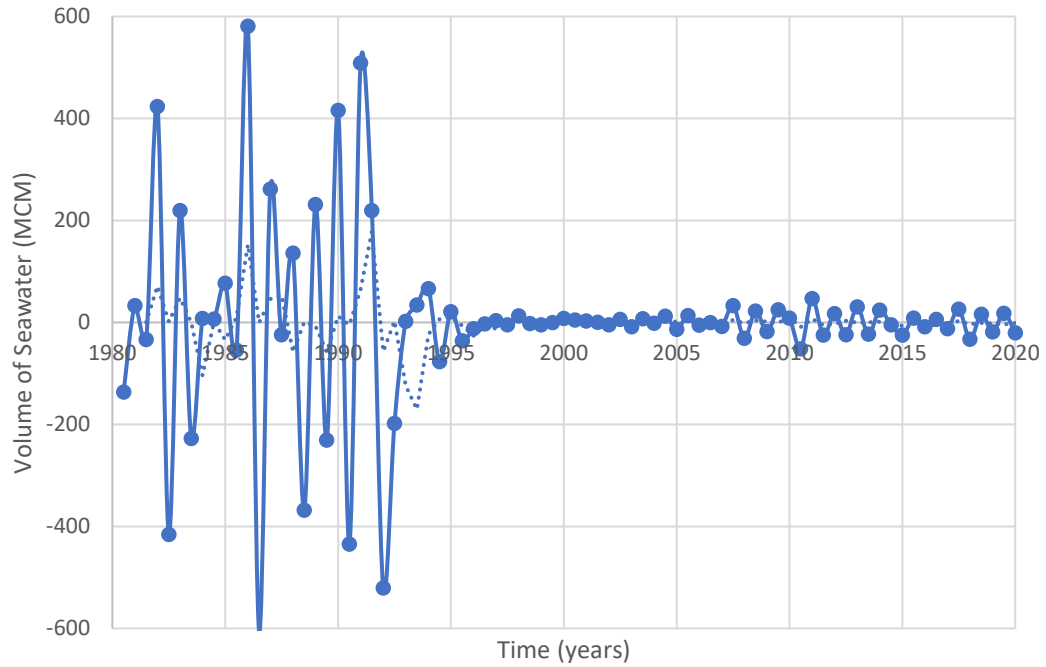


Figure 47: Seasonal Fluctuations in Seawater Volume entering the System

Using the regressive trend of the volumetric time series, a rough estimation of the time can be made, when the volume of the seawater within the system is going to become insignificant. Using the equation of the linear trendline, 59 years will pass until an eventual end comes to the amount of seawater within the system, in a future where the trend continues like this. After that, the moving average technique is used to determine the year of change in the system's water balance where the recharge takes over the intrusion. The moving average for a 2-year period shows a dip in 2010. The year when aquifer recharge takes over seawater intrusion is observed to be 2015. Using the linear regression trendline equation, which is Equation (5.4), for the 2010-2019 period, the time needed for the seawater volume within the system to reach 0 was calculated to be 12 years from 2019 (i.e. 2031).

$$SV = -0.5t + 4.43 \quad (5.4)$$

However, when forecasting using linear regression of a time series, the results obtained are generally unreliable. As a result, another forecasting method was used in the form of ARIMA Modelling.

5.5 Trend Analysis

Mann-Kendall statistics (Z_c statistics) were calculated to determine the trend in time series data on dry and wet periodical groundwater levels as well as average concentration over the aquifer area and rainfall. Wet and Dry season Z_c values for various parameters ranged from 0.20 to 3.58 (Table 9). Since 2 of the results were between the Z-table critical, $Z_c < Z_{1-\alpha/2}$ at a 5% level of significance, the null hypothesis (H_0 : that there is no trend in time series) was accepted, deeming that, no trend exists in Dry Seasonal Saturated Aquifer Volume dataset and Wet Seasonal Rainfall dataset. On the other hand, results were not between the Z-table critical values for the rest of the cases, $Z_c > Z_{1-\alpha/2}$ at a 5% level of significance. Thus, the null hypothesis was rejected.

Table 9: Mann-Kendall's Z_c Statistic and Sen's Slope Estimation for Average Salt Concentration over Aquifer Area (ppm), Available Saturated Water Volume (m^3), and Rainfall (mm)

Dataset	Dry Season			Wet Season		
	Z_c	Sen's Slope	Trend	Z_c	Sen's Slope	Trend
Salt Concentration (ppm)	3.58*	18.57	+	-1.95*	-56.83	-
Saturated Water Volume (m^3)	0.17	3.16	+	-1.34*	-13.72	-
Rainfall (mm)	2.53*	0.61	+	0.20	0.24	+

(* Statistically significant at 5% level or above, + increasing trend in positive direction, - decreasing trend in negative direction.)

The analysis results indicate that there are significantly increasing trends and decreasing trends in dry and wet seasons, respectively. Firstly, considering the NaCl concentration over the aquifer area, the positive sign represents an increasing trend in the dry season and the negative sign represents a decreasing trend. However, the water quality does not increase as a result of a positive trend, as a matter of fact, it decreases. A higher NaCl level means the water usability and drinkability are lower. Thus, the desired outcome of this trend should be a negative one. Secondly, saturated water volume has a significant trend in the wet season. The negative trend means that the water table fluctuations are mostly downwards and the levels are decreasing. Thirdly, the significant positive trend in rainfall is in the dry season. The Mediterranean climate results in extremely dry summer months with mostly below 100 mm of rainfall. The rare summer rains have increased in recent years due to global warming and a few millimeters of rainfall in the summer months result in a high Z_c score, but this does not change the fact that most of the rain occurs in the wet season, meaning a significant rainfall trend in the dry season has little to no relation to the water quality or quantity trends.

After trend identification, Sen's slope estimator was used to identify the slope of the trend line. (i.e. the rate of change in volume/concentration/rainfall per year.) The salt concentration over the aquifer area has a significant trend in both wet and dry seasons. The high NaCl values observed during the winter are generally more frequent than it is in the summer. As a result, Sen's slope estimator does not identify them as anomalies. In fact, these values are not anomalies, the results where the ppm is more than 5000 are obtained due to measurements made on the boreholes directly exposed to seawater. Even though the Z statistic and the trend significance are higher for the dry season, the Sen's slope (Q_i) is larger for the wet season. The difference in the Q_i

value signifies that the larger decrease in the average concentration trend in the wet season, compared to the smaller increase in the dry season, is improving the overall water quality over the aquifer area. Moreover, Q_i for the total precipitation in the dry season suggests that the significantly increasing rainfall trend changes the seasonal value by 0.61 mm per year. Even if a gradual change is occurring in the rainfall values, these changes are insignificant in the scope of this study. Sen's Slope estimation suggests that in the season where the majority of the yearly effective precipitation and natural recharge affects the aquifer, 18.57 MCM of saturated water volume depletion is seen on a yearly basis.

The trends in wet season rainfall and dry season saturated water volume time series were insignificant. Furthermore, the significant trend in the dry season rainfall time series rainfall does not affect the water volume as the magnitude of precipitation is insignificant rather than the trend. These three-time series were concluded to have an insignificant correlation to be used in forecasting. As a result, the Arima model selection process was only repeated for average NaCl concentration time series' and wet season saturated water volume over the aquifer area for Dry and Wet seasons from 1980 to 1990 are 1215 and 6531 ppm, respectively. Where the wet season declined to 2789, the dry season peaked at 2239 ppm from 1991 to 2000. The following two decades did not reach the peak of this decade with dry season decadal values being 1306 and 1150 and wet season values being 1160 and 1288 ppm, respectively. Note that the precipitation falling in the wet season does not affect the aquifer immediately. The single seasonal Lag estimated is confirmed by the wet season concentrations reaching peaks higher than the dry season peaks.

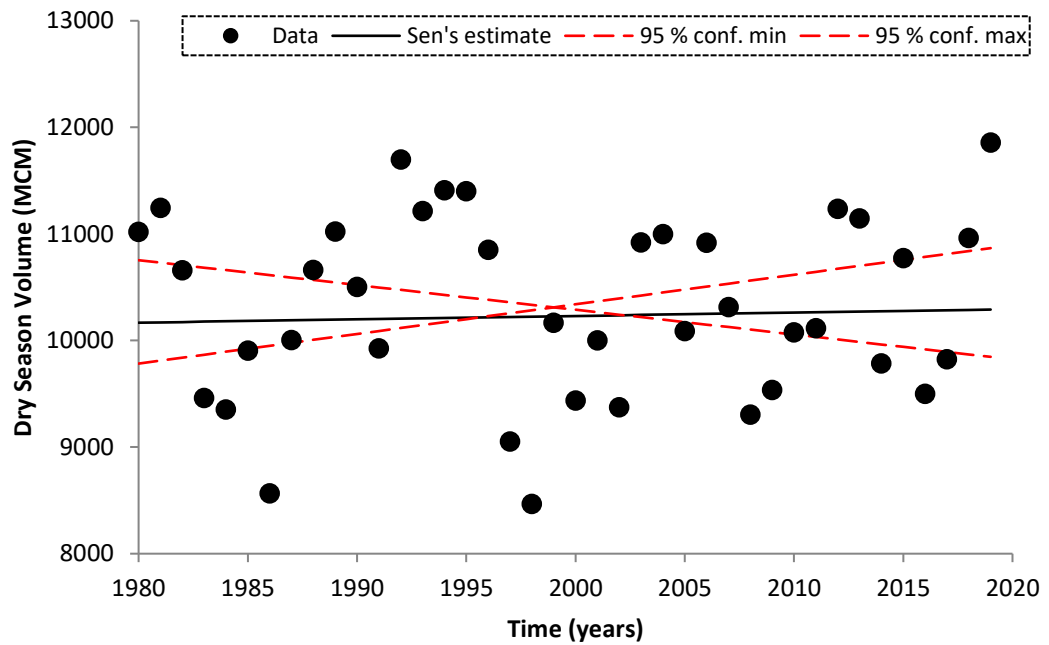


Figure 48: Sen's Slope Estimation with 95% Confidence Interval of Dry Season Saturated Aquifer Volume Time Series in MCM

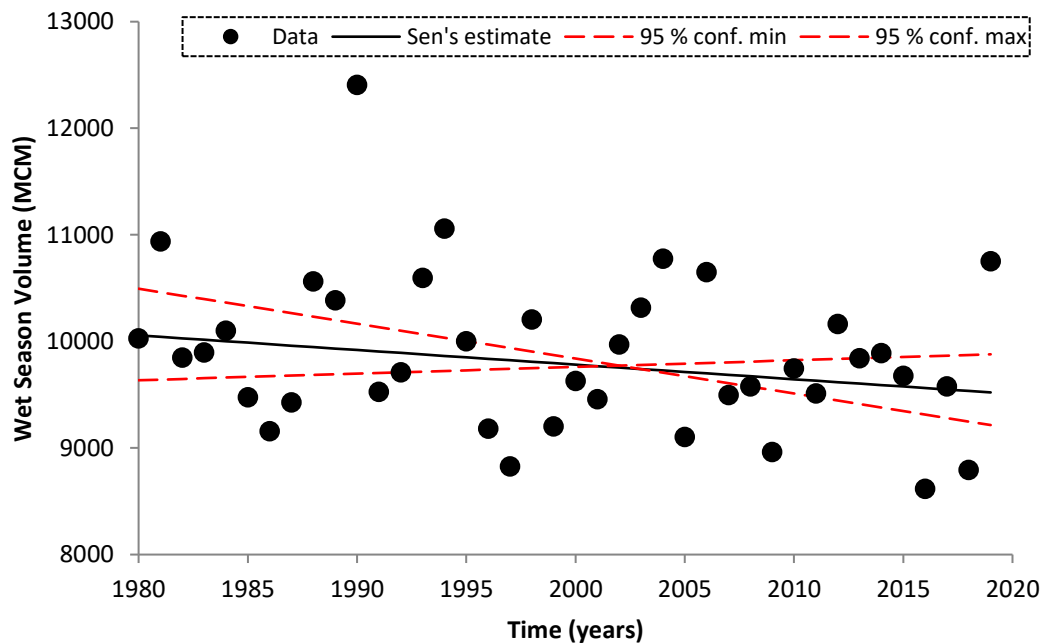


Figure 49: Sen's Slope Estimation with 95% Confidence Interval of Wet Season Saturated Aquifer Volume Time Series in MCM

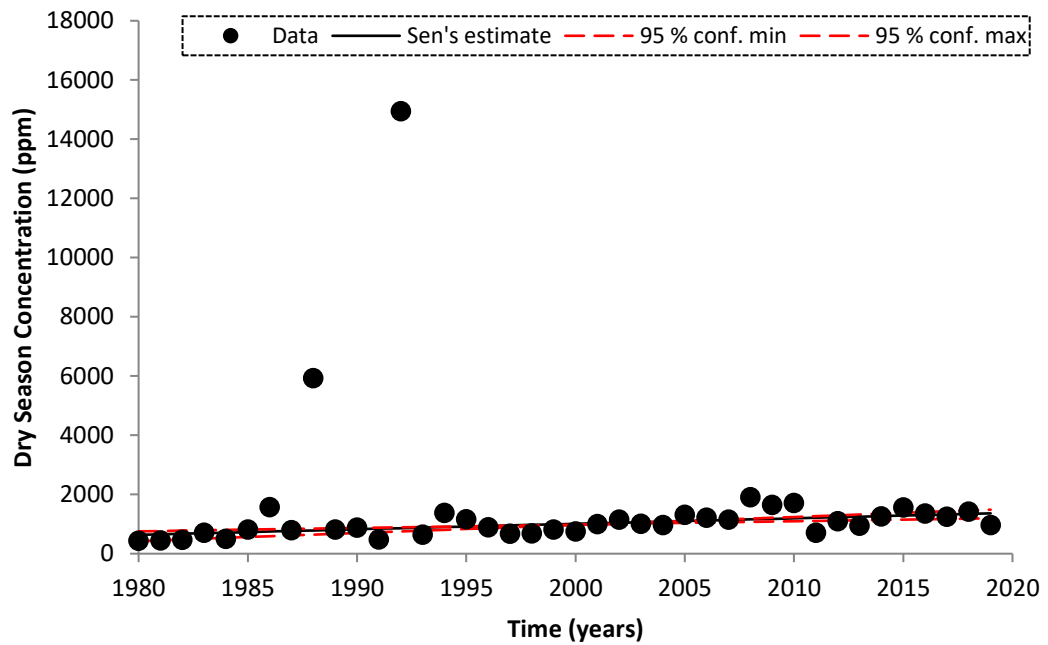


Figure 50: Sen's Slope Estimation with 95% Confidence Interval of Dry Season Average NaCl Concentration Time Series in ppm

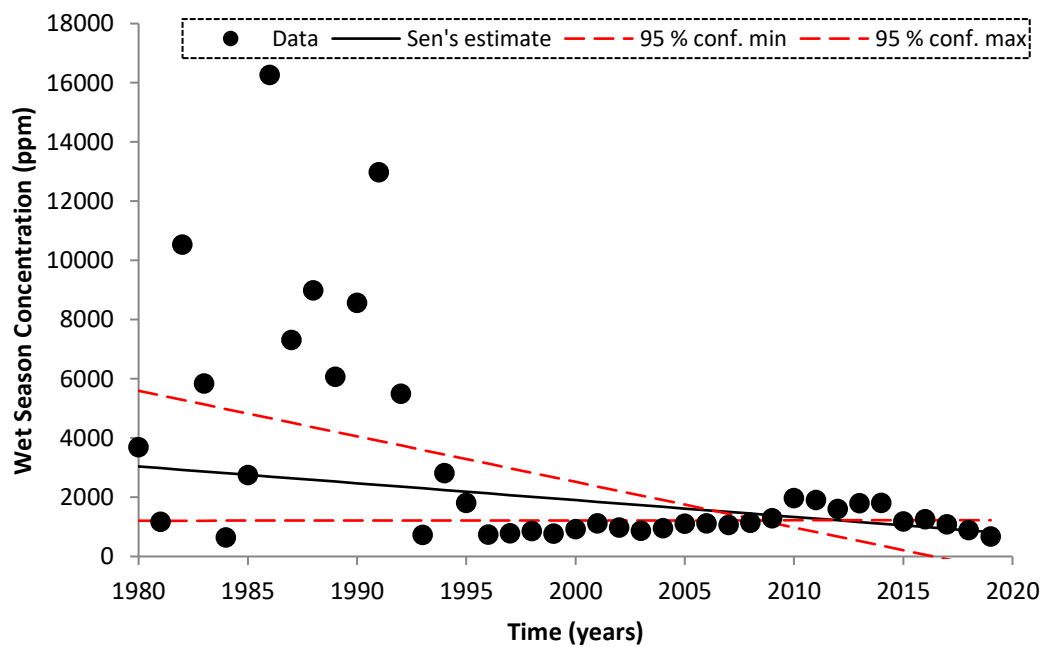


Figure 51: Sen's Slope Estimation with 95% Confidence Interval of Dry Season Average NaCl Concentration Time Series in ppm.

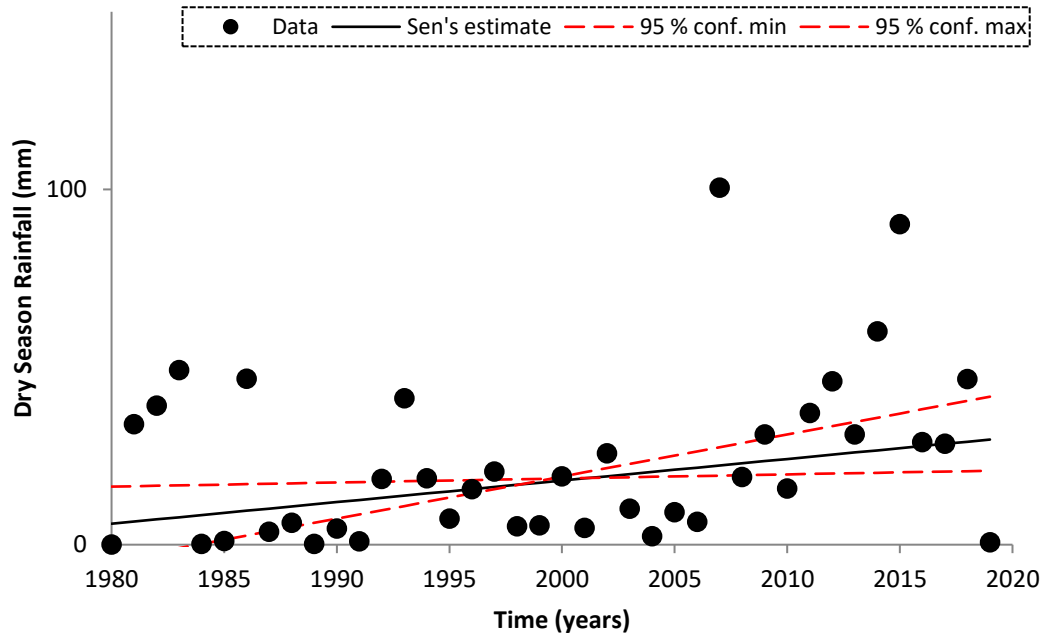


Figure 52: Sen's Slope Estimation with 95% Confidence Interval of Dry Season Rainfall in mm

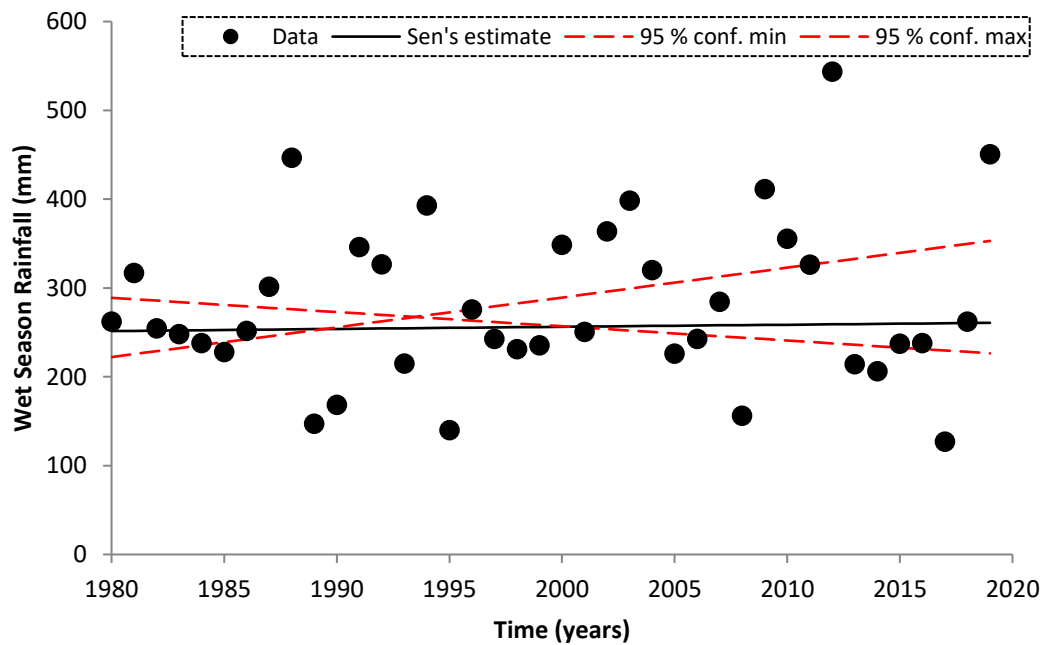


Figure 53: Sen's Slope Estimation with 95% Confidence Interval of Wet Season Rainfall in mm

Seasonal decadal comparison of average NaCl concentration over the aquifer area, average saturated groundwater volume, and total rainfall over the Güzelyurt area was made in Figure 54, Figure 55, and Figure 56. The average decadal NaCl concentration

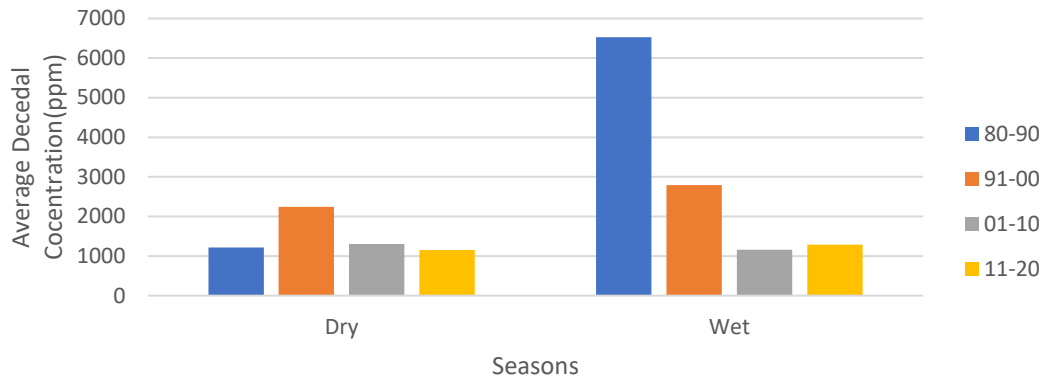


Figure 54: Decadal Comparison of Average NaCl Concentration over the Aquifer Area between Dry and Wet Seasons

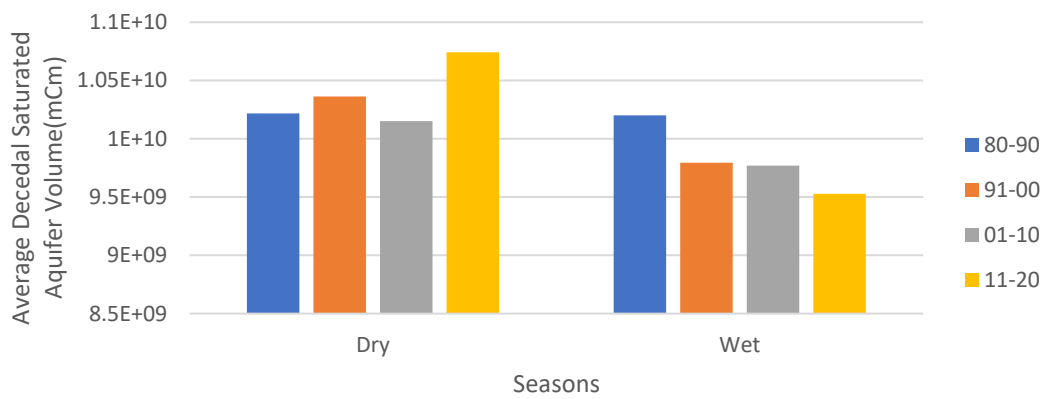


Figure 55: Decadal Comparison of Average Saturated Groundwater Volume between Dry and Wet Seasons

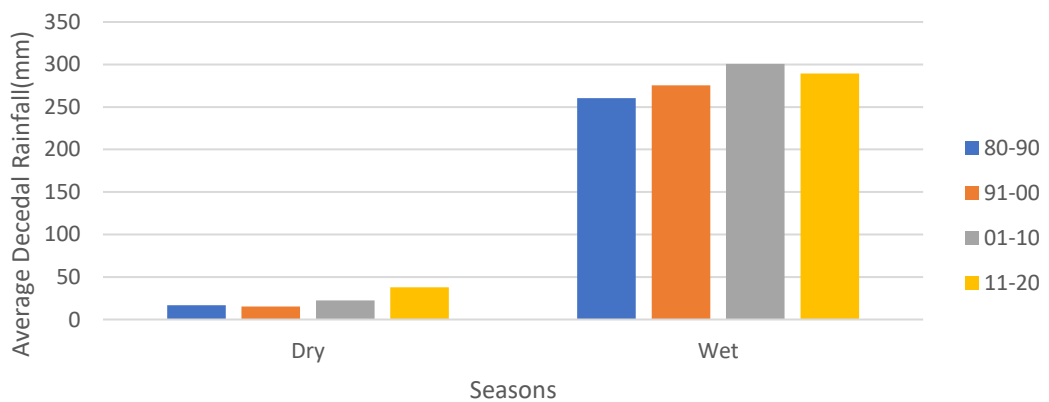


Figure 56: Decadal Comparison of Total Precipitation over the Güzelyurt Area between Dry and Wet Seasons

over the aquifer area for Dry and Wet seasons from 1980 to 1990 are 1215 and 6531 ppm, respectively. Where the wet season declined to 2789, the dry season peaked at 2239 ppm from 1991 to 2000. The following two decades did not reach the peak of this decade with dry season decadal values being 1306 and 1150 and wet season values being 1160 and 1288 ppm, respectively. Note that the precipitation falling in the wet season does not affect the aquifer immediately. The single seasonal Lag estimated is confirmed by the wet season concentrations reaching peaks higher than the dry season peaks.

In addition, the wet season decadal water volume for 4 decades is underneath the dry season decadal water volume results calculated using the water table contour maps and aquifer base map. This result is unexpected at first because the wet season is when most of the precipitation takes place. However, the single-season lag delays the recharge of the aquifer resulting in a full aquifer in the summer. Dry season volume peaks at 10741 MCM, whereas wet season peaks at 10202 MCM. The peak in the dry season is seen in the 2010-2020 decade. On the contrary, the driest decade was seen in the wet season 2010-2020 decade at 95296 MCM. The driest aquifer condition in the dry season was in 2000-2010 at 10153 MCM. In general, the aquifer volume least affected by the rain and faced with depletion and seawater intrusion shows a visually decreasing decadal trend. The wet season is the time majority of the salination happens within the study area.

Decadal average rainfall figures visualize the distinction between wet and dry season rainfall. Where throughout the 40-year timeline decadal average precipitation does not exceed 50 millimeters in the summer, and it does not go below 250 mm in the winter.

5.6 ARIMA Model Selection

The first step in the modeling process was the identification of the time series. The three time series focused on in this model are those with significant trends and with valid information on the state of seawater intrusion phenomena in the upcoming years. These are Wet Season Saturated Water Volume, Dry Season Average NaCl Concentration over the aquifer area, and Wet Season Average NaCl Concentration over the aquifer area.

5.6.1 Estimation of the Parameters

5.6.1.1 ADF Test

The ADF test was performed on the four datasets that are the main focus of this study. If the obtained Z score is smaller than the DF_{CV} , the time series is considered to be non-stationary. The results shown in Table 10 suggest that none of the datasets are stationary when there is no differencing.

Table 10: ADF Test on Average NaCl Concentration and Saturated Water Volume in Wet and Dry Seasons without Differencing

Dataset	Regression Model & DF_{CV}				Stationarity
	No Constant No Trend	Constant Only	Constant Trend	Constant Trend Trend ²	
	-1.9	-2.9	-3.5	-4.0	
Dry S. NaCl Conc.	-1.3	-6.8	-6.8	-6.7	Not Stationary
Wet S. NaCl Conc.	-1.3	-1.8	-4.5	-4.7	Not Stationary
Wet S. S. Water Vol.	-0.3	-5.1	-5.5	-5.4	Not Stationary

On the other hand, the obtained results in Table 11 suggest that the stationarity of the time series is achieved after it has been differenced by a one-year lag. Fittingly, The integrated part (d) of the ARIMA Model can be taken as 1 for all three datasets.

Table 11: ADF Test on Average NaCl Concentration and Saturated Water Volume in Wet and Dry Seasons with Differencing

<i>Dataset (Differenced)</i>	<i>Regression Model & DF_{CV}</i>				<i>Stationarity</i>
	<i>No Constant No Trend</i>	<i>Constant Only</i>	<i>Constant Trend</i>	<i>Constant Trend Trend²</i>	
	-1.9	-2.9	-3.5	-4.0	
<i>Dry S. NaCl Conc.</i>	-7.6	-7.5	-7.5	-7.4	<i>Stationary</i>
<i>Wet S. NaCl Conc.</i>	-6.9	-6.9	-6.8	-6.8	<i>Stationary</i>
<i>Wet S. S. Water Vol.</i>	-5.8	-5.7	-5.6	-5.5	<i>Stationary</i>

5.6.1.2 Correlogram

Figure 57, Figure 58, and Figure 59 present the Dry and Wet Seasonal Average NaCl Concentration and Wet Season Saturated Water Volume ACF and PACF plots, respectively. The confidence limits are shown in the plots as a continuous line above and below the x-axis. The order of p and q for constructing tentative ARIMA models for Dry and Wet seasonal time series of NaCl concentrations and wet seasonal time series of water level was determined based on the plots of ACF and PACF.

Figure 57 ACF for larger lag times decreases when there is differencing. The pattern is similar in other figures as well. This is another representation that shows that the time series has become stationary after differencing. In general peaks in ACF and PACF can be seen in lag times one, two, and three.

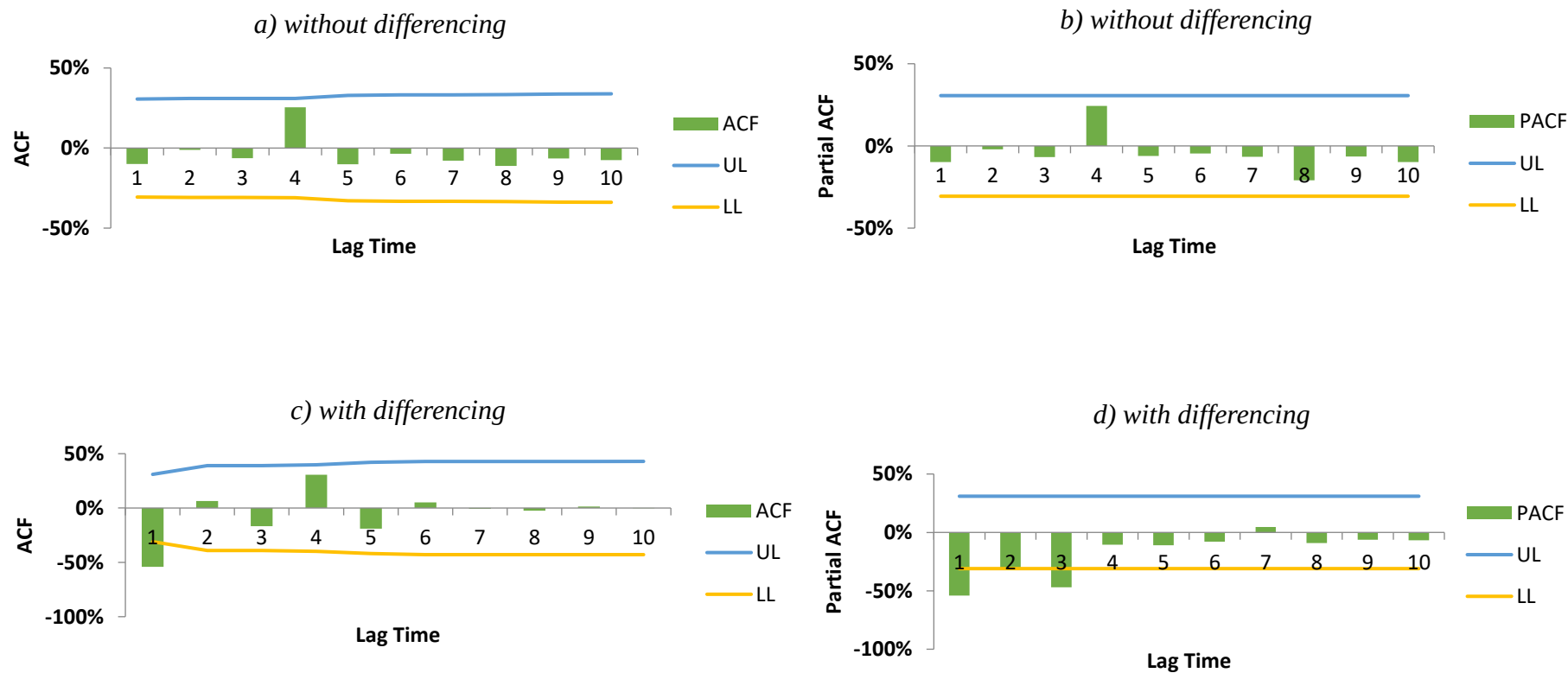


Figure 57: Autocorrelation Function (ACF) and Partial Autocorrelation Function (PACF) of Dry Season Average NaCl Concentration

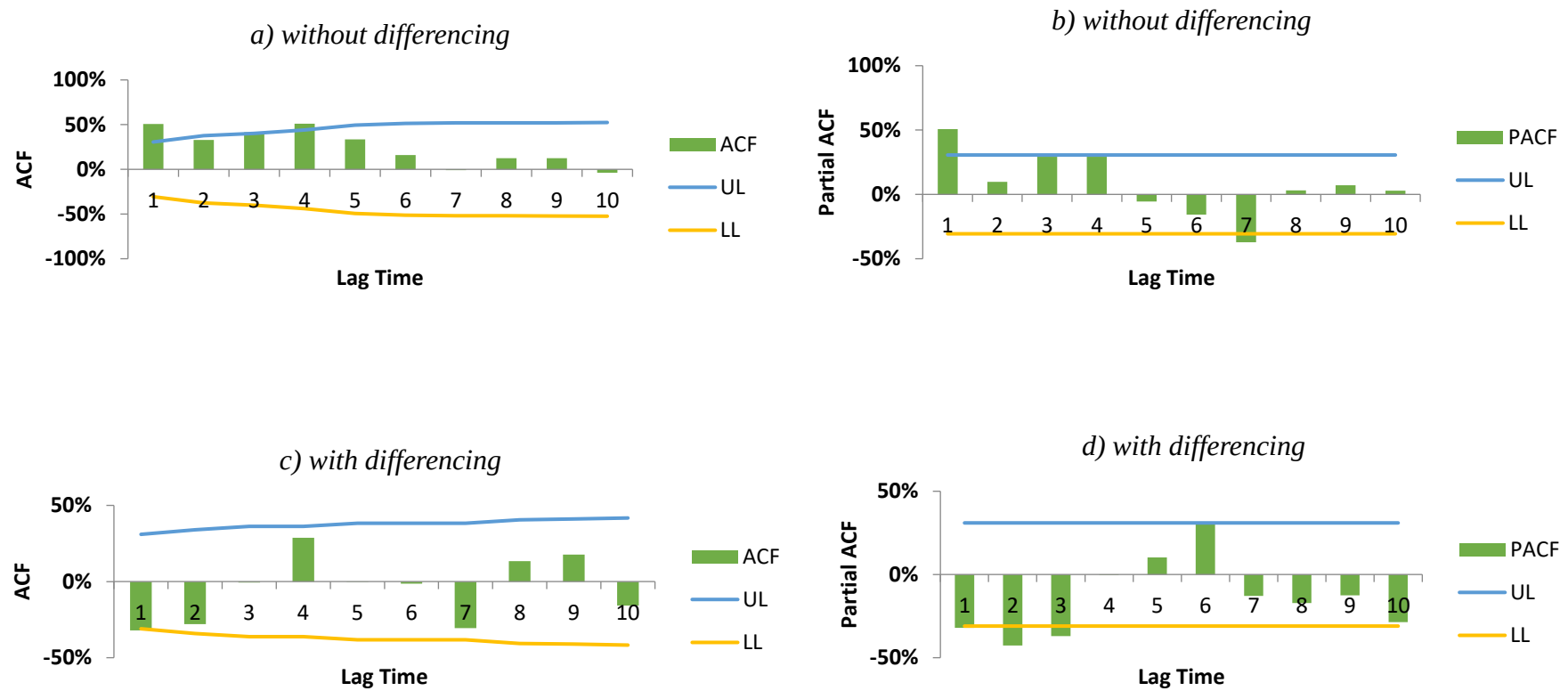


Figure 58: Autocorrelation Function (ACF) and Partial Autocorrelation Function (PACF) of Wet Season Average NaCl Concentration

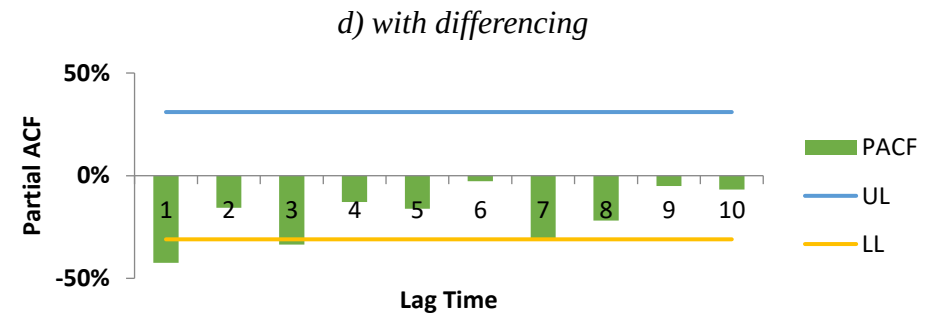
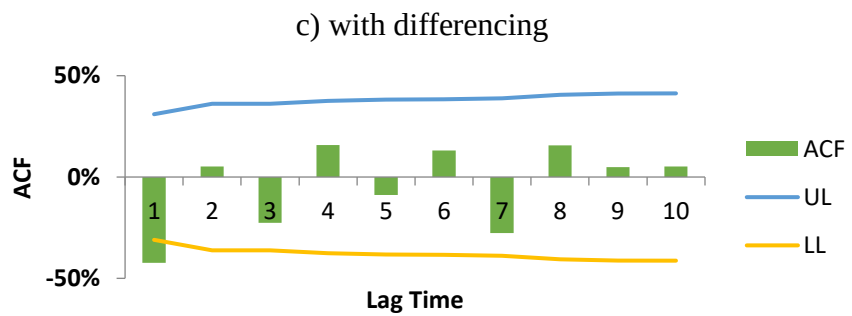
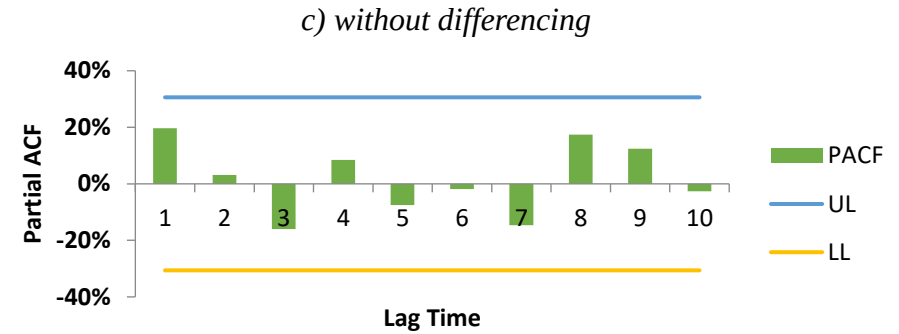
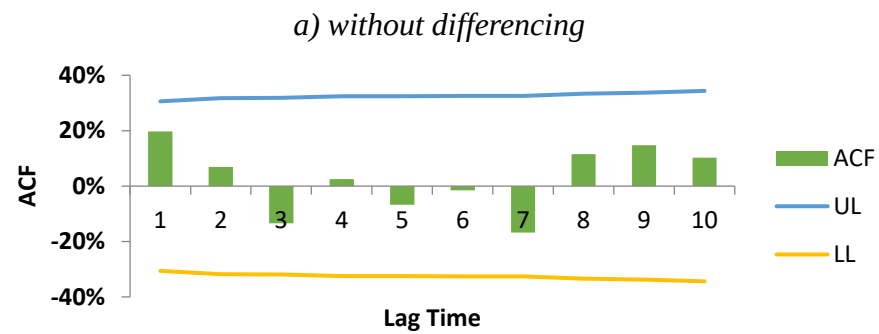


Figure 59: Autocorrelation Function (ACF) and Partial Autocorrelation Function (PACF) of Wet Season Saturated Aquifer Volume

Tentative ARIMA models were selected using the ADF test and ACF/PACF. Peaks in lag-7, lag-6, and lag-10 were seen at Wet Season Saturated Water Volume PACF and Wet Season Average NaCl Concentration PACF and ACF, respectively. However, the models were tried to be kept within a significant range, hence nine tentative ARIMA models were selected with different (p, d, q) values for each time series. These selected models are; ARIMA(1,1,1), ARIMA(1,1,2), ARIMA(1,1,3), ARIMA(2,1,1), ARIMA(2,1,2), ARIMA(2,1,3), ARIMA(3,1,1), ARIMA(3,1,2), ARIMA(3,1,3). Out of these nine models, five were eliminated using Akaike Information Criteria (AIC). The remaining models used in this study can be seen in Table 12.

Table 12: ARIMA Models selected for Diagnostic Analysis

WSASC		DSASC		WSSAV	
ARIMA Model	AIC	ARIMA Model	AIC	ARIMA Model	AIC
3,1,2	757.6	1,1,1	749.8	1,1,1	1762.0
2,1,3	760.8	1,1,2	751.3	3,1,1	1764.1
3,1,3	761.1	2,1,1	751.7	2,1,1	1764.4
2,1,2	762.9	3,1,1	752.2	1,1,2	1764.7

5.6.1.3 Model Validation using Statistics

The model statistics for Wet Season Average Salt Concentration (WSASC), Dry Season Average Salt Concentration (DSASC), and Wet Season Saturated Aquifer Volume (WSSAV) are displayed in Table 13, Table 14, and Table 15, respectively. Out of those used four models, the model with the lowest among these parameters is selected for forecasting. Additionally, 3 different Weighted means (WM) were calculated using RMSE, MAPE, and MAD. If all the weighted means matched in terms of ranking, the model with the lowest result was selected. The applied weighted means are;

$$WM1 = (RMSE + 4MAPE + MAD)/6 \quad (5.5)$$

$$WM2 = (4RMSE + MAPE + MAD)/6 \quad (5.6)$$

$$WM3 = (RMSE + MAPE + 4MAD)/6 \quad (5.7)$$

Table 13: Model Statistics for WSASC Levels

ARIMA Model	R ²	MAD	RMSE	MAPE	WM1	WM2	WM3
3,1,2	0.409	1231	1390	80.6	490.6	1145.3	1065.8
2,1,3	0.854	651	727	40.8	256.9	600.0	562.0
3,1,3	0.406	1226	1385	80.3	488.7	1141.1	1061.6
2,1,2	0.336	1248	1394	82.1	495.1	1151.0	1078.0

ARIMA(2,1,3) was selected for WSASC. R² is 0.854 which is larger than 0.85 so it is acceptable. Furthermore, WM1, WM2, and WM3 results were the smallest among the others for this model with 257, 600, and 562, respectively. The results obtained from the rest of the parameters suggest that ARIMA(2,1,3) is the best selection among the given four.

Table 14: Model Statistics for DSASC Levels

ARIMA Model	R ²	MAD	MSE	RMSE	MAPE	WM1	WM2	WM3
1,1,1	0.009	318	161907	402	32.1	141.4	326.4	284.4
1,1,2	0.431	509	379085	616	49.4	220.4	503.7	450.2
2,1,1	0.007	302	140630	375	30.1	132.9	305.4	268.9
3,1,1	0.005	362	196970	444	35.5	158.0	362.3	321.3

According to the model statistics and WM1, WM2, and WM3, ARIMA(2,1,1) is the best selection for forecasting the DSASC time series. However, the given R² is too low which suggests that the usage of this model for forecasting will not provide accurate results. The maximum R² among the four is 0.431 which is still far too small. Thus,

forecasting of the future DSASC values was abandoned as the results will be unreliable.

Table 15: Model Statistics for WSSWV Levels

ARIMA Model	R ²	MAD	RMSE	MAPE	WM1	WM2	WM3
1,1,1	0.094	397x10 ⁶	673 x10 ⁶	4.43	1.8x10 ⁸	5.1x10 ⁸	3.8x10 ⁸
3,1,1	0.332	377x10 ⁶	662 x10 ⁶	4.22	1.7x10 ⁸	5.0x10 ⁸	3.6x10 ⁸
2,1,1	0.292	405x10 ⁶	676 x10 ⁶	4.52	1.8x10 ⁸	5.2x10 ⁸	3.8x10 ⁸
1,1,2	0.166	406x10 ⁶	518 x10 ⁶	4.33	1.5x10 ⁸	4.1x10 ⁸	3.6x10 ⁸

Similar to DSASC, WSSWV model statistics suggest that usage of ARIMA(1,1,2) for forecasting is the best selection. However, much like the DSASC time series' selected model, ARIMA(1,1,2) has an R² result far below the requirement. Thus, a conclusion has been reached that forecasting saturated aquifer water volume is inappropriate for these time series using Box and Jenkin's method and ARIMA modeling.

5.7 Forecasting

After performing all the necessary steps of the Box and Jenkins method, the only model which has met the requirements was ARIMA(2,1,3) of the WSASC time series. Based on the WSASC data and the selected ARIMA model's p, d, and q, the calibration tool embedded within NumXL was used to formulate the equation below.

$$Y_t = -75.19 + 0.19Y_{t-1} - 0.49Y_{t-2} - 0.84e_{t-1} + 0.53e_{t-2} + 0.38e_{t-3} + 2641.83 \quad (5.8)$$

Calibration is the process where the parameters are found using the MLE approach. The log-Likelihood function is maximized by using the solver add-in available within Excel as an optimizer. Estimation of the maximum likelihood is a process where different iterations of parameter estimations are used to calculate the observed values within the given time series by using that time series (Rossi, 2018). The maximum

likelihood estimate can be defined where the log-likelihood is maximized by an estimate within the possible parameter estimations (Rossi, 2018).

Using the formulated model, the amount of time required for the salt concentration in the aquifer to return to 400 ppm, which is the acceptable natural amount of NaCl expected to be seen in groundwater, was estimated. If the trends continue, the average salt concentration within the aquifer is expected to become 400 ppm by 2029.

Chapter 6

DISCUSSION

In order to efficiently use the freshwater, this study aimed to assess the threat posed by the seawater intrusion phenomena that occur within the Güzelyurt Coastal Aquifer. The first objective of the study was the establishment of the water quality and quantity depletion scenario, in addition to the area most affected by the intrusion. Furthermore, the implementation of statistical analysis and modeling techniques for the trend analysis of the last forty years, topped by a forecast of the year in which the aquifer will no longer suffer from seawater intrusion and improve significantly as desired. The utilization of the salt balance equation was a core part of the study to obtain the up-to-date intrusion velocity. The final aspect of the problem aimed to be resolved in this study was an analysis of the management strategies, followed by recommendations.

In order to achieve these aims, the effect of rainfall on the groundwater was studied and a single-season lagged rainfall was found to have a positive correlation with aquifer water volume. NaCl iso-chloride and water table contour maps were drawn to visually analyze the water quality and quantity, in addition to computing the average seasonal NaCl concentrations and the volumetric difference between aquifer base contours and water table contours. Seawater intrusion velocity was calculated using the derived time series and salt balance equation. The year in which recharge took over intrusion was estimated as 2015 and the date of salinity within the aquifer returning to normal was calculated as 2031 based on the linear regression trend. Mann-Kendall's

analysis identified statistically significant trends in wet and dry season average NaCl concentration of groundwater, wet season aquifer water volume, and dry season rainfall time series. Series with significant trends were put through the ARIMA model computation and selection process where only wet season average NaCl concentration time series was found to be fit for forecasting. Finally, the year of average groundwater NaCl concentration returning to 400 ppm was forecasted as 2029 using a validated ARIMA model.

6.1 Discussion on the Analysis

Spearman Correlation Test and Durbin-Watson Statistic confirmed that there is a significant negative correlation between effective rainfall and saturated aquifer volume. Additionally, when the effective rainfall dataset was lagged by one season a significant positive autocorrelation was seen. In other words, the completion of the infiltration process takes approximately one season. The lagged effect of rainfall can be seen on water table contours. Observations show that the calculated wet-season saturated aquifer volumes are less than dry-season aquifer volumes. Contrary to expectations, water table contours display lower general elevations for wet seasons. The same can be said for iso-chloride maps where the higher average concentrations are in wet seasons. The lack of data is a constraint for this part of the research. As with a month-based analysis, a two or three-month positive correlation is expected, such as the F-test result obtained by Ergil (2000), making it a more reasonable answer (Ergil, 2000). However, the result obtained here is not necessarily exactly six months. The result indicates that the effect of precipitation on groundwater resources is not immediate. On the other hand, Payab's correlation test results indicate that effect of rainfall is seen on the groundwater levels after approximately one year (Payab, Banihabib and Türker, 2020). There is a considerable similarity between the results of

the two studies. However, Payab's study considered the effect of drought on groundwater levels, whereas this study considers the effect of rainfall on groundwater levels (Payab, Banihabib and Türker, 2020). Perhaps, the results may indicate that the effect of an increase in rainfall is observed faster (i.e. one season) than the effect of the lack of rainfall (i.e. one year).

A similarity can be seen between the dry season water table contours of 1980 and 2018. The predecessor was drawn when the phenomenon was just starting, and the successor was drawn at the start of the recharge process. The same cannot be said about the wet season because of the lagged recharge effect. Most of the intrusion occurs at the start of fall, after the irrigation season of the citrus fruits in the summer, when the aquifer is mostly dry, whereas most of the recharge occurs at the end of spring before the irrigation and after the snow has melted and most of the rain has fallen. Although not reflected in the presented contour maps, the time series show that the water stored within the aquifer is higher in the dry season compared to the wet season in general. When the time series generated by saturated aquifer volume dataset was compared with Payab's annual average groundwater level time series, a similarity can be seen between the two figures (Payab and Türker, 2018). The comparison is made based on the slope, particularly where it is ascending/descending. In addition to matching slopes, 1983-1988 drought was also clearly visible with both time series, validating the results obtained.

The linear regression estimation of the saturated aquifer volume is 46 years when the aquifer is put under minimum stress. The result obtained differs from Demis's 73 years (Demir, 2018). Four possible reasons for the forecasted differences are:

1. The recharge of the aquifer for the selected period is relatively faster than the recharge in the upcoming years. This is because the recharge of a dip is faster and the dips after the locations affected by the seawater intrusion are mostly recharged will have less depth after 2019, making a less steep trendline.
2. Linear regression forecasting is an unreliable forecast strategy as it does not have any proven statistical or numerical validation.
3. The conditions used to minimize the aquifer pressure in Demir's model and the scenario, in reality, are not the same, water demand and extraction difference might result in a more optimistic result (Demir, 2018).
4. The water extracted from the aquifer is lesser than the expected water demand and some of the WSP's water is being used for the irrigation of the study area. That's why the results are more like Demir's Scenario 2 where the time taken to recharge the aquifer into its natural state is 48 years (Demir, 2018).

On the other hand, the results from the linear trend estimation of the seawater intrusion velocity indicate that the aquifer diluting all the intruded seawater and reversing the effects of the seawater intrusion phenomenon completely will take 59 years if the trend of the whole time series is used. This result is closer to Demir's Scenario 2 (61 years) prediction (ie. water usage for irrigational purposes was stopped, recharge from precipitation and artificial recharge using dams were allowed). (Demir, 2018). Again, the explanation for the difference between the results might result from the three reasons above. Perhaps, the actual time taken is somewhere in between? When the linear regression of the 2010-2019 period was studied, the year when all the intruded volume will be diluted was found to be 2031 which is much closer to the forecast made by using the ARIMA model.

Seawater Intrusion velocity has been accelerating until the late 1990s. The worst years of intrusion are the late 1980s and early 1990s. The velocity of seawater intrusion from 1980 to 2001 is much faster than the recharge velocity. In 2018, Payab suggested that a drought period was faced in TRNC from 1983 to 1988 (Payab and Türker, 2018). Observed results might also be related to the drought years from 1983-1988 period (Payab and Türker, 2018). Possible management strategies available for implementation such as artificial recharge would change the recharge rate of the aquifer significantly, resulting in a much faster recovery process for the groundwater body. However, as it is now, the aquifer will recover slowly and steadily as the balance of the hydrological components has shifted after 75 MCM freshwater has been incorporated into the water balance equation. The locations where the effects of seawater intrusion felt were the highest are the locations which are about 2 km inland from the coast where water level depths reach lower than minus 40 m. At the start of the recharge process, this area is affected first due to heterogeneity, advection, dispersion, diffusion, and gravity (Ergil, 2000). The aquifer's return to its natural state is more of a gradual process. The time taken for the gradual increase in water table elevation and quality improvement throughout the aquifer is expected to be slower.

The irrigational water demand of Güzelyurt in 2019 is roughly 29.5 MCM. Since 1989, the total surface area used for citrus fruit production was decreased by 21.7 donum (KKTC Tarım ve Doğal Kaynaklar Bakanlığı, 2017). On this basis, irrigational water demand has decreased from 49 MCM to 29.5 MCM in 30 years. The 19.5 MCM difference relieved a significant amount of stress exerted on the aquifer. On the contrary, the water demand of the population based on domestic and municipal consumption has increased from 16.9 MCM per year to 22.3 MCM per year from 2006 to 2021, respectively. (Assuming that the municipal and domestic water demand is 180

lit/capita/day). Nowadays, aquifer water demand based on irrigational and drinking water is not that far apart. Although decreasing citrus fruit production is not good for the economy, it is beneficial to the aquifer. The population of the country is increasing at a rapid rate. The groundwater withdrawn from the aquifer for drinking water supply is significantly less since the completion of the water supply project.

Mann-Kendall test results show the increasing statistically significant monotonic dry season NaCl concentration trend is opposed by the decreasing statistically significant monotonic wet season NaCl concentration trend. (Table 9) The opposition effect is due to the aquifer being exposed to both intrusion and recharge in different seasons. The Z_c statistic for dry season concentration is higher than the Z statistic for the wet season. In addition, the trend was more significant. Sen's Q statistic calculated for both statistically significant trends remarks that the quality is improving overall, and seawater intrusion is compensated by the recharge. As both trends are significant, they were both accepted regardless of their significance. The statistically significant negative trend for both wet season volume and concentration implies that while the aquifer quality is improving, the quantity is not. The amount of freshwater entering might be greater than seawater, but it is not enough to fill the cones of depression. Otherwise, the results might also imply that the improvement in the most recent years is inapparent compared to the extreme depletion faced in the 1980s and 1990s. Furthermore, the missing data after 2020 highly affected the study and forecasting as according to results obtained from this study and Cansu's study, major improvements in water quality and quantity of the Güzelyurt groundwater resources must have been observed. The insignificant wet season rainfall trend analysis specifies that global warming or other natural phenomena do not affect the quality and quantity trends,

although there is a significant trend in the dry season as the changes in mm are too small.

ARIMA model selection process included stationarity, seasonality, and correlation tests, in addition to the statistics used for validation. In opposition to trend analysis statistically significant results, DSASC failed the validation process needed for ARIMA modeling where WSASC passed, indicating that having a statistically significant trend with a high Z statistic is not always fit for forecasting using ARIMA modeling. Even though the estimation of the time when seawater intrusion velocity will reach zero is calculated by a linear trendline equation, the estimated time is similar to the ARIMA forecast. 2029 is not an unrealistic date considering the recent improvement.

The forecasted contour maps drawn by the previous researchers both used Numerical modeling techniques. The Saturated Aquifer Volume time series is mostly similar to Ergil's Scenario (iii), where the amount of water extracted from the aquifer was reduced by 65%, forecasted using Ergil's GFLOW-U1 model (Ergil, 1999). Until 2016, assumptions of this scenario were mostly accurate considering the planted area was shrunk and crops were produced more efficiently (a similar number of crops were produced in tons with less plantation area.). Even though Ergil recommended freshwater transportation from Turkey to Cyprus, he did not foresee a future where it was the reality (Ergil, 1999). After the change in the water budget, the scenario after 2016 is much more like Demir's Scenario 1 (Demir *et al.*, 2022).

Unlike Demir's research, this study does not generate simulations based on different scenarios, but forecasts using the existing scenario. The scenario generated by the

trends of the past decades is like Demir's Scenario 1, where the stress applied to the aquifer is minimized (ie. Pumping from irrigation wells were stopped, where no artificial recharge was applied and only recharge was through precipitation). However, the real scenario in TRNC involves aquifer usage for irrigation and no pumping for drinking water, whereas the opposite was true for Demir's Scenario 1. Even though the components of the water balance equation minimized are different for the two research projects, the obtained results are similar. The predicted date of minimum water table elevation approaching zero using a Numerical Modelling approach was 2028 (Demir *et al.*, 2022). Whereas the forecasted date of NaCl concentration present within the aquifer averaging 400 ppm using a Statistical Modelling approach was 2029. Both pieces of research are done using different modeling approaches with statistically significant models. As a result, a decent improvement in water quality and quantity is expected to be seen by the end of this decade.

Distinct similarities between 2030 forecast of Ergil's Scenario (v), the forecast of this study, and the forecast of Demir's Scenario 1 can be seen. The difference between the three projects is Ergil's scenario (v) assumes that there will be no further extraction of water from the aquifer, whereas the latter two minimize the extraction to an extent (Ergil, 1999; Demir *et al.*, 2022). But why do the three results meld around 2029? An explanation could be that the water budget is balanced by the recharge and components which have been minimized (i.e drinking water, irrigation) was not expected to be minimized to the extent that they were. Another explanation could be the reduced extraction by the South. Scenario (v) was too optimistic, and Scenario 1 was hard to implement as the underlying water distribution system was not ready for change. What we have now works, so do we need to change it?

6.2 Contributions & Limitations of the Study

The study contributes to the case by implementing a statistical modeling approach rather than a numerical modeling approach. Moreover, the period covered by the study includes a massive change in the hydrological water balance. The study covers the effects of the shift in the water budget and its effects on Güzelyurt's hydrogeology.

Challenges faced for this study are the main sources of prediction uncertainty. These are the lack of complete data for accurate estimations of the components of the aquifer recharge, the number, and location of pumping wells that were actively being used, as well as the lack of information on the pumping schedule. This makes the given dataset less reliable. Additionally, the replacement of the missing data was achieved by using a deterministic approach. However, many researchers recommend the usage of Stochastic regression imputation as it provides the random error necessary to not enhance the correlation. Adaptation of a deterministic imputation method decreases the reliability of the results.

The goal of a numerical model is to approximate the solution to the underlying physical problem by combining a large number of mathematical equations (Zafarparandeh and Lazoglu, 2012). Numerical analysis generally revolves around computations motivated by solving non-linear phenomena modeled by differential equations. Data science uses statistical modeling as a method of applying statistical analysis to datasets. A mathematical relationship exists between random and non-random variables in the statistical model (Gilchrist, 1984). Disadvantages of using a statistical model include;

- Unverified: The researcher can only infer patterns and correlations from the data without being able to verify the validity or provide a mechanism for a causation explanation (Robinson, 2021). This implies that the researcher has few alternatives for confirming the accuracy and validity of the data (Robinson, 2021).
- Can be misleading: Data is susceptible to error. As a result, the researcher lacks the ability to corroborate knowledge, making them susceptible to informational distortion (Robinson, 2021). Additionally, data is hard to check and the primary source of data is responsible for providing correct data (Robinson, 2021).

6.3 Management Strategies

A balanced water budget is what water management revolves around. In reality, getting the most water possible in order to achieve the established quality standards at the lowest possible cost is the main goal of basin management (Todd and Mays, 2004). This section of the discussion part focuses mostly on raising awareness of the potential benefits of efficient water resource usage. Following this goal, recommendations were made for water management of both the Island's and Güzelyurt's closed hydrological cycle.

First of all, the management strategy of the highest importance is changing from traditional irrigation to drip irrigation. Almost no water is lost to runoff, deep percolation, or evaporation in a well-constructed drip irrigation system (Shock, 2006). Reduced water contact with plant leaves, stems, and fruit occurs with drip irrigation (Shock, 2006). Consequently, the likelihood of developing an illness may be reduced (Shock, 2006). The potential for higher production and quality is held by the exact management of irrigation scheduling to satisfy crop needs. With drip irrigation,

agricultural chemicals can be sprayed more effectively. The nitrogen already present in the soil is less susceptible to leaching losses since just the crop root zone is irrigated, and additional fertilizer may be utilized more effectively (Shock, 2006). "Subsurface drip irrigation," or SDI, is a term frequently used by growers and irrigation specialists. A drip tape or tube is less likely to be damaged during weeding or cultivation when it is buried beneath the soil's surface (Shock, 2006). With SDI, there is even less evaporation or runoff, maximizing water use efficiency (Shock, 2006). Most if not all the traditional irrigation within use in the region is already switched to drip irrigation. However, making sure that all of the irrigational water usage is through a SDI system can be considered as a strong alternative.

75 MCM of freshwater is not a small amount to be underestimated. The amount of water necessary for the irrigation of citrus plains and drinking/municipal water in 2021 is 29.5 MCM and 22.3 MCM, respectively. Approximately 51.8 MCM freshwater is enough to maintain a self-sufficient society. The amount of freshwater transferred under the name of WSP is more than enough considering the population and irrigation water demand of today. The preliminary design of the WSP was based on a water demand of 38 MCM for irrigation and 37 MCM for drinking water. Thus, the system can be fully utilized to switch most of the irrigation water supply from the aquifer to the freshwater available within Gecitkoy Dam. After the elimination of most if not all water pumpage from the aquifer, the second most important management strategy which can be easily implemented for the benefit of the aquifer is artificial recharge if the freshwater transferred from Turkey is more than the water demand. After a feasibility study on the potential benefits of artificial recharge using boreholes vs artificial recharge using dams, a plan can go into effect for efficient artificial recharge making use of existing dams constructed for recharge or an alternate set of dams

constructed for recharge after the feasibility study. The results indicate that the threat severity is minimal, and the water quality is improving. However, the time it will take for the aquifer to return to its natural state is still lengthy.

The first step to the right route of management is the establishment of aims. Since the water supply project is finished and the water is being delivered, the assumption can be made that for at least 50 years water scarcity problem will remain solved. If the excess is to be used for a combined artificial recharge, that aquifer will return to its natural state by 2062, according to Demir (2018), this is the most environmentally friendly management scenario (Demir, 2018). However, if the government desires an economically friendly approach, plantation area can be increased, and the water can be used for irrigation with the aim of advancing agricultural trading. Regardless, the best set of socioeconomic and environmentally beneficial aims must be determined.

The political future of the island is ambiguous but the water resources must be managed so that the community residing within the borders of the country obtain fresh water by making use of routes beneficial for self-sufficiency. Thus, it is recommended for the community to generate alternative ways of accessing freshwater. The top candidate as an alternative water resource is seawater. Desalination is a popular technique used in South Cyprus. The environmental and economical impacts of the treatment strategy are two huge drawbacks, however seawater is a not a limited resource which is the key reason to make a feasibility study on desalination plants as an alternative.

Chapter 7

CONCLUSION

The threat severity of the seawater intrusion problem in Güzelyurt Aquifer in TRNC has been assessed. The study aimed to identify trends and predict the future of the aquifer salinity and groundwater levels based on the existing significant monotonic trends by using the dataset obtained from the water level contours and iso-chloride NaCl maps drawn in order to visualize the effects of seawater intrusion. Surfer21 was used to visualize these maps, afterwards, saturated aquifer volume and average concentration time series datasets were obtained using tools available within the software. The available data was used with the obtained data to generate a more comprehensive dataset. Additionally, hydrological, hydrogeological, and meteorological data were gathered, catchments were identified, and the components of the water budget were analyzed to define and understand the water

Initially, linear trends of the time series' were established. Though it is unreliable, a forecast of the saturated aquifer volume and seawater intrusion velocity was made based on the linear trendline. A normality test was done on the datasets and most of them were found not to be normally distributed. Thus, the non-parametric Mann Kendall's test and Sen's Slope Estimation Test were used for trend identification. Furthermore, to understand the correlation between rainfall and saturated aquifer volume, Durban Watson Statistic, and Spearman Correlation Test were used. In

addition, the study aimed to identify the salination velocity and whether it is accelerating using the salt balance equation.

ARIMA Model development used Box and Jenkin's Method separating the process into 4 essential steps, time series identification, parameter estimation, validation of the model followed by the final forecast step. To test the stationarity of the datasets and identify the d value, the ADF test was used. Furthermore, Correlograms were created with and without differencing to validate the dataset stationarity and identify possible p and q values. Afterwards, a model is selected and validated based on AIC and Statistics. Finally, Box and Jenkin's Method is completed by forecasting using the model generated using the existing trend of the time series.

The key findings of the study and the answers to the research questions asked in the introduction part essential to this study are listed below:

- Visual changes were identified immediately after WSP's completion. Water table elevations are observed to be similar in 2018 and 1980 where the recharge and salinization were initialized, respectively. Based on the contour maps the locations affected the most by the seawater intrusion were identified, and the immediate effect of water withdrawal minimization was observed.
- Seawater intrusion velocity is 5.57 m/year for the period 1980-2001, -3.46 m/year for the period 2001-2019, and 1.40 m/year for the period 1980-2019. The negative result indicated the dilution of the salinity within the aquifer is more prominent than the intrusion which has been happening for the last 18 years.
- The aquifer saturation and seawater intrusion velocity linear regression forecasts show that 46 years of recharge is necessary following the same trend

as the last 8 seasons for the aquifer to return to its natural state. The results may indicate that freshwater usage from the WSP might be more efficient and effective than predicted.

- Using the linear trendline equations, the estimated stoppage of further seawater intrusion into the system was found to be 2015 based on the linear regression of the 2010-2019 period. Additionally, the year when complete dilution of all the seawater intruded will be achieved was estimated to be 2031 based on the linear equation of the same period.
- Mann Kendall's test revealed that 4 of the 6 time series focused on the study had a significant trend. These positive monotonic trends were for average aquifer salinity and rainfall for the dry season. The negative monotonic trends were seen for saturated aquifer volume for the wet season and average aquifer salinity for the wet season.
- The construction process of the ARIMA model revealed that the time series focused were all stationary. 9 preliminary models were selected using the correlogram and AIC was used to eliminate them until the last 4. Finally, the 4 models selected for the remaining time series were put through a validation process where only ARIMA(2,1,3) of WSSWC passed. The forecasted year of average salinity of the aquifer reaching 400 ppm was 2029.

7.1 Recommendations for Further Academic Research

This study made an attempt on predicting the future based on the past trends of periodically measured data. The most prominent limitation of the study was the missing data. Any error in the model might be based on the imputation strategy. Improvement within data collection management is highly recommended to obtain more accurate results in future studies. Water extraction from the aquifer must be well-

scheduled, monitored, and controlled. The data must be taken from the same boreholes consistently. Better data collection methods will result in more accurate research and management strategies. Additional boreholes were dug in areas where no data is available including Southern Cyprus for more consistent contour maps. The number of boreholes from groundwater level and NaCl concentration data taken from are very low compared to the data used for the 1980-2010 period. Data collection must cover more boreholes. Finally, information on the water budget that is more recent and includes details on the southern portion of the Güzelyurt Aquifer's recharge and discharge conditions is desired for a more accurate study.

There is no denying that both numerical and statistical forecasts involve uncertainty. It is recommended to monitor the hydrological/hydrogeological conditions of the aquifer continuously and consistently. Where the forecasts differ from the previous studies, the source of the difference must be identified, and if it is a local anomaly, such as the pipeline suffering from breaking for a while and additional pressure being put on the aquifer, the implemented management strategies might not need a major change. On the contrary, if a monotonic negative trend is present, changes in management strategies must take place.

Additionally, a feasibility study on the best possible artificial recharge scenario is recommended to determine the most feasible and beneficial approach, both financially and environmentally. The study conducted by Demir can be added upon by implementing realistic future climatic scenarios, economic growth considerations, water demand, population predictions, cost-benefit analyses and potential negative consequences of artificial recharge on the nearby environment should all be taken into account in more in-depth research.

Furthermore, rather than a statistical model, a numerical model of seawater intrusion can be implemented by making use of numerical tools such as SEAWAT. This way density differences will be included in the forecasting of the Güzelyurt Aquifer's hydraulic behavior. More realistic results regarding the saltwater push towards the coastal area might be obtained by combining the flow and density effects in the modeling process. Consequently, the findings of such a study may significantly aid in the decision-making process when determining management methods.

Groundwater extraction from wells over the study area should be governed by rules and regulations for the best management of the aquifer. If the correct artificial recharge techniques are used along with limiting extractions, reversing the damage caused by seawater infiltration is achievable. The irrigation of agricultural lands with treated wastewater effluents and the use of drip irrigation can both reduce the number of irrigational pumps required in the area. The water delivered from Turkey to TRNC with the Water Supply Project should be properly controlled to be able to get the maximum benefit for the sake of the Aquifer. Cooperation of the North and South sides of the Island on data exchange is another crucial factor in the creation of effective management plans for the Güzelyurt Aquifer. The results of future studies can significantly improve if academic relationships can be established with the goal of researching the field as a whole, leading to the development of more reliable methodologies.

Statistically significant positive trends were observed for Dry Seasonal Rainfall dataset. Further research on the statistical trends of island wide hydrological properties such as evapotranspiration, precipitation and surface runoff can be made to understand change and determine if global warming has an effect on the island' hydrology.

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