REPUBLIC OF TÜRKİYE
HARRAN UNIVERSITY
INSTITUTE OF GRADUATE EDUCATION

MASTER THESIS

ASSESSMENT OF GROUNDWATER QUALITY AROUND ERBIL OIL REFINERY IN NORTHERN IRAQ

GORAN AHMED ELIAS ELIAS

DEPARTMENT OF ENVIRONMENTAL ENGINEERING

Şanlıurfa
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ABSTRACT

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Groundwater is one of the world's most vital freshwater sources, essential for drinking, agriculture, and industry. It supplies nearly one-third of the global population's water needs and plays a crucial role in sustaining ecosystems,As urbanization and industrialization expand, particularly in developing regions, pressure on groundwater systems increases, making its protection an urgent priority. Industrial activities, especially oil refining, pose a major risk to groundwater quality. Refineries generate numerous contaminants, including hydrocarbons, heavy metals, and organic solvents. These can seep into the soil and leach into aquifers, altering groundwater chemistry and threatening both human health and environmental stability. The proximity of refineries to aquifers increases the risk, especially if spills or improper waste disposal. This study was conducted to assess the water quality of groundwater wells in Erbil Oil Refinery in Northern Iraq under potential pollutant pressure from some industries. The Water Quality Index (WQI) was used to evaluate the results of the water quality monitoring study. Also, representing the mechanism controlling of groundwater quality and classification of groundwater. WQI map elements distribution map from spatial distribution interpolationInverse Distance Weighted (IDW) in ArcGIS platform were used to evaluate the results. Results indicate varying water qualities. Throughout the study period, the water quality at the Erbil Refinery generally fell within the range of "Poor to good" for groundwater systems from S1 to S22, with a CWQI range of 42.39-92.14. The findings show that the rock-dominant effected the quality of groundwater. However, Piper and Schoeller classification representing groundwater water quality type was (Ca-Mg-SO_4-bicarbonate water type). Also, from the CWQI analysis indicate that the water quality in areas distant from the Erbil Refinery, as well as in collectives and villages such as S5, S6, 7, S20, S21, S18, and S2, was found to be satisfactory and good. The degradation of water quality has been seen at various sites in close proximity to the Erbil Refinery, including S1 (Inside the Refinery boundary), S14, and S16, as well as in areas near settlements such as S4 and S8. The observed phenomenon could potentially be attributed to the escalating contamination of untreated water sources, including urban trash, precipitation, and human-induced activities and might be the refinery effect. There are still certain places, namely S2, S3, and S15, that have a favorable water quality index and are in close proximity to facilities. In general, the groundwater quality in the vicinity of Erbil Oil Refinery seems to be appropriate for drinking, while there are a few specific areas that need more monitoring and remediation measures to guarantee the long-term safety of the water.

KEYWORDS: Ground water quality, Water pollution, Geographical Information System, interpolation inverse distance weighted , water quality index

ÖZET

YÜKSEK LİSANS TEZİ

IRAK'IN KUZEYINDE BULUNAN ERBIL PETROL RAFINERISI ETRAFINDAKI YERALTI SUYU KALITESININ DEGERLENDIRILMESI

GORAN AHMED ELIAS ELIAS

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LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ
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Yeraltı suyu, içme, tarım ve sanayi için gerekli olan dünyanın en hayati tatlı su kaynaklarından biridir. Küresel nüfusun su ihtiyacının yaklaşık üçte birini karşılar ve ekosistemlerin sürdürülmesinde çok önemli bir rol oynar. Özellikle gelişmekte olan bölgelerde kentleşme ve sanayileşme arttıkça, yeraltı suyu sistemleri üzerindeki baskı da artmakta ve korunması acil bir öncelik haline gelmektedir. Endüstriyel faaliyetler, özellikle de petrol rafinasyonu, yeraltı suyu kalitesi için büyük bir risk oluşturmaktadır. Rafineriler hidrokarbonlar, ağır metaller ve organik çözücüler de dahil olmak üzere çok sayıda kirletici madde üretmektedir. Bunlar toprağa sızabilir ve akiferlere sızarak yeraltı suyu kimyasını değiştirebilir ve hem insan sağlığını hem de çevresel istikrarı tehdit edebilir. Rafinerilerin akiferlere yakınlığı, özellikle dökülmeler veya uygunsuz atık bertarafı durumunda riski artırmaktadır. Bu çalışma, Kuzey Irak'taki Erbil Petrol Rafinerisi'nde bazı endüstrilerden kaynaklanan potansiyel kirletici baskısı altındaki yeraltı suyu kuyularının su kalitesini değerlendirmek için yapılmıştır. Su kalitesi izleme çalışmasının sonuçlarını değerlendirmek için Su Kalitesi İndeksi (WQI) kullanılmıştır. Ayrıca, yeraltı suyu kalitesini kontrol eden mekanizmayı ve yeraltı suyunun sınıflandırılmasını temsil etmektedir. Sonuçları değerlendirmek için ArcGIS platformunda mekansal dağılım enterpolasyonundan Ters Mesafe Ağırlıklı (IDW) WQI harita elemanları dağılım haritası kullanılmıştır.Sonuçlar su kalitesinin değiştiğini göstermektedir. Çalışma dönemi boyunca, Erbil Rafinerisi'ndeki su kalitesi, 42,39-92,14 CWQI aralığı ile S1'den S22'ye kadar olan yeraltı suyu sistemleri için genellikle “Zayıf ila iyi” aralığında kalmıştır. Bulgular, kaya baskınlığının yeraltı suyu kalitesini etkilediğini göstermektedir. Bununla birlikte, yeraltı suyu kalite tipini temsil eden Piper ve Schoeller sınıflandırması (Ca-Mg-SO4-bikarbonatlı su tipi) olmuştur. Ayrıca, CWQI analizinden, Erbil Rafinerisi'nden uzak bölgelerin yanı sıra S5, S6, 7, S20, S21, S18 ve S2 gibi kolektif ve köylerdeki su kalitesinin tatmin edici ve iyi olduğu görülmüştür. Su kalitesindeki bozulma, S1 (Rafineri sınırları içinde), S14 ve S16 gibi Erbil Rafinerisi'ne yakın bölgelerin yanı sıra S4 ve S8 gibi yerleşim yerlerine yakın bölgelerde de görülmüştür. Gözlemlenen bu olgu, kentsel çöpler, yağışlar ve insan kaynaklı faaliyetler de dahil olmak üzere arıtılmamış su kaynaklarının artan kirliliğine bağlanabilir ve rafineri etkisi olabilir. S2, S3 ve S15 gibi olumlu su kalitesi endeksine sahip ve tesislere yakın olan bazı yerler hala mevcuttur. Genel olarak, Erbil Petrol Rafinerisi çevresindeki yeraltı suyu kalitesi içme suyu için uygun görünmekle birlikte, suyun uzun vadeli güvenliğini garanti altına almak için daha fazla izleme ve iyileştirme önlemlerine ihtiyaç duyan birkaç özel alan vardır.

ANAHTAR KELİMELER: Yeraltı suyu kalitesi, su kirliliği, Coğrafi Bilgi Sistemi, enterpolasyon ters mesafe ağırlıklı, su kalite indeksi

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SYMBOLS

&: and

g : Gram

L : Liter

m: Meter

µ : Micro

℃ Celsius degree

ABBREVIATIONS

APHA : American Public Health Association

As : Arsenic

AWQI : Australian Water Quality Index

Ba : Barium

Bo : Boron

Cd : Cadmium

Cl : Chloride

Cn : Cyanides

Cu : Copper

CWQI : Canadian Water Quality Index

EC : Electrical Conductivity

Fe : Iron

GPS : Global Positional System

IDW : Inverse Distance Weighted

K : Potassium

Li : Lithium

Mg : Magnesium

Mn : Manganese

Na : Sodium

Ni : Nikel

NO_2 : Nitrite

NO_3 : Nitrat

nse : Normalized sum of excursions

NTU : Nephelometric Turbidity Unit

Pb : Lead

pH : Hydrogen ion concentration

SO_4 : Sulphate

SPSS : Statistical Package for the Social Sciences

TDS : Total dissolved solids

THC : Total Hydrocarbon Content

TPH : Total Petroleum hydrocarbons

TSS : Total suspended solid

UNEP : United Nations Environment Program

USDA : United States Department of Agriculture

USEPA : United State Environmental Protection Agency

WHO : World Health Organization

WQ : Water Quality

WQI : Water Quality Index

Zn : Zinc

1. INTRODUCTION

Groundwater, regularly denoted to as the "hidden treasure" under our feet, stands as a cornerstone of global freshwater resources, playing an essential role in sustaining life, driving agricultural practices, and fuelling industrial processes. It serves as the main source of fresh water for approximately one-third of the population in the world, meeting their daily domestic water needs and quenching their thirst (Li et al., 2021). Moreover, it fulfils the demands of food production, facilitating irrigation systems that underpin agricultural self-sufficiency, and provides the lifeblood for industrial endeavours that fuel economic growth and development.

As the population of the world surges and urbanization hastens, the importance of groundwater is further underscored. Rapidly expanding urban centers have given rise to the concept of "megacities," referring to cities with populations exceeding ten million inhabitants, and a striking fact emerges: approximately half of these urban giants lean heavily on groundwater for their water supply (Morris et al., 2003). With megacities mushrooming across the world, it is imperative to recognize the burgeoning reliance on groundwater for meeting the escalating water requirements of these vast urban populations. For instance, in the case of China, a country renowned for its dynamic growth and colossal urban landscapes, over 60% of its cities - a staggering 400 out of 657 - predominantly source their water from beneath the ground (Liu & Zheng, 2016). This global reliance on groundwater is both a testament to its significance and a source of profound responsibility.

Groundwater is not just a lifeline for human populations it is an irreplaceable resource for the ecological systems that form the web of life on our planet. The vast aquifers beneath our feet support the health and vitality of ecosystems, and their sustenance is pivotal for preserving biodiversity, wetlands, and a multitude of wildlife species. Therefore, it is incumbent upon us to ensure that groundwater remains not only a source of life but also a guardian of life's intricate balance on Earth (Shaikh & Birajdar, 2024).

The spectre of chemical pollution has been a predominant theme in recent investigations of groundwater. Whereas it poses a considerable danger to the public and the environment, it paradoxically offers a unique window into the hidden depths of our underground aquifers. Groundwater contamination serves as both a challenge and an opportunity - an imperative issue that compels researchers to delve deeper into the intricacies of our aquifers' evolution. Simultaneously, it presents policymakers with a quandary: how can we ensure the continued availability and quality of this precious resource while navigating the challenges that beset it (Lin, 2009).

The Canadian government offers a succinct yet comprehensive definition of groundwater contamination: the introduction of unwanted substances into the subsurface by human activities (Gibson & Kavanaugh, 2008). The list of potential culprits is extensive, encompassing a wide spectrum of agents, from chemicals to brines, microbes, viral contaminants, fertilizers, petroleum and medications. Nevertheless, what sets the pollution of groundwater apart from surface water pollution is its inherent invisibility. While we can visibly observe the pollution of surface water bodies, groundwater pollution remains concealed beneath the Earth's surface, often eluding detection until it causes substantial harm.

The present analysis directs its attention towards a crucial facet of groundwater contamination, specifically delving into the involvement of oil refineries within this conceptual framework. Oil refineries have a vital role in the worldwide energy infrastructure by making substantial contributions for meeting the increasing worldwide energy requirements, which is primarily met through the utilisation of fossil fuels. Refineries have a crucial impact on the transformation of crude oil into a range of different products, thereby contributing significantly to economic growth and development. This specific sector of industrial activity holds significant significance in the examination of environmental consequences, specifically regarding the contamination of groundwater (Khalefah et al., 2024).

However, this role comes with environmental repercussions, primarily concerning the quality of groundwater. As oil refineries operate in close proximity to aquifers and often draw upon groundwater for various purposes, the potential for contamination is a matter of profound concern. Groundwater, as mentioned earlier, is not merely a tap for human consumption; it is a life-sustaining force for ecosystems and a reservoir of fresh water.

What is more, groundwater occupies a pivotal position in the United States, supplying a remarkable 25% of the nation's fresh water. Oil and gas production process necessitates the drilling through aquifers to access oil and gas reserves that lie at significant depths beneath the surface of Earth. As the oil and gas industry burgeons, safeguarding groundwater assumes paramount importance, and a growing focus is directed towards the possibility of aquifer contamination. The presence of methane, produced water, or hydraulic fracturing fluid raises concerns about contamination and prompts a surge in comprehensive investigations into the mechanisms, probabilities, and mitigation strategies associated with groundwater contamination (Allison & Mandler, 2018).

The ongoing monitoring and mitigation of potential impacts of oil refineries on groundwater quality remain matters of critical importance. The Erbil Oil Refinery are located in the northern region of Iraq, has recently come under the research spotlight. A study conducted by Nematollahi et al. (2022) set out for examining the incidence and dispersion patterns of polycyclic aromatic hydrocarbons (PAHs) in soil samples obtained in both the Kirkuk and Erbil oil refineries. This research aimed to scrutinize potential contamination sources, trace the fate and transport mechanisms of PAHs in the soil, and evaluate the associated health risks. The outcome of the research unveiled a substantial correlation between the presence of the Erbil and Kirkuk oil refineries and the contamination of soil with polycyclic aromatic hydrocarbons (PAHs).

Additionally, a separate investigation, conducted in the Erbil Central Sub-Basin, evaluated the susceptibility of groundwater to nitrate and total dissolved solids (TDS). This research employed a revised form of the DRASTIC model, which assesses groundwater susceptibility. The model delineated four distinct groundwater vulnerability zones: very low (1.8, 1.6%), low (18.7, 18.3%), moderate (45.9, 42.3%) and high (33.6, 37.8%). Sensitivity analyses identified the depth to the water table and the influence of vadose zone parameters as the most influential hydrogeological factors, with mean effective weight values of 23.7% and 22.6%, respectively (Smail & Dişli, 2023).

The ongoing presence of oil spills carries the potential to negatively impact the groundwater resources utilized not only by the general public and agricultural practices but also by the broader natural environment and biodiversity. The ramifications extend beyond human concerns, encompassing the welfare of livestock and wildlife. The identification of oil spills, even when concealed beneath the surface, can be accomplished via the utilization of cutting-edge technologies, like satellite imagery, which offers a bird's-eye view of the surface of the Earth and can pinpoint contamination sources (Temitope Yekeen & Balogun, 2020).

The fundamental significance of groundwater as an essential water resource for sustaining life and maintaining ecosystem equilibrium is widely acknowledged.

Groundwater is the silent force beneath our feet, and its resilience and purity are critical for human societies and the natural world. while the world grapples with the dual encounters of environmental change and population rise, groundwater assumes an even greater role in safeguarding our future. Hence, there is a pressing need for the comprehensive assessment of groundwater quality in terms of temporal and spatial dimensions, particularly in developing nations undergoing industrialization and social and economic transformations (Saito et al., 2021).

Countless studies have been carried out in numerous regions across the globe to investigate water quality degradation resulting from climate change and anthropogenic activities. Researchers have employed a multitude of methods and techniques for assessing the groundwater quality, as outlined by Giao et al. (2023) and Othman and Ibrahim (2021). Such studies serve as a testament to the global endeavour to understand, protect, and preserve groundwater.

Chemical analysis of groundwater in a given region holds significant importance in the framework of water resources and the evaluation of its suitability as a vital natural resource. One such investigation was conducted in the Erbil-Pirmam Area, located in the North of Iraq. The research comprised of a total of 62 groundwater samples, obtained throughout two distinct recharge stages. The physical analysis encompassed measuring temperature, electrical conductivity and pH whereas the chemical examination involved the determining the main anions and cations. The samples of groundwater, collected during two different seasons, offered a comprehensive view of seasonal variations in water quality. A piper diagram, a powerful tool in hydrogeology, was employed for classifying the groundwater in the area, revealing that all water samples from both periods belonged to the bicarbonate water type (Esmael & Seeyan, 2023).

The overarching aim of this study is to carry out a rigorous evaluation of the quality of groundwater in the neighbourhood of the Erbil Oil Refinery, a facility pivotal to the northern region of Iraq. The research endeavours to investigate the possible impacts of refinery activities on groundwater resources, aiming to detect any potential instances of contamination that may have transpired. Groundwater quality is a topic of paramount significance, and this research aspires to provide valuable insights for policymakers, environmental protection agencies, and all individuals with vested interests in the region. Additionally, it aims to contribute to the implementation of necessary actions, ultimately safeguarding groundwater reserves and preserving their quality for the well-being of current and future generations.

The Objectives of the research

1.Carrying out a comprehensive assessment of the quality of groundwater in the vicinity of the Erbil oil refinery,

2.Examining the chemical and physical property of the underground water in the area, and contaminant parameters,

3.Identifying the affect of refinery activities on the local aquifer system. By identifying potential sources of contamination, evaluating health risks associated with groundwater consumption, and assessing the environmental implications,

4.Providing valuable visions for effective management of the water resource and environmental protection.

2. PREVIOUS STUDIES

2.1. Oil Refineries and their Negative Impact on the Environment

Transportation, energy production, and industrial activities are the primary contributors to environmental contamination caused by humans. This is particularly true for operations in the oil industry, which use enormous quantities of consumable fuel in petroleum refineries. This industry is especially detrimental to the environment because of the high levels of toxic gas and particulate matter emissions that it produces in comparison to other industries (Afaj & Al-Khashab, 2008).

This is especially true in situations once refineries are situated in close proximity to or in the cities. An oil refinery, which is also referred to as a petroleum refinery, is a kind of manufacturing processing facility that utilizes crude oil to generate a diversity of useful byproducts, counting gasoline, diesel engine fuel, asphalt, fuel oils, kerosene, naphtha, and LPG (Al-Rubaye et al., 2023; Van Fan et al., 2019) .The term "petroleum refineries" refers to large industrial complexes that are characterized by massive pipe networks that convey fluid streams through distillation columns and other chemical processing equipment. In the petroleum industry, refineries often play a vital part in the company. In the year 2020, the total capacity of the refineries throughout the globe to produce petroleum was 101.2 million barrels per day. In the year 2020, Mostafa and Islam as a consequence of this, oil refineries are considered to be the primary perpetrators of pollution, which is an issue that affects the whole planet. Biological systems are susceptible to suffering significant harm if petroleum pollutants that include hydrocarbons are released into the environment, discharged, or buried. Some of the telltale indications of environmental contamination include the release of chemical and organic contaminants into the atmosphere, heavily polluted soil, vegetation, and groundwater, or the possibility that these contaminants would disseminate to neighboring regions (Oprea & Mihul, 2003).

The presence of compounds in the air that have the probability to result in pain, disease, or harm to plants and other living things is called air contamination. Air contamination is defined as the occurrence of certain substances. These compounds have the potential to exist in three distinct states: particles, liquids, and gaseous forms.The SO_2 and nitrogen oxides NO_2 that are discharged into the atmosphere surrounding refineries are the most abundant gases that are emitted into the atmosphere (Al-Dabbas et al., 2012). Toluene, phenol, polycyclic aromatic hydrocarbons, and heavy metals comprising copper, zinc, lead and cadmium are some of the extra compounds that are released into the environment. Other chemicals that end up in the environment include heavy metals. It is found that the most prevalent harmful gas that is discharged by refineries is sulfur dioxide. There is a high probability that it will get caught in the air layer that is lower in the atmosphere (Al-Rubaye et al., 2023 ; Chen & Driscoll, 2005 ; Al-Rubaye et al., 2023).

A rise in the amount of soluble SO_2 in the air is caused by several factors such as rainfall, humidity, and a warm environment. It is often found in greater concentrations in the soil and the tall plants that are located in the vicinity of refineries. One of the most significant issues that arises with regard to this subject is the conflict that arises between worries about the economic and environmental benefits and the universal need for refineries (Abdul-Wahab & Yaghi, 2004; Al-Jahdali & Bisher, 2008). For this reason, it is vital for conducting an analysis of the environmental effect that is caused by existing oil refineries in order to prepare for the development of novel procedures in the future. Environmental indicators have been used for comparing the environmental performance of the production procedure in the past and present to the environmental objectives that were established at the commencement of production and the beginning of production (Zaharova & Lihacheva, 2021).

2.1.1. Effect Oil Refineries Pollution on the Human

In accordance with the findings of a number of researches, residing in close proximity to a refinery might result in long-term health consequences owing to the presence of explosions, dangerous gasses and chemical spills. There are a number of negative impacts on health, including a higher chance of getting asthma, cancer, birth abnormalities, cardiovascular and neurological impairment, respiratory difficulties, and blood diseases. Furthermore, according to study (Churg et al., 2003; Khatatbeh et al., 2020) living fifteen kilometers far from an oil refinery does not always lessen the probability of having health problems that are connected with being in close proximity to such a facility. In addition, the pollutants that are emitted might have an effect on a significant number of people living in the same route as the refinery's emissions (Auchincloss & De Roos, 2019). The Delaware River was polluted as a consequence of an explosion that occurred at a refinery in Delaware City in the year 2001. The explosion did not only result in the death of one employee but also in the injury of numerous others. Additionally, the event resulted in the deaths of thousands of crabs and fish altogether. Both sulfuric acid and nitrogen dioxide were released into the atmosphere as a consequence of an explosion that took place at a refinery in

Richmond, California, in the year 2012. Multiple personnel at the factory as well as citizens in the neighboring area were injured because of this catastrophe (Uno, 2021).

2.1.2. Effect Oil Refineries Pollution on the Aquatic Environment

The contamination of the aquatic environment is caused by a number of different reasons, including oil refineries specifically. Various compounds that are present in oil refineries, like phenol, hydrocarbons, sulphides, ammonia, and may be found in the effluents of oil refineries in varying concentrations. According to the findings of toxicological tests, refinery wastes, mostly, are deemed dangerous, but to significantly diverse degrees. Additionally, various research has shown that the effluents may often have a less significant influence on development and reproduction than their deadly effects (Wake, 2005). Some of these researches have been carried out. The presence of toxic residues has the potential to have a harmful impact on aquatic ecosystems, encourage the development of hazardous algae, and make rivers unfit for human recreational activities. Furthermore, the water's hydrodynamics and characteristics that is receiving the oil refinery effluent have a significant influence in determining how the effluent interacts with the ecosystem after it has been emitted into the environment. It is a given that the waste will combine with the water that is receiving it. However, the degree of dilution that occurs is contingent upon the size of the catchment and whether or not the outfall is subtidal (Bhateria & Jain, 2016).

2.2. Water Quality Assessment

The assessment of water quality is a procedure that involves the assessment of water's biological, chemical, and physical properties. The use of GIS technology in conjunction with the IDW interpolation approach has allowed for the frequent evaluation and observation of ground-water quality in recent years. Several research (Aravindan et al., 2010; Magesh & Elango, 2019; Shankar et al., 2010; Soujanya Kamble et al., 2020) have shown that this method is useful for assessing and examining spatial data of water resources. Using this technology, you may quickly and easily analyze massive amounts of data to find patterns, correlations, and pollution hotspots in the form of geographical distribution maps and projections. Various groundwater quality characteristics were evaluated for their regional distribution using the GIS approach in this research.

Water quality of is evaluated according to WHO standards based on the (WQI). It is a numerical expression utilized for assessing and summarizing the general water quality or condition in a particular area or system. It provides a concise way for communicating information on the water quality to policymakers, scientists, and the public. WQIs are commonly used tools in environmental science and water resource management for assessing the suitability of water for numerous purposes, like drinking, swimming, aquatic ecosystems, and industrial processes. Based on weighted mathematical computation, Horton (1965) first recognized the water quality index. Utilizing the weighted arithmetic technique to obtain ratings and weights for various water quality metrics, several researchers have created WQI models (Bawoke & Anteneh, 2020; Brown et al., 1972; Karuppannan & Kawo, 2019; Kavitha & Elangovan, 2010). With a range from zero to one hundred, the water quality index is a number that lacks dimensions. The WQI is a one-of-a-kind digital grading system that reflects the overall water quality condition (good, bad, etc.) at a precise site and time using a number of water quality criteria. To address the quality challenges at hand, the water quality index is being utilized as a valuable instrument to compare the quality of groundwater and their management agreement in a specific area (Jagadeeswari & Ramesh, 2012). It shows how various water quality metrics interact with one another and helps the public and lawmakers understand water quality so they can create effective policies and put water quality programmes into action (Kalavathy et al., 2011). The hydrochemistry of groundwater in aquifers and the breakdown of minerals from different source rocks are significantly impacted by mineral interactions (Modibo Sidibé et al., 2019).

2.3. Groundwater Quality Assessment

Groundwater is a crucial worldwide resource and serves as the greatest reservoir of freshwater, excluding the ice caps. Currently, the amount of groundwater being taken out of the Earth equals around 26% of the total amount of freshwater being withdrawn worldwide (Van Der Gun, 2012). Groundwater accounts for about 50% of the world wide’s drinking water and 43% of the total water utilized for agriculture. Furthermore, it has significant importance in the industrial sector and serves as a vital energy source. In dry and semiarid regions around the globe, groundwater is the only reliable source of potable water. It has a substantial role in maintaining baseflow in rivers and supporting ecosystems that rely on groundwater(Siebert et al., 2010).

Groundwater offers a notable benefit for drinking water supply as it has inherent safeguards against several pollutants. Specific aspects like temperature, aquifer structure soil conditions, and groundwater flow might promote denitrification, which naturally reduces excessive levels of nitrates and other pollutants caused by human activity. In water-scarce regions, the reliance on groundwater will grow as droughts and climate change become more prevalent. This is due to groundwater's ability to function as a buffer and withstand sudden changes. The quality and quantity of groundwater might be impacted by climate change; thus, it is imperative to consider this while assessing groundwater (Barbieri et al., 2023). A worldwide groundwater quality evaluation is necessary for many reasons. Firstly, human activities and climatic unpredictability are exacerbating the strain on groundwater supplies, however groundwater, being imperceptible, often goes unnoticed and unconsidered by the majority of people. Secondly, preserving our groundwater resources is essential for safeguarding human well-being, ensuring food security, and preserving ecosystems. In addition, certain areas and nations depend on naturally uncontaminated groundwater due to the impracticality of implementing modern water treatment methods from an economic standpoint. Hence, it is crucial to have knowledge about the origins of uncontaminated groundwater and to comprehend the potential hazards that might jeopardize this valuable resource (Carrard et al., 2019).

2.3.1. Groundwater Quality Index

The crucial resource for drinking water supply is groundwater, particularly in hard rock terrain1. In addition, because of its many important chemical, biological, and physical properties, groundwater is essential for human consumption. (Chaurasia et al., 2018). The WQI serves as a critical evaluation tool for groundwater quality assessment. This index integrates multiple physicochemical parameters to provide a comprehensive quality rating. Key measured variables encompass pH, EC , TDS , alkalinity, hardness, and concentrations of major ions (calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, fluoride, nitrate) along with trace metal content.

The WQI is used for categorizing the water quality into various categories such as excellent, good, poor, which is relatively beneficial for inferring the water quality to the individuals and policy makers in the related zone (Chaurasia et al., 2018).

The use of WQI, which relies on certain water quality indicators, has significant promise and serves as a valuable tool in any geographical area. In Malaysia, the classification of surface water quality was conducted utilizing the

WQI, which encompasses six parameters: pH, BOD,DO, COD, SS, and AN (Wong et al., 2020).

The correlation research between numerous physicochemical characteristics discloses substantial relationships as well. For example, the correlation between pH and TDS specifies the availability of certain contaminants. A high TDS value might propose the presence of injurious substances such as heavy metals or salts that can affect the taste or safety of the water (Ram et al., 2021). The WQI is a valuable tool for evaluating the groundwater quality. It offers a comprehensive indication of the suitability of water for human use according to a variety of chemical, biological, and physical parameters. Nevertheless, it’s imperative to note that the WQI is just one tool among many, and a full understanding of the local geological and hydrological context is crucial for accurate water quality assessment.

2.3.2. Groundwater Pollution

The ground water composition is primarily affected by the sort and depth of soils and geological formations of the subsurface that it transports through. The groundwater quality might also be impacted by the input from the surface water bodies and atmosphere.

Effective management of water resources is a pressing issue in many countries worldwide. Around three percent of the water on the Earth is classified as fresh water resources, with about thirty percent of that being accessible as groundwater. This groundwater is vital in supporting human health, ecosystems, the energy industry, and other fields that depends on water. The rising requirement from industrial, residential and agricultural sectors has resulted in the reduction of groundwater and a deterioration in its quality in various areas. Considering the perspective of sustainable development, it is important to acknowledge that water pollution can have significant environmental, economic, and social consequences in any region of the world. Thus, it is crucial to give careful consideration to the preservation of water resources (Kalhor et al., 2019).

A crucial source of drinking water for humans and animals as well as industrial and agricultural purposes worldwide is groundwater. Water resources are closely tied to the hydrological cycle and rely on factors such as rainfall and recharge methods. The quality of groundwater is determined by its biological, physical, chemical and properties. The groundwater quality has a crucial role in the determining its appropriateness for different purposes. Assessing water quality is a vital tool for effectively sharing information about the characteristics of water with the public. It serves as a measure of the quality of water. The goal of evaluating the quality of water is to transform complex data into easily understandable information that is crucial for the general public. Several investigators have carried out a research on the quality of groundwater by guesstimating the WQI to support the understanding of variations in groundwater quality (Mohan et al., 2019).

The presence of a water supply is crucial for human survival, as it relies on both its quality and quantity. Water scarcity has become a pressing issue in various areas of the globe because of the growing demand for water over the years. The circumstance is worsened by the issue of pollution or water contamination. Some countries are currently grappling with a serious freshwater crisis, primarily caused by the inadequate management of water resources and the degradation of the environment. This results in a lack of access to safe drinking water supply for millions of people (Mohan et al., 2019).

Notably, groundwater serves as the primary drinking water source for a significant proportion of the global population, highlighting its critical role in water security (Lin, 2009). As per the findings of the UNEP , there are thirty-two cities globally that have a population exceeding 10 million, commonly referred to as "megacities." Interestingly, approximately 16 of these cities heavily depend on groundwater as a vital resource. In China, for instance, more 50% of the cities rely on groundwater as their main water source (Gibson & Kavanaugh, 2008). The importance of subsurface water/groundwater cannot be denied as a crucial water resource for humanity.

Additionally, it has a significant role in preserving the ecological system on earth. Preserving this water resource's sustainability, accessibility, efficacy, and efficiency is one of the major problems for researchers in the related field. Nevertheless, groundwater quality is under substantial threat because of farming, industry, urbanization and climate change. Harmful substances like toxic metals, hydrocarbons, and various contaminants pose a risk to natural ecosystems, human health, and the long-term socioeconomic development (Faisal et al., 2021; Morris et al., 2003). In the recent decades, Chemical pollution has been a significant focus in groundwater researches. It presents a considerable risk to human populations, but it also offers an opportunity for scientists to obtain understandings into the development of underground aquifers.

This knowledge can be used by decision makers to determine methods for preserving the quality and quantity of these valuable resources (Li et al., 2021). As per the Canadian government, the groundwater contamination denote the introduction of unwanted substances through human activities (Liu & Zheng, 2016) . Various factors can contribute to groundwater contamination, including microbes, chemicals, medications, brines, fertilizers, viral infections and fuel. On the other hand, groundwater contamination is distinct from surface water pollution because it cannot be easily detected, and restoring the resource is a challenging and costly process given the current level of technology (Li & Wu, 2019).

Because of various natural and human activities, groundwater can sometimes contain chemicals and pollutants. Metals like arsenic, cadmium, and iron have the potential to dissolve in groundwater, leading to the possibility of high concentrations. Groundwater contamination is largely caused by a few human activities, such as trash disposal, industrial discharges, and agricultural practices. In addition, this could occur as a result of urban activities like the overemployment of pesticides, chemicals and fertilizers leading to the passage of contaminants to groundwater and ultimately reaching the water table. Irrespective to that the utilization of groundwater for some purposes like irrigation, industrial or drinking requires numerous examinations to guarantee its suitability for these specific uses(Aamile Islam, 2024).

When groundwater is utilized for agricultural purposes or drinking, the presence of inorganic pollutants in groundwater is a significant issue. If the pollutants are found in the groundwater at concentration exceeding the suggested level, they can lead to health issues through the food chain (Siddiqui et al., 2019).

Furthermore, the discharge of organic contaminants into water resources and the environment is a momentous issue that directly impacts human health. (Schaider et al., 2014) . In addition, the ecological system can be impacted (Lehosmaa et al., 2018). Regularly, groundwater pollutants can originate from two main sources. The first source includes sewer leakage, solid waste disposal lands, storage tanks leakage and landfills. The second source is related to agriculture and farmyard drainage (Foster et al., 2003).

Groundwater in aquifers, regardless of whether they are shallow or deep, is never fully devoid of life in the environment (Khan & Ahmad, 2012). The primary sources of groundwater microbiological contamination are bacteria and coliform organisms. It is crucial to address these pollutants promptly to safeguard lives from the spread of harmful diseases. Microbiological contaminants are commonly found in the environment due to the presence of human and animal intestines, as well as plants. These microorganisms have the potential to cause typhoid fever, dysentery, and various diseases (Khan & Ahmad, 2012).

2.4. Groundwater Characteristics

A vital element of environmental sustainability and health is groundwater quality. In the context of oil refinery processing plants, the impact on groundwater quality cannot be understated. The disposal of wastewater, which can contain harmful pollutants, and the potential for leaks or accidents can pose significant threats to groundwater resources. The followings are some groundwater characteristics.

2.4.1. pH Value

It is the primary parameter that is often analyzed in investigations of water and soil. pH represents the alkalinity or acidity of a liquid and is measured on a scale from 1 to 14. Although pH has no direct impact on human existence, it is intimately associated with a number of chemical elements in water (Narsimha & Sudarshan, 2017).

With the exception of the studies conducted by Zangana et al. (2014), Jadoon et al. (2015), the value of pH was the measured parameter in practically all of the research conducted in Erbil city. The results of all examinations indicated that the value of pH of 8.9 was the highest in Zone two of Erbil city (Daham et al., 1998). The pH level of water in this region exceeds the acceptable limit for drinking water (6.5-8.5) as specified by the USEPA (2018). Aziz and Fakhrey (2016) recorded a pH value of 8.23 in Small Agulan in January 2015, indicating a significant level of alkalinity. The remaining pH levels fell within the allowed range (8.25 to 6.8) for drinking purposes.

2.4.2. Turbidity

It refers to the clarity of water or the degree of cloudiness. Water that is very cloudy due to the presence of coal ash, bacteria, silt, organic particles (such as organisms or precipitants like iron and manganese), and plant fibers is highly polluted (WHO, 2011). The principal cause of turbidity in surface water is the presence of plankton or soil particles that are linked to mining, logging, or drilling activities. Nevertheless, the process of blasting and building causes the bedrock of aquifers to become fractured. This mostly results in the cloudiness of groundwater. The presence of several inorganic minerals, like Mg and Fe, may cause instability and result in the cloudiness of groundwater (Akhtar et al., 2014).

As to the USEPA regulation, in drinking water, the acceptable level turbidity should be below five Nephelometric Turbidity Units (NTU). The majority of water samples within the examined area are deemed appropriate for consumption and domestic use. Nevertheless, only two regions of the water samples analyzed exhibited turbidity levels that were close to or above 5 NTU. The water in the wells of Erbil city has exceeded the acceptable level of cloudiness in zone one and two (Daham et al., 1998).

2.4.3. Solids

Water may be categorized into three types of total solids: settleable solids, dissolved solids and suspended solids. Calcium, Sulphur, nitrate, iron, chlorides, phosphorus, and other ion particles that are dissolved in surface and groundwater are transported via a filter with pores around two microns in diameter. The total dissolved solids in a water solution are the inorganic salts and trace quantities of organic molecules. In contrast, a variety of particulate materials, including clay and silt particles, algae, plankton, and small organic debris, may produce suspended solids. A 2-micron filter will collect these particles. In 2003, the WHO was the source that was quoted. The USEPA (2018) has established a maximum allowable concentration of 500 mg/L for TDS in the secondary Drinking Water Regulations. Furthermore, the World Health Organization (2017) specified that water with a TDS level below 1000 mg/L is typically considered acceptable. Water with TDS concentrations above 1000 mg/L becomes notably unpleasant to taste. The incidence of TDS in water in close proximity may have an impact on its flavor (Bruvold & Ongerth, 1969).

2.4.4. Electrical Conductivity

The quantity of total substitution dissolved in water is known as electric conductivity (Yilmaz & Koç, 2014). Electrical conductivity is a tool for estimating TDS and water salinity. While it helps help determine TDS and total salinity, it doesn't tell you anything about the ions in the water (Hem, 1985). In the majority of the research, the total electrical conductivity value exceeds 400 (µmohs/cm).

2.4.5. Total Alkalinity

Alkalinity denotes to the capacity of a body of water for resisting alterations in pH. It maintains the water's ability to balance bases and acids, ensuring a stable pH level. In the absence of alkalinity potential to neutralize the water, the presence of acid on a water surface might straightly impact its pH (Akhtar et al., 2014). Rocks and soil contribute significantly to the alkalinity found in water. Significant concentrations of calcium carbonate (limestone, $CaCO_3$) in geological formations tend to raise the alkalinity concentration in water. In addition, certain wastewater from industries and plants can contribute to the alkalinity of water. In water with low alkalinity, the pH level will decrease, resulting in a tendency for the water to become acidic. This corrosive water has the likely to cause harm to household plumbing due to its acidic nature. There is a possibility that copper and lead may be released from the pipe system. In addition, eye irritation can be a side effect of low alkalinity. On the other hand, a high quantity of alkalinity may cause scaling in plumbing fixtures and pipes, as well as dry skin among susceptible individuals. When it comes to groundwater, it is of the highest significance to ensure that the alkaline balance is effectively maintained. However, To better understand the state of the water, it is usual practice to evaluate alkalinity levels in addition to pH values.

Alkalinity is not addressed by the standards set by the world health organization and USEPA. The recommended alkalinity range for swimming pool water in Canada is 80-120 mg/L, while in India, the satisfactory top limit is set at 200 mg/L. The alkalinity concentrations of the samples under investigation differ significantly, ranging from 19.8 mg/L to 410 mg/L. It is worth noting that the highest levels of alkalinity were found in the groundwater of area in Erbil city (Daham et al., 1998).

2.4.6. Total Hardness

Magnesium and Calcium are two compounds that are commonly responsible for water hardness. The two main types of Total Hardness (TH) in water are hardness that is transitory and hardness that is permanent. The mixture of these two makes up TH. While chronic hardness needs more involved treatment techniques, transient hardness may be successfully removed by boiling water. Water chemistry can be affected by the incidence of a significant amount of Mg and Ca. The soap becomes insoluble because of the high concentration of hardness present. Water that has a high level of hardness can lead to the formation of scum and curd when boiled, resulting in discoloration of fabrics, as indicated in table 2.1. Additionally, it has been linked to potential health problems, including heart diseases (Smith & Crombie, 1987). It's crucial to take the whole hardness of drinking water into account. The WHO (1996) sets the highest allowable limit at 500 mg/L, while the most desirable limit is 100 mg/L. Groundwater with a total hardness level exceeding 300 mg/L is regarded to be significantly hard and unsuitable for various applications (Sawyer & McCarty, 1967). An appropriate hardness range as ($CaCO_3$) is 80 to 100 mg/L, which strikes a balance between preventing scale buildup and minimizing corrosion. According to a study by Daham et al. (1998) et al., the highest TH was found in zone three in Erbil city.

Table 2.1. The Range of Total Hardness in Ground Water

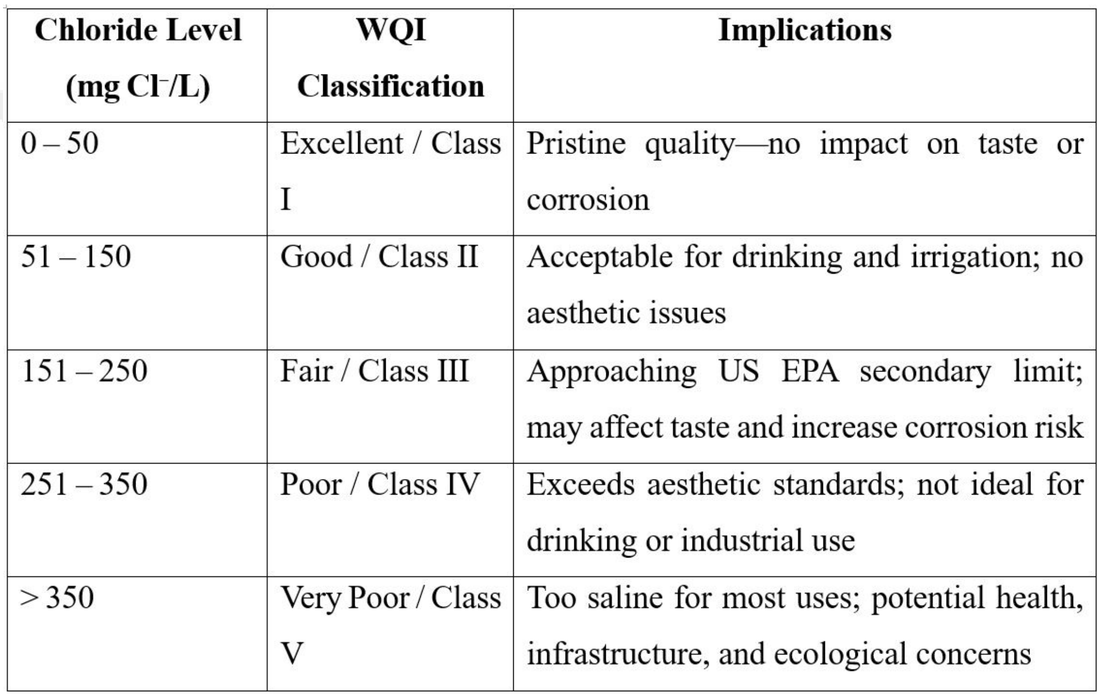
TH Range (mg $CaCO_3$/L)	**Water Quality Descriptor**	**Typical WQI Impact**
0 – 60	Soft	Favorable—minimal influence on WQI score
61 – 120	Moderately Hard	Acceptable—moderate WQI sub-index contribution
121 – 180	Hard	Less desirable—higher WQI sub-index burden
181 – 300	Very Hard	Poor—significant WQI sub-index contribution
> 300	Extremely Hard	Very Poor—major negative impact on WQI

2.4.7. Chloride

The presence of metals and minerals can impact the overall groundwater quality as they interact with the water while it gradually permeates through the rocks and sands of the soil deposit. There are multiple factors that significantly impact the quality of groundwater. As it flows through fractures in rocks, groundwater often accumulates minerals, gradually increasing its mineral content. Older waters might have a significant mineral concentration, which is why it is more profound (Smith, 1982).

Sea salt and brines are the primary sources of chloride. Chloride is found in the environment due to a number of factors, such as industrial processes, fertilizer, salt used on streets, and waste from people and animals. Because of these sources' quick chloride uptake by the soil, elevated concentrations of the mineral in shallow groundwater may result. Based on the findings of WHO (2011), level of Chloride at 250 mg/L or higher are probably to be detectable by taste. Nevertheless, it is vital to bear in mind that the recommended health guideline for chloride in portable water may not be applicable in this case, as shown in table 2.2).

Table 2.2. The Limited Values of Chloride in Ground Water



Chloride Level (mg Cl^-/L)	WQI Classification	Implications
0 – 50	Excellent / Class I	Pristine quality—no impact on taste or corrosion
51 – 150	Good / Class II	Acceptable for drinking and irrigation; no aesthetic issues
151 – 250	Fair / Class III	Approaching US EPA secondary limit; may affect taste and increase corrosion risk
251 – 350	Poor / Class IV	Exceeds aesthetic standards; not ideal for drinking or industrial use
> 350	Very Poor / Class V	Too saline for most uses; potential health, infrastructure, and ecological concerns

2.4.8. Calcium (Ca) and Magnesium (Mg)

Calcium, an essential mineral, is widely distributed in the human body and has a significant role in bone and dental health, muscle contraction, nerve transmission, and blood regulation. For calcium, drinking water can be an adjunct to dietary intake (usually providing 5–20% of daily intake) and in relatively broad concentration range (e.g., 1–135 mg/L in North American waters) and highly mineralized sources can supply over 40% of daily requirements. Whilst WHO and USEPA do not provide specific advice on calcium in drinking water, WHO's public health significance report proposes a desirable minimum level of calcium in water of 20mg/L with an optimum range of 40–80mg/L, which supports bone health and possibly reduces hypertension. Therefore, the Ca level within this interval is enough to guarantee water is a normal regulator without side effects or formation of water hardness (Gu et al., 2024).

Mg is a mineral that is prevalent in the human body. It is widely seen in nutritional supplements, several foods, added to other meals, and included in some pharmaceuticals. The human body need magnesium to operate properly. It is vital in various aspects of the body, comprising bone health, DNA and RNA synthesis, and acting as an antioxidant through glutathione. Additionally, the process includes the dynamic movement of calcium and potassium ions across cell membranes (Ross et al., 2020).

Mg and Ca are commonly originated in various soils and rocks, particularly in gypsum, dolomite, and calcium limestone. Seawater contains abundant amounts of magnesium. It helps to produce scale and makes the water harder. The tanning, industrial, textile, and electroplating sectors prefer water with low calcium and magnesium content, refer to (table 2.3). Calcium and Magnesium are the primary culprits behind the creation of scale in water heaters, pipes, and boilers, as well as causing soap to create an unpleasant curd. The mineral components mentioned in the study have a notable influence on the value of water for both household use and industrial procedures (Smith, 1982).

USEPA and WHO do not specify any particular advice for calcium and magnesium. Moreover, the Canadian Drinking Water Quality has declared that there is no proof that the presence of calcium and magnesium in drinking water has any negative health consequences. Consequently, a guideline value is not necessary (HealthCanada, 2022).

Table 2.3. Mg and Ca Limited Values

Parameter	Concentration Range (mg/L)	Mean Value	WHO Permissible Limit (mg/L)	WQI Implication
Ca^{2+}	53 – 135	86.8	75	
Mg^{2+}	14.6 – 54	32.6	30	>30 mg/L exceeds WHO recommendation; elevated Mg^{2+} sub-index may lower WQI

2.4.9. Metals

Testing for metals and heavy metals is crucial in the context of managing water resources because of their substantial impacts on groundwater quality and, by extension, human health (Belkhiri et al., 2018).

Groundwater is typically known for its purity and cleanliness, as the natural filtration process effectively removes any particles. Nonetheless, groundwater can contain both natural and human-induced chemicals. Metals like iron dissolve in groundwater and end up in considerable concentrations in the liquid. Waste disposal sites, agricultural practices, hazardous chemical accidents, municipal operations, industrial discharges, and septic tank leaks are other possible sources of metals in groundwater. These sources of contamination are likely to leak into groundwater, where it may concentrate and migrate in the direction of the water table (Waller, 1988).

Extensive testing has been conducted on the groundwater to analyze the incidence of various metals and heavy metals. Na,K,Si,Zn, Cr,Co,Fe, Mn,Mo,Ni, As,V, Pb, and many more metals were included in the investigations (Jagadeeswari & Ramesh, 2012), Cd, B, F,Cu, Li, Al, Se, Sr, Ba, and Te. Guidelines for drinking water standards do not include a recommendation value because of the decreased danger and concentration of certain metals. Compared to the other metals, Na has a range of 0.85 to 16 mg/L, which is much less than the WHO recommendation. Zn has a recommendation value of 5 mg/L in both the USEPA and Canadian standards. The groundwater has a range of values from 0.015 to 0.419 mg/L. In addition, the level of Cd falls below the recommended value of 0.03 set by the WHO (2017). According to (USEPA, 2018),Cr poses no risk to groundwater, with a maximum value of 0.096 mg/L. Nevertheless, the WHO and Canadian Drinking

Water standards limit (0.05 mg/L) is exceeded by this figure.

The maximum pollutant level defined by the USEPA, WHO, and Canadian drinking water regulations is not exceeded by Cu in the groundwater of the three provinces. The concentration of Boron (B) in the sample falls within the range of 0.0063-0.0196 mg/L. According to the WHO and Canadian Drinking Water Standard recommendations, this range is safe. The approved Maximum Contaminant Levels are 5 mg/L and 2.4 mg/L, correspondingly. The content of F, in drinking water is marginally beyond the limits established by the WHO and the Canadian Drinking Water Standard, with a maximum value of 1.65 mg/L. However, it is still below the highest pollutant concentration in accordance to the USEPA(2018). In addition, the highest recorded levels of As, Se, and Ba were 0.008 mg/L, 0.042 mg/L, and 0.215 mg/L respectively. The safety of these values is supported by reputable sources such as WHO, Canadian Drinking Water Standard, and USEPA, as presented in table 2.4.

Table 2.4. Limited Values For Metals

Metal	**Desirable Level (mg/L)**	**Risky Level (mg/L)**
Arsenic (As)	≤ 0.010	0.010
Barium (Ba)	≤ 1.0	1.3
Cadmium (Cd)	≤ 0.003	0.005
Chromium (Cr)	≤ 0.05	0.10
Copper (Cu)	≤ 1.0	1.3
Fluoride (F)	≤ 1.5	4.0
Lead (Pb)	≤ 0.01	0.015
Selenium (Se)	≤ 0.01	0.04

2.4.10. Phosphate and Sulphate

Phosphates and sulphates have a connection as they are both types of salts derived from acids and can be found naturally as minerals. Despite their molecular structures, which can vary, these substances are formed from a range of acids, consist of diverse minerals, and have distinct functions.

Phosphorus is an element that exhibits high reactivity and has a critical role in supporting life and creating a variety of mixtures in aquatic and terrestrial ecosystems. It can present in water as orthophosphate, as stated by Domagalski Domagalski and Johnson (2012). Phosphate from agricultural fields is mostly transported to surface waterways via surface runoff and seepage during rainstorm events, according to research and analysis on diffuse source phosphate (Heathwaite et al., 2005; Withers & Haygarth, 2007). There has been limited focus on estimating transfers through groundwater in previous studies (Heathwaite et al., 2005; Kilroy & Coxon, 2005). Even though orthophosphate can dissolve in water, it has the ability to bind or adhere to soil particles. Soil saturation may lead to the movement of dissolved phosphorus downward into the unsaturated zone and ultimately into groundwater (Domagalski & Johnson, 2012).

Phosphate in water should not include more than 0.02 mg/L, according to the Canadian Drinking Water Quality Guidelines. The range of phosphate levels reported in the evaluated research is 0.02 mg/L to 1.67 mg/L, all of which are higher than the maximum permissible value (Zhang et al., 2024).

Sulphate was detected in numerous surface water and aquifers with notable levels. Sulphate is a form of sulphur that undergoes oxidation. During the sulphide mining process, In the presence of oxygen, sulphur undergoes a transformation and becomes sulphate. Another source of sulphate is Gypsum, which can be found in specific aquifers. Minerals found in water pipes can lead to the buildup of scale, similar to other minerals. A bitter taste in the water may sometimes arise from this, and both people and young animals may have laxative effects (Brian, 2014). In adult males, consuming 7 g of magnesium sulfate and 8 g of sodium sulfate stimulated bowel motions(Cocchetto & Levy, 1981; Morris & Levy, 1983). The cathartic impacts are typically experienced by individuals who consume drinking water with sulphate concentrations exceeding 600 mg/liter. (Hospital & Facilities, 1962), It is commonly supposed that humans will gradually adjust to higher levels of concentration overtime. Dehydration was also found to be a communal side-effect after consuming large quantities of magnesium or sodium sulphate, according to research conducted by USEPA in (Fingl, 1980).

The concentration of sulphate in drinking water is dependent on certain limits set by different organizations. The highest satisfactory level is 500 mg/L In Canada, while the USEPA has set a highest pollutant concentration of 250 mg/L. However, in accordance to the WHO (2017), Sulfurate concentrations in drinking water are not harmful to human health.

In the studies that were examined, the sulphate level in the sample ranged from 0.31 to 716 mg/L. Several areas of study have sulphate concentrations that exceed the guideline values set by Canadian government as well as the standards established by USEPA in (2018).

2.4.11. Nitrate

The incidence of nitrate in water might have substantial implications. While naturally occurring nitrate in low amounts is not uncommon, excessive concentrations can pose a threat to groundwater contamination. It is worth noting that nitrate itself is colorless, odorless, and tasteless. This could potentially have significant health implications (Mahler, 2007).

Agricultural waste, human waste from septic tanks and municipal sanitation systems, and fertilizers are typical sources of groundwater nitrate. Rural and industrial areas often have soil that has higher levels of nitrate. Because of irrigation or rainfall, nitrate may quickly pollute groundwater. An increased risk of nitrate contamination is associated with shallow wells in agricultural regions, wells in sandy soil, and poorly built or maintained wells(Jia & Qian, 2025).

Excessive levels of Nitrate can cause probable hazards to the public health and the environment. Research suggests that elevated levels of nitrates can contribute to the extreme algae growth, leading to eutrophication in water bodies (Bhatnagar & Sillanpää, 2011). The nitrate level rise in drinking water has been found to have negative effect on health. Specifically, It may cause "blue-baby syndrome" (methemoglobinemia) to develop, which is particularly concerning for children. Furthermore, there is a chance that carcinogenic nitrosamines will be produced (Majumdar & Gupta, 2000). Current studies and related references have indicated that elevated concentration of Nitrate in drinking water can potentially cause various types of cancer in humans.

The standard values for Nitrate are 10 mg/L according to USEPA in (2018). The guideline values set by WHO (2019) for Nitrate is 50 mg/L. After reviewing the studies, it was found that the levels of Nitrate range from 1 to 58 mg/L. When examining these findings in relation to the established standard, it becomes evident that certain areas in the North of Iraq have groundwater that is contaminated with Nitrate.

2.4.12. Coliform

All endothermic hosts carry coliform bacteria as a part of their physiological flora, and fecal shedding results in widespread environmental contamination. Commensal organisms such as these, normally present in low numbers, are considered to represent a low level of risk to health, but in potable water, their detection in general indicates fecal contamination, and the possible presence therein of enteric pathogens (e.g., salmonella, cryptosporidium) bearing a mammalian excreta profile. The process of testing drinking water for every potential pathogen is costly, time-consuming, and complicated. The process of testing for coliform bacteria is simple and affordable. When tests reveal the presence of coliform bacteria in a sample of water, water systems look for the contamination source and restore clean drinking water.

Escherichia coli (E. coli) is a kind of bacteria that is frequently present in the animals and human's guts. Identifying the presence of E. coli in water serves as a reliable indication of potential pollution from sewage or animal waste. E. coli assists as a dependable indicator of faecal contamination in water sources, as it is commonly found alongside harmful faecal pathogens that can pose a risk to human health, leading to various diseases including diarrhea. In addition, the study conducted in Juba, South (Rohmah et al., 2018) highlights the heightened risk of diarrheal diseases associated with the drinking of groundwater polluted by this bacteria. Elevated levels of these bacteria are often indicative of an increased incidence of injurious microorganisms, besides other disease-causing microorganisms like protozoans and viruses. Escherichia coli thrives in a temperature range of 10 - 45 ℃, with its ideal temperature being 37℃. It prefers a pH level of 7 - 7.5 for optimal growth, with a lowest pH of 4 and a highest pH of 9 (Faridz & Hafiluddin, 2007).

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2.5. Researches Conducted around the World

It is broadly recognized that the groundwater is a valuable water sources for various purposes including sustaining life and ecosystem balancing. Therefore, spatial and temporal groundwater quality assessment is remarkedly required in different parts of the globe particularly in developing countries which are facing industrialization and social and economic developments. Number of studies have been undertaken in several part of world in term water quality as it has been contaminated because of climate change and human activities. Several method and procedures were utilized to evaluate the groundwater quality, as mentioned some of them as follow (Giao et al., 2023; Othman & Ibrahim, 2021).

Radelyuk et al. (2021) sought to evaluate the global effect of the oil refinery sector on water resources in relation to sustainable development (SD). An analysis was conducted on the national legislation, reports from the environmental and industry authorities, as well as the circumstances of the ultimate disposal system. The study examined key features, including current treatment system techniques, the quality of treated wastewater, and methods to ensure their safety. The contrast among industrialized nations (represented by the United States of America and Europe) and emerging nations (for instant Kazakhstan) revealed the presence of various obstacles, including legal loopholes, historical contamination, and miscommunication among stakeholders. These obstacles persist in spite of the formal endorsement of the notion of sustainable development. The report recommended that the policy be implemented based on rigorous scientific research, by considering the potential integration of important technical advancements, implementing a comprehensive system for assessing environmental effect, and ensuring fair operational monitoring.

Ugwoha and Omenogor (2017) have conducted a study for evaluating the influence of a crude oil leak on groundwater quality in two studied areas the spill-impacted areas serving as the study area and the uninfluenced areas serving as the control. Hand-dug wells were utilized for collecting and analyze groundwater samples in both the study and control sites. Total hydrocarbon content (THC), BOD, temperature and DO were considered as some of the water variables that were evaluated and compared among the two regions and to national guidelines. The findings were observed that a substantial and remarkable increasing in the BOD, temperature and THC in the location of the study, while a significant decreasing was detected in the pH and DO in the study area, when comparing with the control region and established standards. According to these findings, the study determined that the groundwater in the examined location is contaminated and requires treatment prior to consumption.

In a study conducted by Tomar et al. (2012), water samples were collected from 67 sites in Karnal district, Haryana throughout both before and after monsoon seasons of 2011. These samples were then analyzed for their chemical characteristics. The water composition in the research location was found to be predominantly sodium-calcium bicarbonate and magnesium bicarbonate type during the pre- and post-monsoon seasons of 2011, as determined by hydro-chemical analysis. Using chemical analysis, the water samples collected before and after the monsoon were categorized according to various irrigation standards. This was done to examine the chemical alterations caused by rainfall and natural recharge. Prior the monsoon season of 2011, the dominant type of water was Na-Ca-HCO_3, while subsequent the monsoon season shifted to Mg-HCO_3.

Patil et al. (2013), Patil et al. (2013) carried out a study on water samples of seven bore wells in the vicinity of a landfill site in Turmuri, Belgaum. The aim of the study was to determine the influence of the dumpsite on groundwater quality by conducting physic-chemical and bacteriological analysis. As part of the study, a total of 7 bore wells were chosen in the vicinity of the landfill, with distances ranging from 500 to 1000m. Using normal laboratory techniques, the following parameters were investigated during the research period: pH, TDS, Total Hardness, Nitrate, Most Probable Number (MPN), and heavy metals like Lead. The levels of pH in February and March were found to be acidic, ranging from 6.01 to 7.3. All of the wells, however, had normal pH values in April and May. The water in wells located within a distance of 500-700m is unfortunately affected by the leachate from the nearby landfill, resulting in contamination of the pH levels. The levels of hardness, TDS, and nitrate varied between 0 and 80 mg/L, 49 and 190 mg/L, and 4 and 79.89 mg/L, correspondingly. The investigation was conducted over a period of four months, from February to May. The findings indicated that bore wells within a 500 m radius were found to be contaminated with E-Coli bacteria. Additionally, the concentration of nitrate exceeded the acceptable level set by the WHO and the Bureau of Indian Standards for drinking water. Furthermore, the pH levels were found to be acidic in nature. The contaminated water necessitates specific concentration of treatment prior to its utilization. It is highly recommended to raise public awareness about waste sorting, embrace clean technology, implement climate change mitigation plans, and utilize sanitary landfills for preventing any further pollution of groundwater flow.

In a study conducted by Sarala and Ravi Babu (2012), the focus was on analyzing the quality parameters of groundwater in the wells surrounding Jawaharnagar, situated in the upper Musi catchment area of Ranga Reddy district in Andhra Pradesh. Two seasons—the post-monsoon in December 2007 and the pre-monsoon in June 2008—were used to gather data on bore wells in the research region. The groundwater has a high acidity level and is known for its hardness. It is accomplished through the utilization of Arc GIS software. The analysis shows that, with the exception of a few instances where overall hardness and fluoride concentrations are increased, the concentrations of the key components are within the acceptable limits of IS-10500-1994. The concentration of fluoride exceeded the permissible limit. Based on the examination, it was detected that the groundwater in the whole research location is contaminated. Recently, there has been a significant upsurge in the utilization of surface and groundwater for drinking, industrial, and agricultural purposes. However, it is concerning to note that this increased utilization has led to water pollution, which in turn is negatively impacting soil nutrients, environment and human and animals health in specific regions.

In a recent research conducted by Tank and Chandel (2010), the researchers examined the spatial distribution of groundwater quality in the Dhankawadi ward of Pune. They utilized GIS technology to analyze the data and draw meaningful conclusions. The organization has implemented a standard laboratory procedure to evaluate the ground water quality. The map of spatial distribution indicates that the chlorides, magnesium, pH and sulphate levels are within the acceptable range according to standard guidelines. The concentrations of TDS and Nitrate in the ground water of the research area are discovered to be higher than the permissible limit at the central location near Katraj Dairy in Pune. Groundwater is available for domestic purposes and drinking in the research location, with the exception of upper Katraj Nagar in Pune.

Adetunde et al. (2011) studied the physicochemical and bacteriological properties of well water in two local government areas of Ogbomoso North and South, Oyo State, Nigeria to assess the potable quality of groundwater in these areas. In each district samples of water were obtained from twenty manually dug wells. The temperatures, pH and chemical features of water were within the (WHO) recommended levels for home and drinking purposes. The water was soft, the mean alkalinity was between 30 and 390 mg/Lin the North, while it was between 40 and 236 mg/L in the South, respectively. The pH values ranged from 6.2 to 8.8 (all the betting value as marked bold), and the concentration of SO_4^{2-}, and Cl^- were under the prescribed WHO standard for both areas. Average hardness was 40–504mg/L in the North and 60–384mg/L in the South, some areas on the reserve showed a tendency towards the hard side for water. A major problem identified in the study was that of microbial contamination, which has been identified as a major hazard threatening water quality, the risk of water borne diseases in the two areas of Oyo State.

Ghoraba and Khan (2013) undertook an intensive survey of the 29 different Balochistan sites of Pakistan collecting a total number of about 120 groundwater samples. The study centered on different attributes of water quality such as pH, TDS, bicarbonate, carbonate, calcium, magnesium, sodium, potassium, chloride, sulphate, and nitrate. The hydrochemical study showed a clear heterogeneity between the samples and chloride is the most present ion. High contents of iron, nitrate, and fluoride were also reported from different areas in Balochistan. Durov diagram interpretation of the pH data revealed that the ground water of study area was, in general, alkaline in nature. Furthermore, most samples showed electrical conductivities which met Pakistan standards of drinking water. However, according to the EC plot and SAR plot, good proportion of the ground water was not suitable for irrigation unless the proper drainage and salinity control method would have been set up. Nevertheless, the groundwater in the majority of the studied areas has been found to be acceptable for human consumption with regard to WHO (2011) guidelines of drinking water quality. Particularly, TDS content displayed substantial variations within the samples denoting the heterogeneity of the groundwater quality.

Sayyed et al. (2013) studied groundwater in the southeastern part of Pune city for seasonal variations in water quality parameters. The Piper diagram was used in this study to successfully categorize groundwater into hydrogeochemical facies according to the variation in major ion concentration. The multivariate technique showed that the quality of groundwater is significantly affected by anthropogenic activities through hydrogeochemical facies. Wells showed the occurrence of leachate in both Fursungi and Mantarwadi areas with contaminated (SO_4 and Cl) water at significantly higher concentration on average throughout the year.

Mane and Hingane Hemalata (2012) conducted a study on the quality of water evaluation of Katraj lake in Pune. They conducted water examination for various parameters of lake water, including pH, DO, BOD, COD, TDS, Calcium, Magnesium, and Hardness. The water quality analysis discloses a temperature in the range of 24°C.The pH ranged from 7.3 to 8.45. The water has a slightly alkaline pH level. The DO levels varied from 4.8 to 5.7 mg/l. The total hardness levels observed in the research varied from 160 to 298 mg/l, exceeding the accepted limit. The turbidity of the water measured between 28 to 42 NTU, which exceeds the limit set by APHA.

In a recent study conducted by Onyeiwu et al. (2022), the focus was on examining the physicochemical features of groundwater in the Kaduna refinery environment, as well as its potential for bioremediation. The research delved into understanding the properties of the groundwater and exploring the possibility of using bioremediation techniques to address any contamination issues. It has been mentioned that the contamination of groundwater by oil hydrocarbon significantly effects on the quality of water for drinking and other domestic purposes, causing a hazardous risk to the water environment. Conventional approaches were employed to analyse the physicochemical characteristics of groundwater in six different locations. The research findings revealed that the water from the village well had a slightly acidic pH level of 5.67–6.17, whereas the monitoring wells exhibited to some extent alkaline pH level of 7.14-7.67. The temperature was discovered to be within the ideal range for bioremediation. The levels of DO in the sites (6.70 – 7.69mg/l) do not pose a limitation to hydrocarbon biodegradation. Bioremediation is hindered by the low levels of nitrate and phosphate. The presence of a high level of sulphate in one of the wells at the dump site (350mg/l) suggests the existence of contamination and corrosion issues. High levels of NTU, chloride level, BOD levels, and electrical conductivity suggest the presence of contamination.

Giao et al. (2023) highlighted the significance of groundwater as a valuable resource for the people of Vietnam. However, they also noted that the quality of groundwater has been steadily declining due to human activities, particularly hydrocarbon production. The purpose of their study was for evaluating the appropriateness of groundwater for drinking purposes in Vietnam, using a combination of advanced statistical techniques and a WQI based on weights. The groundwater quality of 64 observation boreholes in the studied area was assessed based on eight physio-chemical parameters. These parameters included NO_3, pH, total hardness, lead (Jagadeeswari & Ramesh), As, Fe, coliforms, and Hg . The findings of their study indicated that certain small groundwater areas were found to have undrinkable conditions, as determined by the WQI . The area is experiencing groundwater contamination with high concentrations of iron, coliform, and total hardness. The results of this research provide essential guidance for decision makers in effectively managing groundwater resources in the region.

In a study conducted by Hagras and Agamy (2014) evaluated the groundwater quality and hydrochemical characteristics in Punjab. The researchers collected groundwater samples from various cities in the Punjab city and analysed them for four weeks different water quality parameters. An evaluation was carried out for determining the suitability of groundwater for domestic and irrigation determinations, utilising the standards set by (WHO) and the (USDA). The percentage sodium (Na%) and SAR values in various sites suggest that most of the samples of groundwater are appropriate for agricultural purposes. This research study highlights the concerning issue of water safety in numerous cities across Pakistan. It reveals that the water is unfit for human use because of the incidence of chemical and bacterial contaminants.

2.6. Research Conducted in Iraq

In a recent study, Al-Tameemi et al. (2020) explored the assessment of the quality of groundwater through the utilisation of the water quality index methodology. The suitability of Kirkuk's groundwater for various purposes, including aquatic, irrigation, drinking, recreational, and animal utilizations, was assessed using the CWQI and GIS. This assessment was carried out in 60 wells from 2017 to 2019. The assessment of the quality of groundwater was conducted utilizing the guidelines provided by Iraq and the (WHO). The Iraqi standards were utilised for portable applications. The WHO criteria were utilised for the purposes of aquatic activities, irrigation, leisure activities, and livestock usage. An Excel spreadsheet called CWQI was utilised for evaluating the quality of groundwater in the wells being examined, encompassing all relevant criteria. Specimens were collected and analysed for fifteen important variables.in accordance with the CWQI, the groundwater samples collected were catagorized as marginal in 2017 and 2018, and in 2019, they were determined to have low quality for drinking purposes.

A recent study by Younus (2021) investigated the groundwater quality in wells situated near the Basra refinery in southern Iraq's Al-Zubair area. In the spring of 2016, a grand total of sixteen PAH compounds were found in the water. These compounds were discovered in both the dissolved and suspended fractions. The abundance of dissolved and suspended hydrocarbons, coupled with the transportation of petroleum hydrocarbon pollutants through rain, enabled the transfer of particles and dissolved substances from the soil pores to the groundwater. The study found that oil refineries had a substantial effect on the pollution of nearby water wells with harmful and carcinogenic polycyclic hydrocarbon pollutants.

In a recent study conducted by Amin Al Manmi et al. (2019) the focus was on investigating the effects of subpar management practices within the oil and gas industry on the surrounding groundwater and soil. Specifically, the study examined the impact in the vicinity of a gas station and an oil refinery unit. Moreover, their objective was to develop a map that illustrates the level of pollution risk in the region. A comprehensive investigation was carried out on a total of 51 soil samples and 25 water samples to identify the presence of Light Non-aqueous Phase Liquid (LNAPLs). Additionally, one soil sample was specifically analysed to detect Dense Non-Aqueous Phase Liquid (DNAPLs). In addition, 6 soil samples were evaluated for Tetraethyl Lead (TEL) analysis. The results showed that seventeen wells were found to have contamination from LNAPLs, while the soils were heavily polluted with different components of DNAPLs, primarily (PAHs). The GIS platform utilised seven parameters to generate the PRI map, which included factors such as depth to water table, distance to source, lineaments, slope, lithology, soil and recharge proportion. It is exposed that the western and eastern regions of the research location were categorised as having a significantly higher risk level, whereas the central region was classified as having a very low to low risk level.

Alikhan et al. (2020) evaluated groundwater quality utilizing a WQI. An assessment of the quality of groundwater is conducted utilizing the WQI, which takes into account specific factors and utilises a weighted arithmetic approach. The pH water quality index water quality index is categorised as good, while the electrical conductivity in the research region is deemed unsuitable for drinking purposes according to the classification of water quality. In addition, the WQI reveals that the levels of sulphate and total dissolved solids are categorised as highly unfavourable. The WQI for magnesium, calcium, potassium, sodium, and chloride was determined to be poor based on the same water quality categorization. In addition, the WQI has an average score of 100.206, which falls into the poor category. This greatly affects the social, economic, and health conditions of individuals.

Ibrahim et al. (2018) examined the environmental evaluation of heavy metals in groundwater and surface water in Samarra City, which is situated in Central Iraq. It was found that the concentration of Uranium was bigger in most water samples, except for SW1, SW2, SW3, and GW1, according to the investigation. This difference may be explained by military activities. Nevertheless, apart from SW2 and GW4, all samples were found to be contaminated with Co. The increased levels of Co are most likely a result of industrial activities and oil spills. The investigation produced findings for various physical and chemical parameters, like pH, BOD, EC, TDS, COD, TSS, DO, and turbidity. The water studies revealed that the physical and chemical properties of the water samples surpassed the permissible limits set by WHO standard and the IQS2009 standards for drinking water. It was observed that all surface and groundwater samples showed a substantial rise in the levels of BOD and EC. It was discovered that only the ground water samples showed higher levels of TDS, COD, and turbidity.

2.7. Research Conducted in Erbil Area

Aziz (2004) conducted a study to investigate the seasonal fluctuations of water and wastewater in Erbil, specifically focusing on groundwater. The author conducted a study on well No.3 in Iskan Quarter and observed that its quality remained consistent throughout the year. Based on this finding, Aziz recommended collecting samples from the wells on an annual or biannual basis. In addition, different areas of Erbil city's groundwater have been thoroughly examined.

Toma (2006) assessed the suitability of ten wells in the Ainkawa area for drinking purposes. The findings revealed that all the wells examined in this investigation met the international standards for drinking water.

In a study conducted by Toma et al. (2013) the WQI of 6 wells located in different quarters of Erbil City was examined. The included wells were Azadi 8, Ronaky 1, Rizgari 1, Ankawa 9, Tayrawa 1, and Badawa. The findings indicated that the water quality is appropriate for human consumption.

In addition, in Erbil city, Daham et al. (1998) conducted tests on fifty wells. The paper documented elevated levels of total hardness, pH, alkalinity and turbidity in Erbil City. Additionally, Jadoon et al. (2015) examined five wells in the Bakhtiari and Ainkawa quarters. Through comprehensive testing of all five wells, the authors discovered that the water contained significant levels of contaminants, including high concentrations of nitrates and pathogens.

In their study, Babir and Ali (2016) examined a total of 30 wells and 3 springs located in the Koya Basin. It was mentioned that certain springs and wells exhibit elevated levels of sulphate, EC and TDS. This could be attributed to the presence of gypsum and thick claystone layers in the local geological formation. In addition, Hammam Jalli's Spring was investigated as a thermal spring in Koya District.

In a study conducted by Zangana et al. (2014) it was found that the pH and conductivity levels of the water from hammam jalli springs are within the acceptable standards for drinking water. Additionally, the water from Hammam Jalli was found to have low mineral contents.

In Soran District, Al-Barwary et al. (2018) conducted a study where they gathered water samples from 20 wells and 20 springs. It was found that the water samples from eight wells and four springs need to be treated before they can be used for drinking purposes.

Aziz and Maulood (2015) conducted tests on wells to measure total dissolved solids, total suspended and total solid. The findings indicated that the total suspended solids exhibited a variation from 180 to 300. The highest level for total dissolved solids in both researches was 900 and 1000 mg/L. total dissolved solid has a maximum concentration of 900 and 1000 mg/L, which falls within the limited standards set by the WHO.

Othman and Ibrahim (2021) stated that the groundwater serves a vital role in fulfilling the drinking, domestic, and farming necessities of the inhabitants in the proximity of Erbil city, northern of Iraq. Consequently, it was imperative to evaluate the groundwater quality by employing standardized approaches for measuring a range of chemical and physical parameters. The 16 groundwater wells in the west and south of Erbil city were sampled to assess their quality. The analysis involved the application of the CWQI Formula WQI, which encompassed 22 parameters including total hardness, total alkalinity, EC, pH, nitrate, sulphate, chloride, Mg, Na, calcium, potassium, dissolved oxygen, orthophosphate, biological oxygen demand, oil and grease, cadmium, zinc, lead, copper, nickel, iron, and mercury. The findings showed that the calculated WQI value for the groundwater was determined to be 38.87, indicating its poor quality. Consequently, direct drinking of the water was deemed unsuitable, necessitating treatment measures to be implemented in order to mitigate waterborne diseases.

3. MATERIALS AND METHODS

3.1. The Study Area's Description

The city of Erbil is located in the northern of Iraq. Erbil spans approximately 18170 square kilometers in size. The Erbil oil Refinery is situated in the north-west of Erbil city, with the Greater Zap River to the north-west and the Lesser Zap River to the southeast (latitude 36.3179, longitude 43.7573). Figure 3.1 shows the location of the Erbil oil refinery. Erbil oil refinery is about 30KM far from Erbil city. The Erbil refinery ranks as the fourth biggest refinery in Iraq. The Erbil refinery currently consists of five production lines for refining crude oil, meeting standards for production, storage, distribution, and supply of petroleum products. It is the first crude oil refinery in northern Iraq. The building of this refinery commenced in 2005. The refinery manufactures naphtha, kerosene, gasoil (diesel), fuel oil, gasoline (automobile's benzene), and liquid gas (after activating the second production line). These items are kept and dispersed in storage tanks before being moved through loading stations by tankers. Alternatively, they can be transferred via a pipeline to Erbil Depot upon request. The Resource Geographic Information System (RGIS) software was used to draw the study area maps (RGIS, 2023).

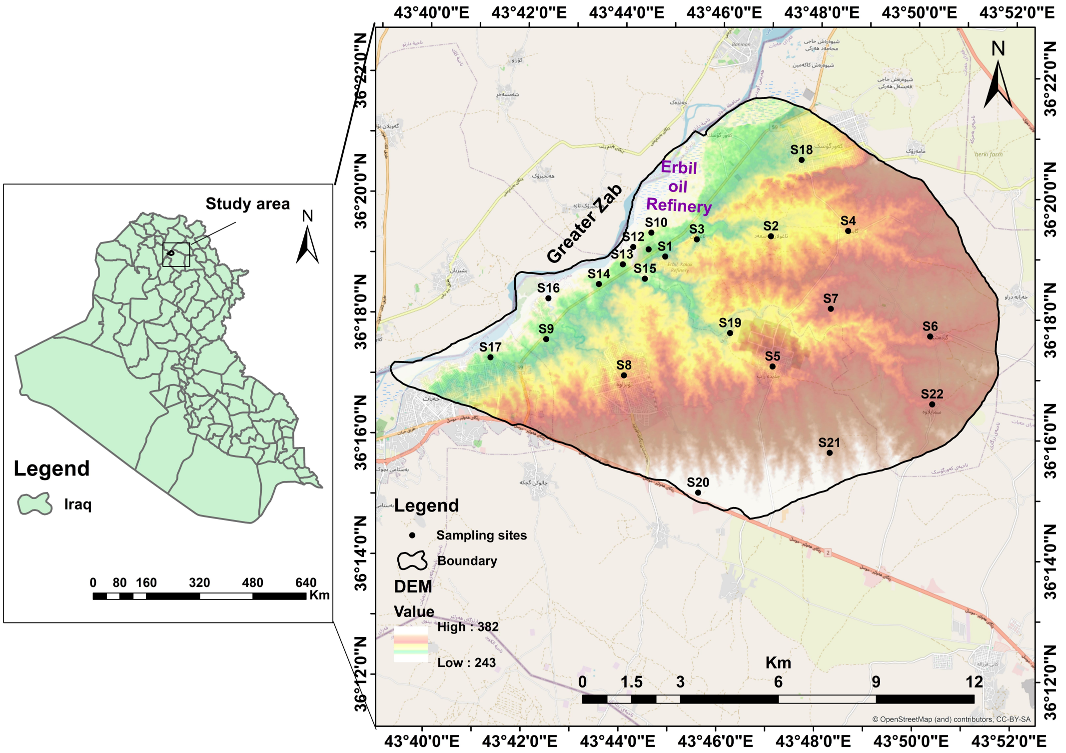


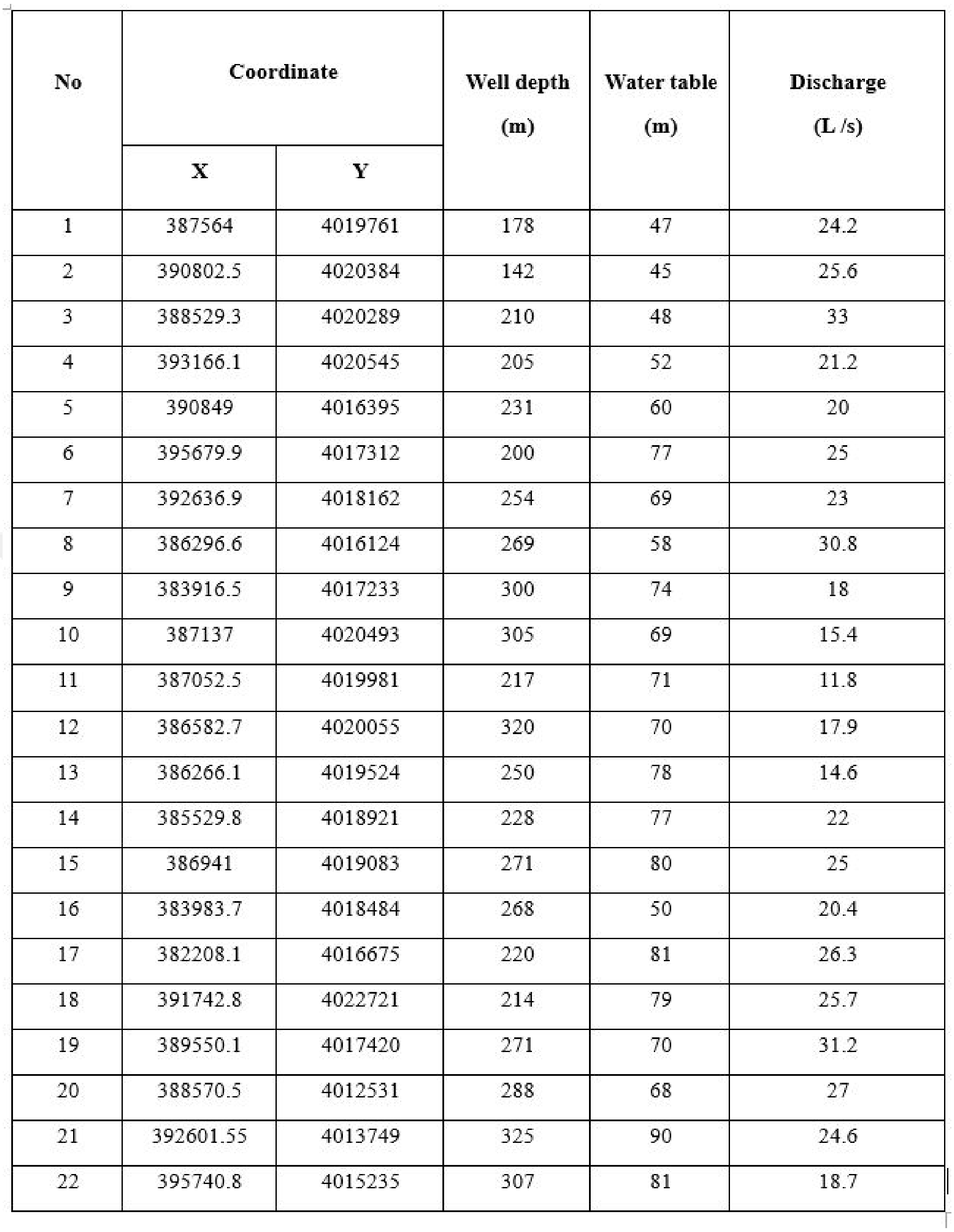
Figure 3.1. Study Area and Sampling Points

3.2. Data Collection Method

During the day, the samples of groundwater were gained at numerous times to consider the likelihood of daily water quality fluctuations. the water was allowed to flow for 15 minutes throughout the sampling procedure to verify that the samples accurately represented the groundwater's steady-state condition. This approach was crucial for acquiring precise and indicative water quality data. The samples were collected from wells situated in several topographical environments, yielding a thorough assessment of the groundwater conditions across various landscapes. Figure 3.2 shows the process of sampling collection.

Sampling took place at 22 well sites spread evenly across the study area. Each well was assigned a unique sample number, identified from 1 to 22, as shown in table 3.1. The precise latitude and longitude of each well were carefully documented to precisely pinpoint the sampling points' location. The latitude values of the wells range from 36.251259 to 36.343464, and the longitude values range from 43.688305 to 43.838209 as listed in Table 3.1. The precise geographical coordinates were essential for properly recording the spatial arrangement of the samples and guaranteeing a thorough representation of the study area. Using latitude and longitude coordinates improves the reproducibility and spatial accuracy of the research, aiding in the identification and description of each sampling location (Agency, 2020).

Table 3.1. Sampling Point at the Site



No	Coordinate		Well depth (m)	Water table (m)	Discharge (L /s)
	X	Y			
1	387564	4019761	178	47	24.2
2	390802.5	4020384	142	45	25.6
3	388529.3	4020289	210	48	33
4	393166.1	4020545	205	52	21.2
5	390849	4016395	231	60	20
6	395679.9	4017312	200	77	25
7	392636.9	4018162	254	69	23
8	386296.6	4016124	269	58	30.8
9	383916.5	4017233	300	74	18
10	387137	4020493	305	69	15.4
11	387052.5	4019981	217	71	11.8
12	386582.7	4020055	320	70	17.9
13	386266.1	4019524	250	78	14.6
14	385529.8	4018921	228	77	22
15	386941	4019083	271	80	25
16	383983.7	4018484	268	50	20.4
17	382208.1	4016675	220	81	26.3
18	391742.8	4022721	214	79	25.7
19	389550.1	4017420	271	70	31.2
20	388570.5	4012531	288	68	27
21	392601.55	4013749	325	90	24.6
22	395740.8	4015235	307	81	18.7

Figure 3.2. Sample Taking From a Well

3.3. Analyzed Parameters and Devices

This study included the analysis of many factors for determining the groundwater quality. The criteria include several chemical and physical qualities, like pH, EC, Turbidity, TDS, Sulphate, and Chloride levels(Barzinji & Ganjo, 2014). The document also provides a comprehensive study of TPH. In addition, the levels of several heavy metals, including Silver, Arsenic, Magnesium, Barium, Beryllium, Calcium, Manganese, Cobalt, Potassium, Aluminium, Molybdenum, Thorium, Sodium, Boron, Selenium, Thalium, Antimony, and Vanadium were quantified(Adelekan & Abegunde, 2011). Additionally, a microbiological examination was carried out for detecting the incidence of Faecal Coliform and E. coli (Chidiac et al., 2023).

The analysis utilised various instruments for specific measurements. As the following:

The Shimadzu Nexis GC-2030 Gas Chromatograph is used for measuring hydrocarbons (Figure 3.3). The method involves the separation of hydrocarbons in a sample by passing them through a column within the GC, where they elute at different times based on their volatility and interaction with the column's stationary phase. This technique is widely used in environmental monitoring, quality control, and oil and gas industries (Murcia-Morales et al., 2024).

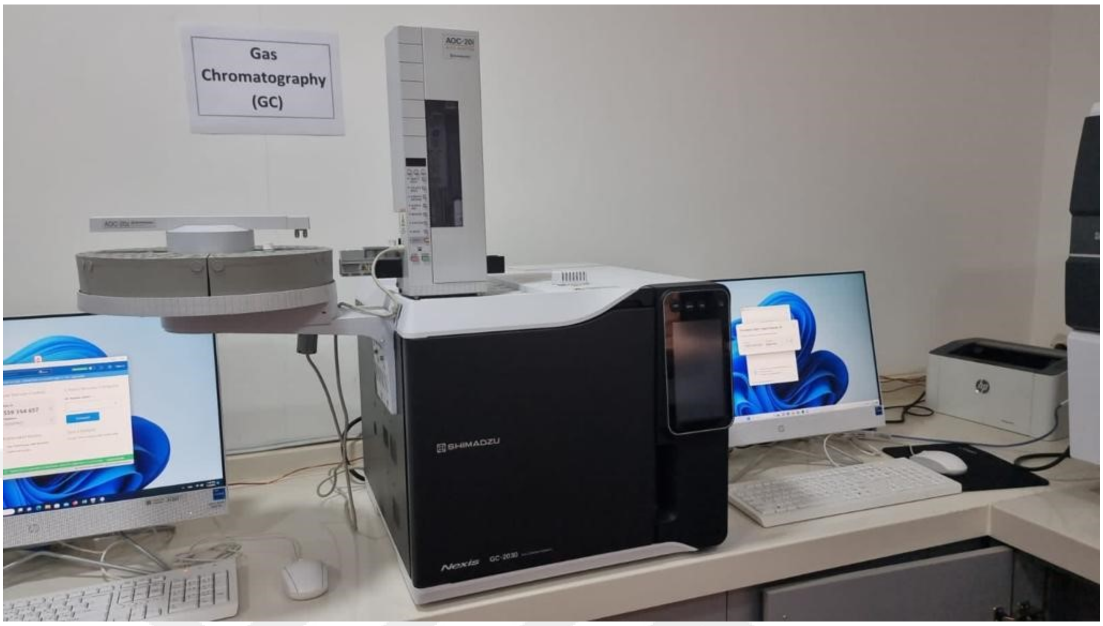


Figure 3.3. Gas Chromatography With Flame Ionization Detection (GC-FID) For Total Petroleum Hydrocarbon Analysis

In our fieldwork, the Hach HQ30D Flexi used to measure conductivity and luminescent dissolved oxygen (LDO) (Figure 3.4). Its easy-to-use interface—complete with guided calibration and clearly displayed stabilization alerts—made it reliable and intuitive to operate in remote field conditions near the refinery site. More importantly, this meter has been validated in environmental research(Yan et al., 2020).

Figure 3.4. Dissolved Oxygen Meter (Hach HQ30D Flexi)

The Hach HQ411D Laboratory pH-Meter is a sophisticated digital meter built for water quality professionals (see Figure 3.5). It is a dependable and user-friendly gadget that eliminates the guesswork from pH readings. Overall, the Hach HQ411D Laboratory pH-Meter is a dependable and simple tool for taking normal pH readings in the lab. To use the gadget, first calibrate the meter using buffer solutions before measuring the pH of the sample to be examined. In addition to pH, the gadget can measure mV, RedOx, and ORP levels (Figure 3.5) (Hassani et al., 2023).

Figure 3.5. pH Meter (Hach HQ411d)

The WTW inoLab® Cond 7110 is a versatile benchtop conductivity meter designed for routine laboratory and field water-quality analysis. It is used to measure the conductivity, salinity, TDS. The meter accommodates both standard and specialized conductivity probes—such as the 4-electrode TetraCon® 325—allowing precise measurements from ultrapure to highly saline waters. Featuring the Auto Read function, it automatically detects measurement stabilization, improving repeatability, and its calibration timer ensures ongoing accuracy by prompting timely calibrations (Figure 3.6). it operates in a wide temperature range (–5 °C to +105 °C), conforming to pharmacopeia guidelines for pure-water testing and making it suitable for environmental monitoring, drinking water analysis, and industrial applications (Said et al., 2004).

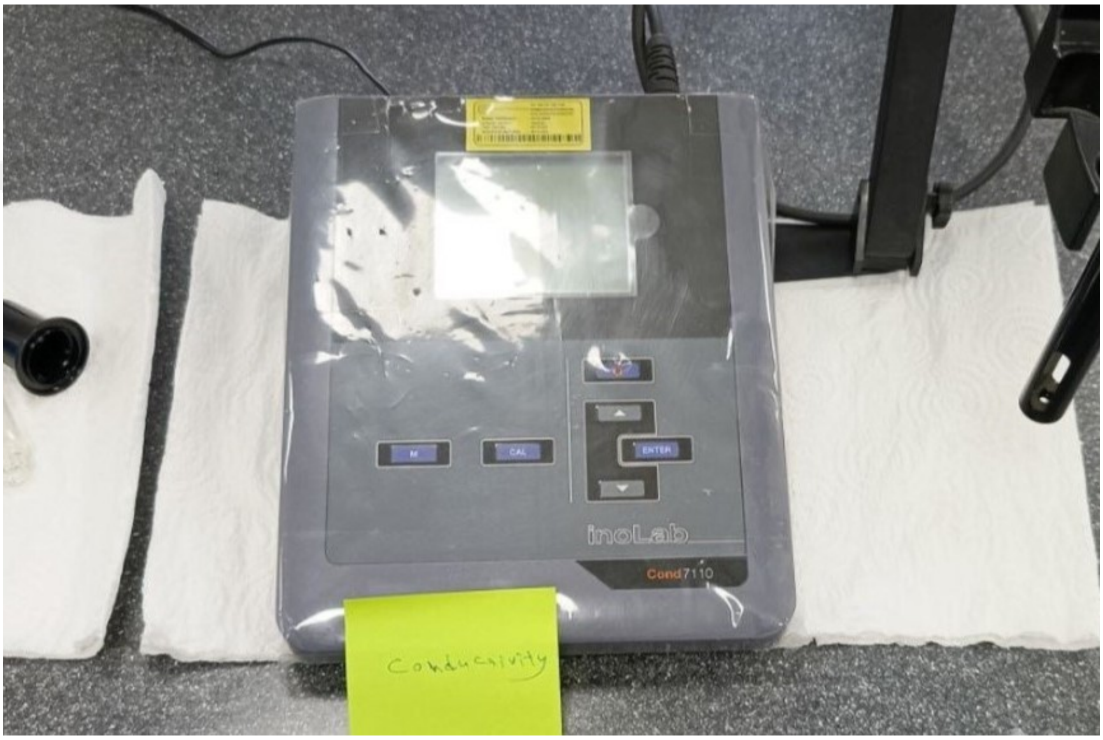


Figure 3.6. Electrical Conductivity meter(WTW inoLab TM7110)

The Shimadzu ICPE-9820 model shown in figure 3.7 is a highly sensitive analytical instrument used for detecting trace metals and several non-metals in various types of samples. Equipped with advanced detection systems, the ICP spectrometer can handle complex matrices with precision, contributing significantly to the study of groundwater quality and pollution assessment (Zhang, 2025).

Figure 3.7. ICP-OES For Heavy Metal Analysis

HANNA Instruments HI 93703 Microprocessor Turbidity Meter.It is a portable, handheld device designed to measure the turbidity of water, which is the cloudiness or haziness caused by particles that are invisible to the naked eye, typically suspended solids, as indicated in figure 3.8. The measurement range indicated is from 0.00 to 1,000 Formazin Nephelometric Units (FTU), which is a broad range that can accommodate various types of water quality applications, from drinking water to wastewater. The microprocessor-based technology allows for precise measurements and may include features such as data logging and calibration reminders (Wu et al., 2014).

Figure 3.8. Turbidity meter(Hanna HI93703)

The Groundwater samples were analyzed for nitrate (NO_3^-) and sulfate (SO_4^{2-}) as per APHA procedures using standard analytical methods. The amount of nitrate was measured by preparing a sample and measuring it with UV-Visible spectrophotometer (Hach DR 5000) (Figure 3.9). The UV–Visible spectrophotometer (Hach DR 5000, USA) is a high-precision analytical instrument designed for quantitative determination of various chemical substances in water and environmental samples. It operates by measuring the absorbance of light in the ultraviolet and visible wavelength ranges, enabling detection of compounds such as nitrates, sulfates, and other analytes based on their characteristic absorption spectra (da Ascenção et al., 2024).

Figure 3.9. UV-Vis Spectrophotometer(Hach DR5000)

The samples of groundwater were analyzed for fluoride according to APHA procedures utilizing standard analytical approach. Fluoride concentration was determined with a fluoride ion-selective electrode (Orion 9609BNWP, Thermo Scientific, USA) employing the ion-selective electrode method with total ionic strength adjustment buffer (TISAB) to maintain constant ionic strength and pH during analysis, as indicated in Figure 3.10.

This device is a high-sensitivity fluoride ion-selective electrode designed for precise measurement of fluoride concentrations in aqueous samples. It employs a lanthanum fluoride crystal sensing element, providing fast response times, high selectivity, and reliable performance across a wide concentration range (Begum et al., 2024).

Figure 3.10. Fluoride measurement electrode (Thermo Scientific Orion 9609BNWP)

Analysis of chloride was done by automatic titration using silver nitrate ($AgNO_3$) as a standard titrant and potassium chromate indicator, the end point being a continuous red-brown color. An automatic titration instrument, Figure 3.11, is a laboratory device that performs titrations with high precision and minimal operator intervention. It automates the controlled addition of titrant, continuously monitors the reaction endpoint through sensors such as pH, conductivity, or redox electrodes, and calculates the analyte concentration based on titration curves (Kakiuchi et al., 2023).

Figure 3.11. Automatic Titration Instrument

3.4. Preservation and Transportation of the Samples

Utmost care was taken in the preservation and transportation of the samples. Post-collection, the samples were immediately stored in a controlled environment to prevent any alteration in their composition. Parameters such as pH, TDS, EC and temperature were measured on-site to capture their real-time values. The remaining samples were swiftly transported to the laboratory, typically within 1 to 2 hours from the collection time, for detailed analysis. This prompt transportation was crucial for maintaining the integrity of the samples, especially for parameters that are sensitive to time and environmental changes(APHA, 2017; USPAE, 2013).

3.5. CCME Water Quality Index

The Water Quality Index (WQI) is a comprehensive instrument that is used for the purpose of evaluating and reporting the overall quality of surface water bodies. It is administered by the Canadian Council of Ministers of the Environment CCME. A simplified method of communicating complicated information on the quality of water to the general public, policymakers, and other stakeholders is provided by this information(CCME, 2017). The index is composed of three factors:

Factor 1: Scope

F1 (Scope) illustrates the level of non-compliance with water quality guidelines during the specified time frame. It has been taken straightly from the British Columbia Index:

$$F1 = \left(\frac{Numberoffailedvariable}{totalnumberofvariable}\right) * 100 \tag{3.1}$$

As variables represent the water quality parameters that were examined within the specified time frame for the index calculation.

Factor 2: Frequency

F_2 (Frequency) indicates the percentage of individual tests that do not meet objectives, also known as "failed tests":

$$F2 = \left(\frac{Numberoffailedtest}{Totalnumberoftest}\right) * 100 \tag{3.2}$$

This factor's formulation is directly derived from the British Columbia Water Quality Index.

Factor 3: Amplitude

F3 (Amplitude) indicates the extent to which unsuccessful test standards fall short of their goals. F3 is determined through a three-step process. The development of the third factor is based on research conducted by Alberta Agriculture, Food and Rural Development (Khan, 1999).

$$excursion_i = \left(\frac{FailedTestValue_i}{Objective_i}\right) - 1 \tag{3.3}$$

i) The frequency by which the concentration of individual surpasses (or falls below, in the case of a lowest objective) the objective is referred to as "excursion" and is calculated as follows. Once the test value should not surpass the objective:

$$excursion_i = \left(\frac{Objective_i}{FailedTestValue_i}\right) - 1 \tag{3.4}$$

ii) The total deviation of individual tests from their objectives is measured by adding up the differences and then dividing by the total number of tests. Calculating the normalized sum of excursions involves determining this variable, also known as nse:

$$nse = \left(\frac{\sum_{i=1}^{n} excursion_i}{numberoftests}\right) \tag{3.5}$$

iii) F3 is determined using an asymptotic function that scales the normalized summation of the excursions from objectives (Tchobanoglus et al., 2003) to produce a range from 0 to 100.

$$F3 = \left(\frac{nse}{0.01nse + 0.01}\right) \tag{3.6}$$

Next, the CCME WQI is calculated using the following:

$$CCMEWQI = 100 - \left(\frac{\sqrt{F1^2 + F2^2 + F3^2}}{1.732}\right) \tag{3.7}$$

The factor of 1.732 comes from the possibility of each of the three individual index factors reaching up to 100. This implies that the vector length can be extended.

$$\frac{\sqrt{100^2+100^2+100^2}}{100}=\frac{\sqrt{30000}}{100}=1.732 \quad (3.8)$$

As a maximum division by 1.732 brings the vector length down to 100 as a maximum.

3.6. Categorization of Index Values

Assigning CCME water quality index values for categorising water quality involves a serious yet slightly subjective process known as "categorization." It should rely on the most up-to-date data, expert opinions, and the public's perception of water quality. This classification provided is initial and will likely be adjusted as the index is further tested. Due to the characteristics of the index, it is challenging to ascertain whether the ranking results from significant fluctuations in a single variable or frequent minor fluctuations in multiple variables. Developed with support from Alberta Agriculture, Food and Rural Development, the prototype Water Quality Index calculator enables users to identify the main variables influencing the index's behaviour(CCME, 2001; Lumb et al., 2006). Categorizing WQI is exposed in table 3.2.

Table 3.2. Categorizing Water Quality Index

Water Quality Category	CCME WQI Value Range	Description
Excellent	95-100	The water quality is maintained at a level where there is minimal threat or harm, closely resembling natural or pristine conditions. To obtain these index values, all measurements must consistently meet the set objectives.
Good	80-94	Water quality is maintained with minimal threat or impairment; conditions seldom deviate from natural or desirable levels.
Fair	65-79	Water quality is typically safeguarded but can be at risk or compromised at times; situations may deviate from the ideal or natural levels.
Marginal	45-64	Water quality is regularly at risk or compromised, with conditions frequently deviating from ideal or natural levels.
Poor	0-44	Water quality is frequently at risk or compromised, often deviating from ideal or natural levels.

3.7. Water Quality Index Mapping by GIS

One way to visualize water quality characteristics across a specific region is via (WQI) map. These maps are created using ArcGIS with interpolation from (IDW) technique. These parameters include physical, chemical, biological, metals and nutrient concentrations. Insights into the geographical distribution of water quality are provided by the WQI map, which identifies locations with high or poor water quality levels. In order to improve water quality and safeguard aquatic ecosystems, this data is crucial for environmental monitoring, resource management, and decision-making(RGIS, 2023).

3.8. Data Analysis by using Statistical Package for the Social Sciences (SPSS)

To evaluate groundwater quality parameters, a series of statistical tests were conducted utilizing SPSS software. To characterize the variability and central tendency of the groundwater quality metrics, descriptive statistics were used, including median, range, standard deviation, and mean. Also, to look for connections between variables and determine how significant any differences or correlations(George & Mallery, 2024).

3.9. Hydrogeochemical Classification of Groundwater

Groundwater samples were classified using Piper and Schoeller diagrams. The Piper diagram was employed to categorize the samples into hadrochemical facies, revealing dominant cationic and anionic compositions (Fetter, 1994). The analysis indicated that all samples were classified within Area C (Magnesium-type water) and Area E (Bicarbonate-type water). The Schoeller diagram was used to compare ion concentrations on a semi-logarithmic scale, providing further classification of groundwater based on major cationic and anionic compositions.

3.10. Mechanisms Controlling Groundwater

Chemistry The Gibbs diagram illustrates the mechanisms controlling water chemistry, including precipitation, rock interaction, and evaporation dominance. To investigate the primary geochemical processes influencing groundwater quality, a TDS vs. Na/ (Na + Ca) weight ratio plot was generated. This analysis identified the relative contributions of rock-water interactions, ion exchange processes, and anthropogenic influences in shaping the groundwater's chemical characteristics. However, the results do not necessarily indicate that groundwater formation is entirely unaffected by human activities, as quantifying the extent and impact of anthropogenic influences remains challenging.

4. FINDINGS

Ground water samples from twenty-two water wells around Erbil Oil Refinery were collected and tested for physical, chemical, bacteriological and heavy metal characteristics. All results were compared with the drinking water standard recommended by Iraqi guideline 2001.CCWQI estimated for groundwater quality in the study area. Also, mechanism effects the groundwater quality and groundwater classification from (Gibbs diagram, Piper diagram and Schoeller classification) were considered and calculated for current ground water samples in the study area.

For statistical analysis, correlation coefficient of Pearson correlation was used to determine each variable's deviation as well as the covariance between them.

4.1. Physical Parameters

4.1.1. Turbidity

In this study, S12 exhibited a turbidity value of 4.9 NTU because it closed to the Erbil oil refinery (Figure 4.1 and Table 4.1). The aforementioned values of turbidity remain below the Iraqi Guideline 2001 (5NTU). In the present study, the statistical analysis revealed a negative correlation ($p<0.01$) between turbidity and DO even with heavy metals (Table 4.4 and Figure 4.19).

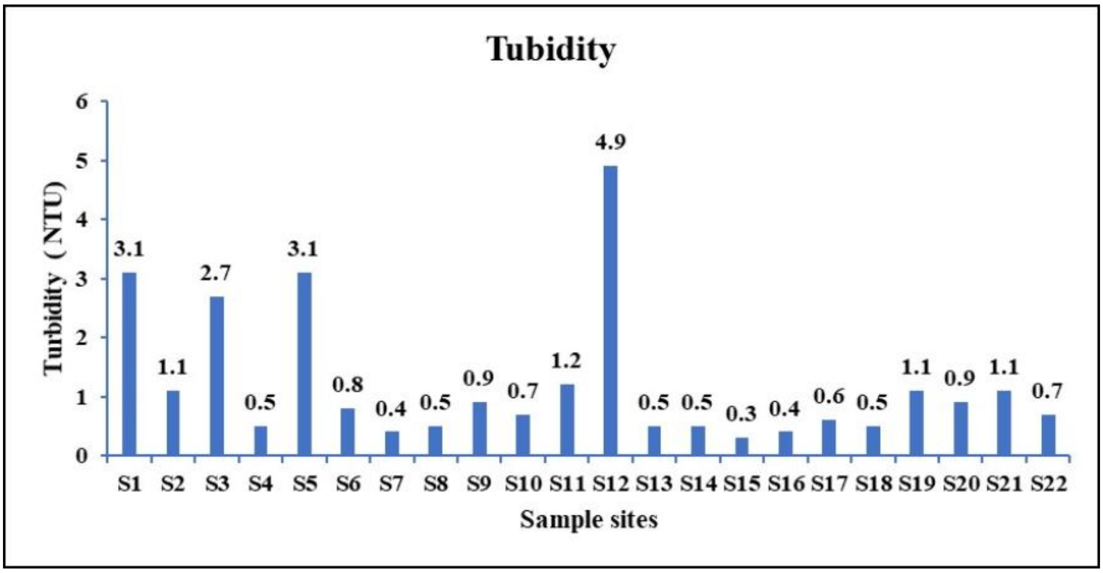


Figure 4.1. Turbidity (NTU) Levels Shown in The Studied Sampling Sites

4.1.2. Electrical Conductivity (EC)

The analysis of EC in the studied well water samples show that the mean value of EC is about 438.181 µ. S/cm with ranges are 325 µ.S/cm was in S3 and 696 µ.S/cm was in S12 and the mean standard deviation of these parameters was 108.006 (Table 4.1; Figure 4.2). According to correlation coefficient, a positive association between EC with TDS, alkalinity, chloride, calcium, arsenic, and lead. Conversely, a negative correlation was observed between EC with dissolved oxygen, manganese, vanadium, and boron (Table 4.4 and Figure 4.19).

4.1.3. Total Dissolved Solids (TDS)

The average TDS value for all studied well sites was 219.09 mg/L, with a standard deviation of ± 54.0032. Nevertheless, the range of TDS concentrations were varied between 162.5 was in S3 and 348 was in S12 mg/L in the study region (Table 4.1 and Figure 4.2). Also, the statistical consideration of the data unveiled distinct correlation coefficients between the TDS and several parameters such as EC, Alkalinity, and Hardness (Table 4.4 and Figure 4.19).

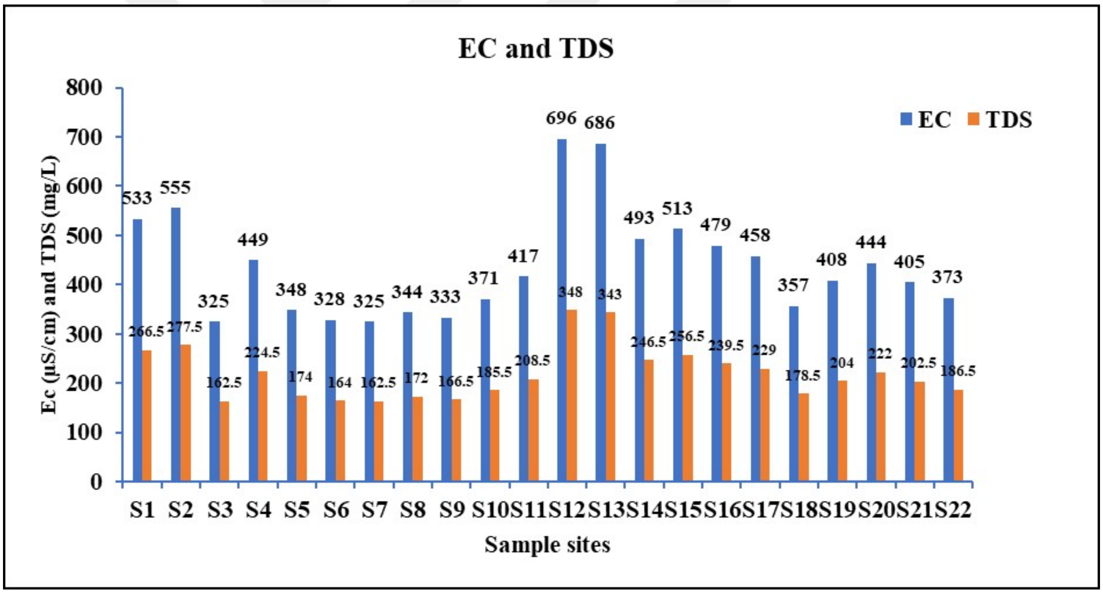


Figure 4.2. Electrical Conductivity (µS/cm) And Total Dissolved Solid (mg/L) Levels Shown in The Studied Sampling Sites

4.2. Chemical Parameters

4.2.1. pH

The mean pH value in current study is 7.35 from the range of 7.0 in S2 to 7.8 in S17 (Table 4.1 and Figure 4.3). The pH value of studied wells has a standard deviation of ± 0.232. The present investigation witnessed a statistically significant correlation coefficient between the pH and Turbidity parameters (Table 4.4 and

Figure 4.19).

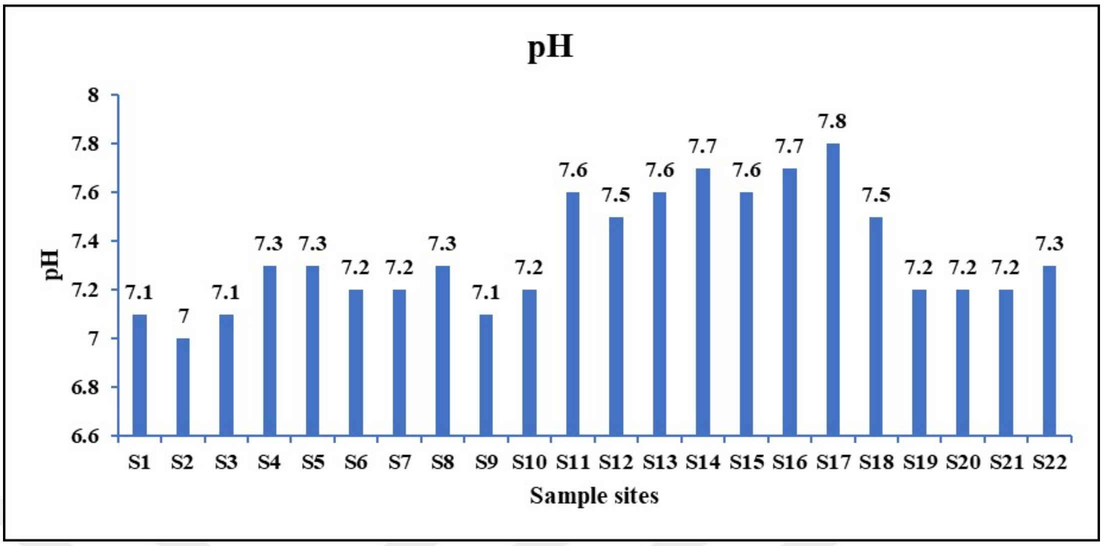


Figure 4.3. pH Levels Shown in The Studied Sampling Sites

4.2.2. Total Hardness

The findings indicate that the mean total hardness value throughout the current experiment was 309.18 mg $CaCO_3$/L, with an average standard deviation of ± 104.97 (Table 4.1). The highest recorded value of total hardness in the study area was 678 mg $CaCO_3$/L recorded at S1, while the lowest value was 209 mg $CaCO_3$/L measured at S8. S1 had considerably elevated levels of hardness(Located inside Refinery) (Table 4.1 and Figure 4.4). In contrast, the statistical analysis of the data reveals a significant correlation coefficient ($P < 0.01$) between hardness and the variables Ca, Mg, Na, K (Table 4.4 and Figure 4.19).

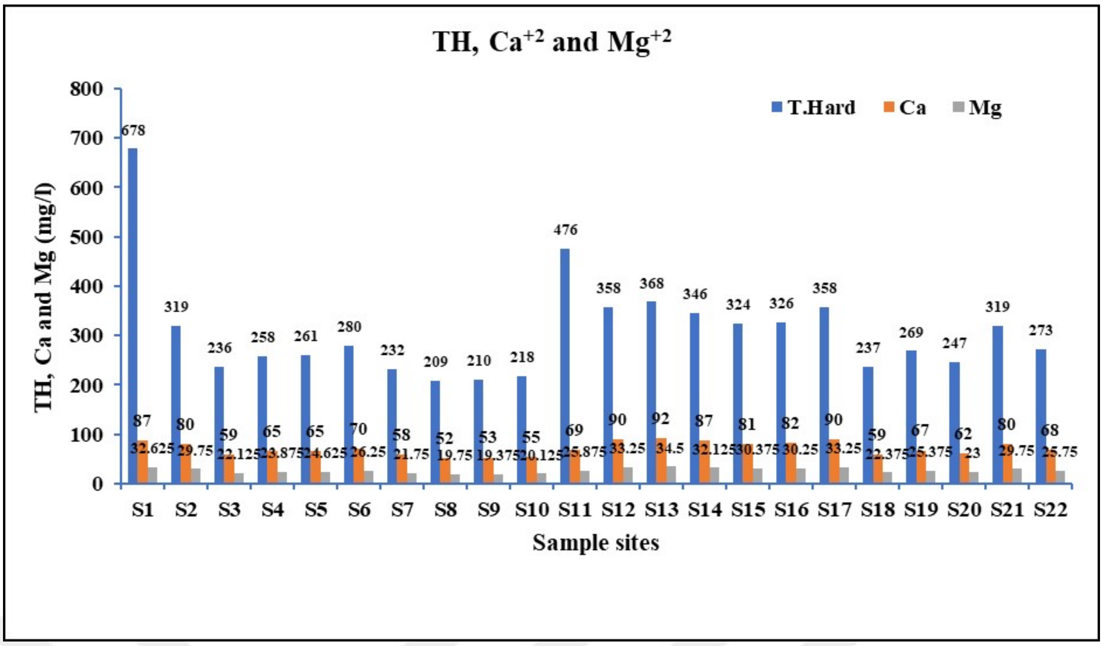


Figure 4.4. TH, Ca and Mg Levels Shown in The Studied Sampling Sites

4.2.3. Sodium (Na^+)

The concentration of sodium cation in studied water wells were found to be relatively high, with an average value of 33.7 mg/L and a standard deviation of ± 43.86 (Table 4.1). The lowest recorded value 5.0 mg/L was measured at site S3, whilst the highest recorded value of 194 mg/L was detected at site S1(Table 4.1; Figure 4.5). The statistical analysis of the present findings reveals a significant correlation coefficient ($P<0.01$) of Na^+ with K , SO_4^{-2}, and some heavy metals. The correlation coefficient value between Na and K is 0.90, while the correlation coefficient between SO_4^{-2} and Na is 0.613 (Table 4.4 and Figure 4.19).

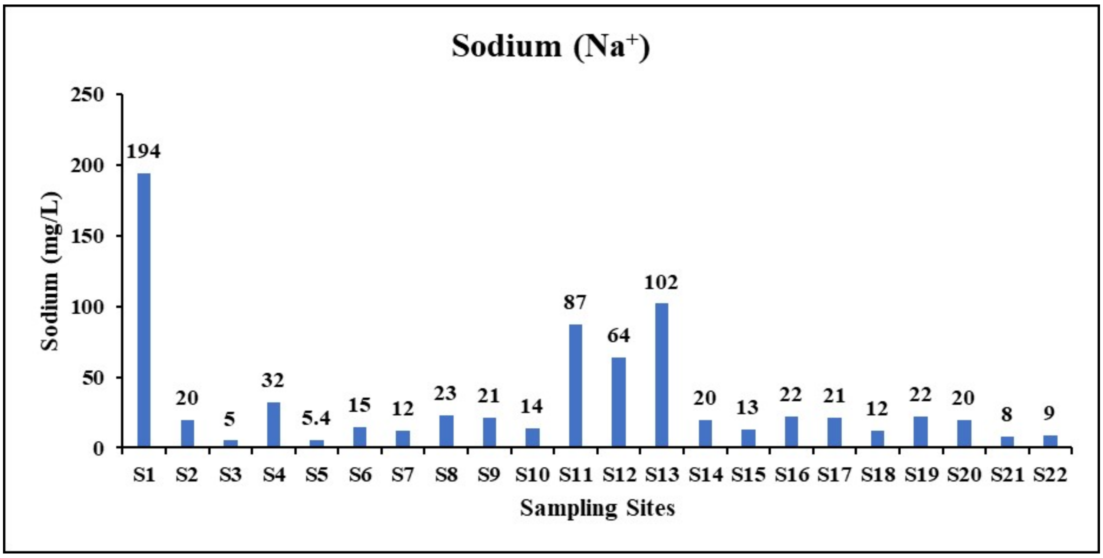


Figure 4.5. Sodium Levels Shown in The Studied Sampling Sites

4.2.4. Potassium (K^+)

The present investigation observed a mean concentration value of potassium is 1.12 mg/L, with a range of 0.7 was in S3 and 3.2 mg/L was in S1 and standard deviation of ± 0.527 (Table 4.1 and Figure 4.6). The findings revealed a correlation coefficient between the examined sites and the parameter, as evidenced by the data presented in (Table 4.4 and Figure 4.19).

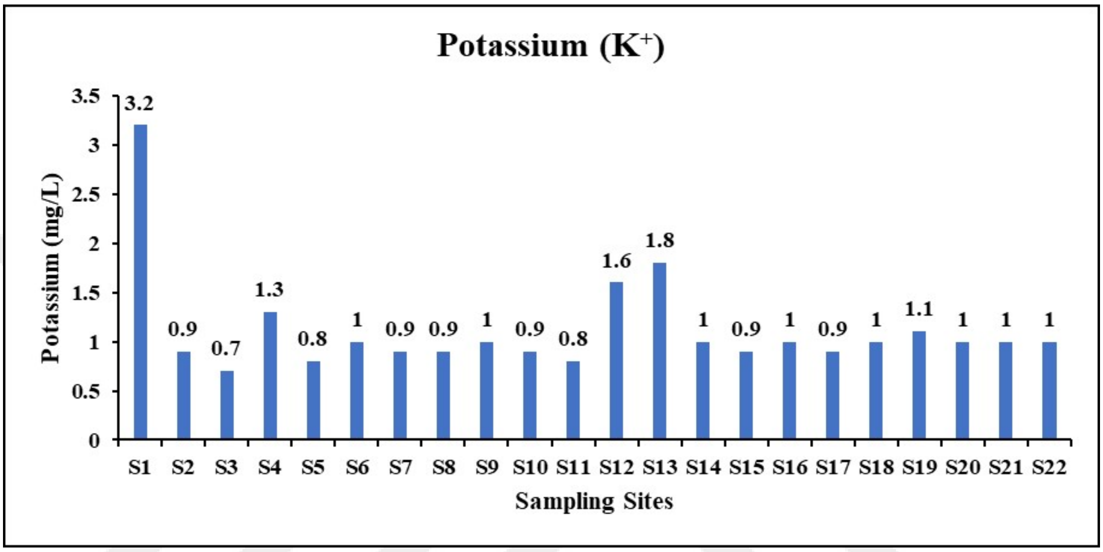


Figure 4.6. Potassium Levels Shown in The Studied Sampling Sites

4.2.5. Alkalinity

The current analysis yielded an average alkalinity of 206.5 mg $CaCO_3$/L, with a mean standard deviation of ±29.85 (Table 4.1). S12 exhibited a somewhat higher alkalinity value of 288 mg $CaCO_3$/L, while S3 had a minimum value of 161 mg $CaCO_3$/L (Table 4.1 and Figure 4.7). The findings from the analysis of alkalinity indicate a significant positive association ($P<0.01$) between alkalinity and EC, TDS, Ca, Mg, while a negative correlation was observed with heavy metals (Table 4.4 and Figure 4.19).

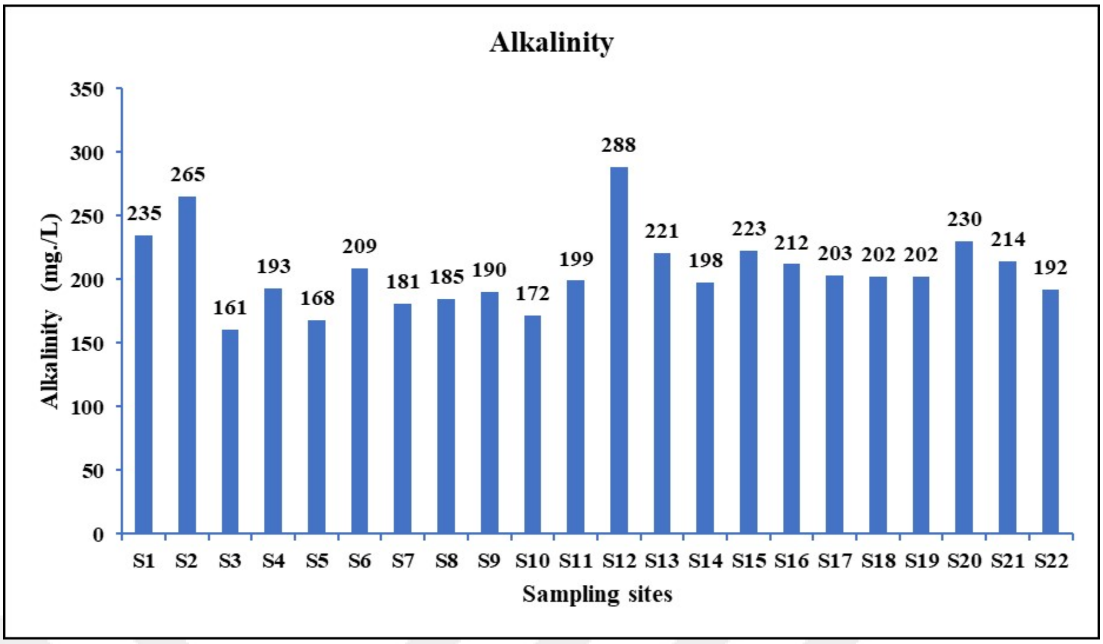


Figure 4.7. Alkalinity Levels Shown in The Studied Sampling Sites

4.2.6. Sulphate (SO_4^{-2})

The mean value of sulfate 26.05 and standard deviation of ±15.576 were reported in (Table 4.1). Sulfate concentrations are relatively greater in sites S1, S12, and S13 if compared to other sites in the study area (Table 4.1 and Figure 4.8). The maximum sulfate concentration was observed at S12, nevertheless, it did not exceed the Iraqi standards established in 2001 (250 mg/L). The findings of sulfate analysis in studied water samples revealed a statistically significant correlation ($P<0.01$) between SO_4^{-2} in the water wells under investigation and the EC, TDS, DO, Ba, and As (Table 4.4 and Figure 4.19).

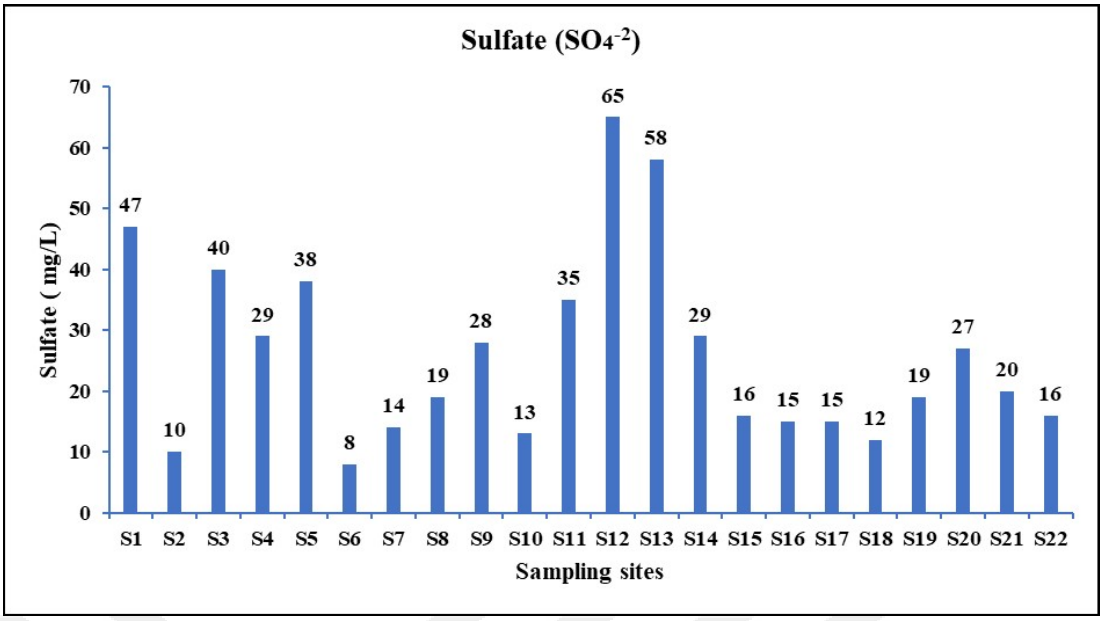


Figure 4.8. Sulfate Levels Shown in The Studied Sampling Sites

4.2.7. Chloride (Cl^-)

The concentration of chloride ions in studied water wells exhibited an average value of 22.68 mg/L, accompanied by a mean standard deviation of ± 9.20 (Table 4.1). However, observed concentrations of chloride were varied between 8.0 to 46 mg/L. The lowest recorded chloride value was observed at S20, whilst the highest recorded chloride value observed at S13 (Table 4.1 and Figure 4.9). The findings indicated a significant correlation coefficient ($P<0.01$) among the water wells that were examined (Table 4.4 and Figure 4.19).

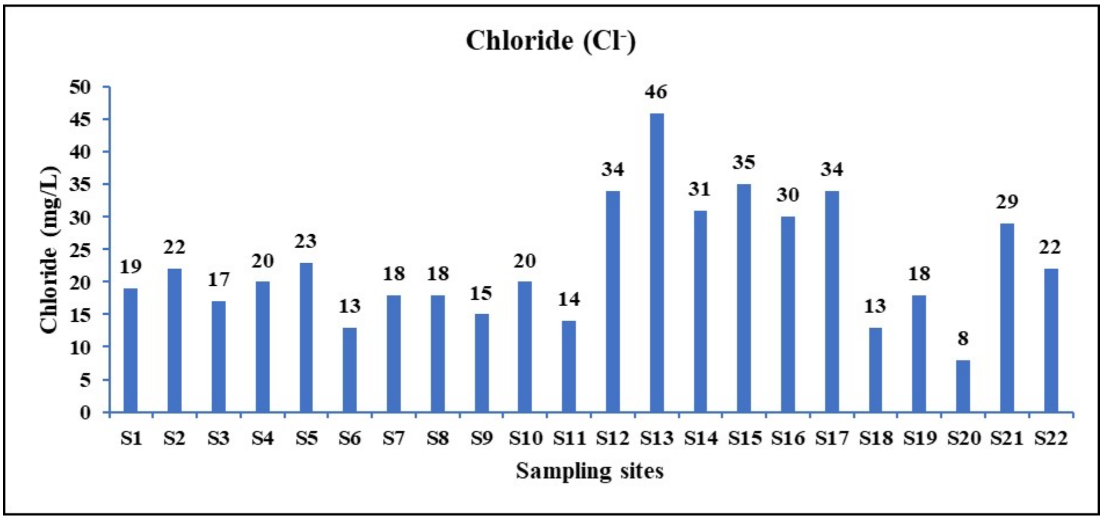


Figure 4.9. Chloride Levels Shown in The Studied Sampling Sites

4.2.8. Nitrate (NO_3^-)

In the present study, nitrate concentrations exhibited a significantly elevated levels, as evidenced by a mean value of 39.22 mg/L with a standard deviation of ±20.83 (Table 4.1). The observed nitrate contents in the studied water samples were varied between a minimum value of 19 mg/L was in S20 and a high value of 97 mg/L was in S19 (Table 4.1 and Figure 4.10). Results of statistical analysis in current study revealed a negative correlation coefficient between nitrate and many environmental factors, including pH, alkalinity, dissolved oxygen, copper, vanadium, and zinc (Table 4.4 and Figure 4.19).

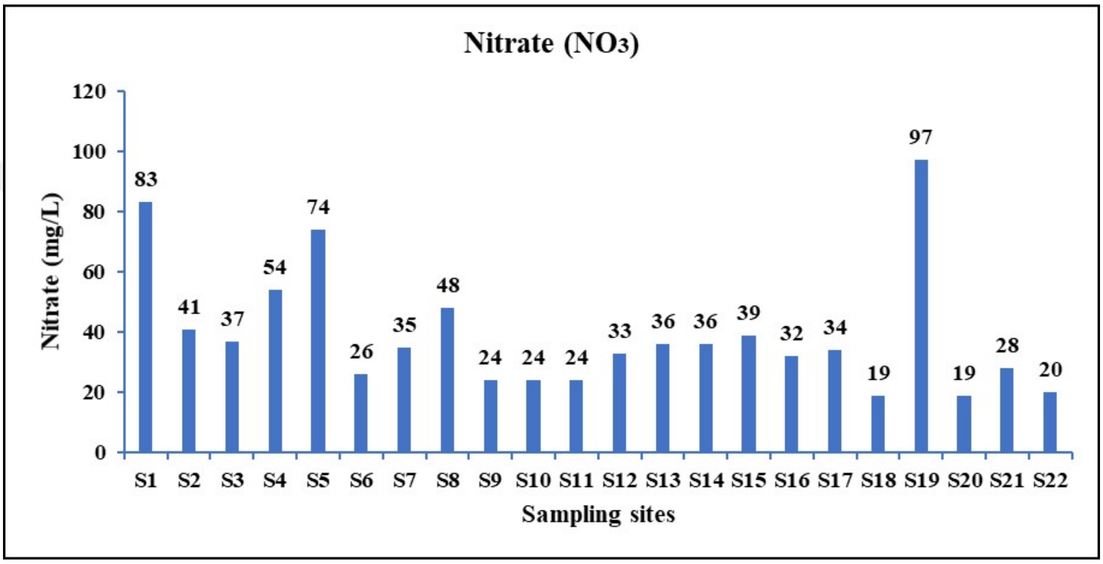


Figure 4.10. Nitrate Levels Shown in The Studied Sampling Sites

4.2.9. Fluoride (F^-)

The fluoride content in current study ranged from 0.04 to 1.21 mg/L, with an average of 0.378 (Table 4.1). The lowest fluoride value was 0.04 mg/L measured at the S11 sample site, while the maximum fluoride value was 1.21 mg/L recorded at S19 (Table 4.1, and Figure 4.11). Fluorides correlated positively with TPH, Pb, $SO_4^{-2,}$ and DO. There was a negative association between fluoride, vanadium, manganese, and chromium (Table 4.4 and Figure 4.19).

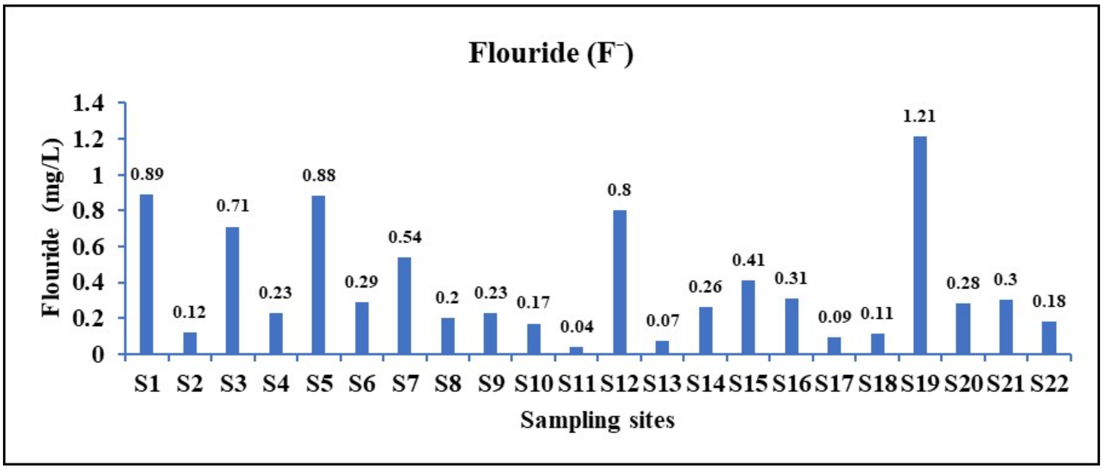


Figure 4.11. Fluoride Levels Shown in The Studied Sampling Sites

4.3. Biological Parameters

4.3.1. Total Coliform Bacteria

The Coliform Bacteria content in current study ranged from 2.2> to 16 Colony/100 ml (Table 4.2). The lowest Coliform Bacteria value was <2.2 Colony/100 ml in mostly samples and, while the maximum Coliform Bacteria value was 16 Colony/100 ml recorded at S1, 5, 12, 13 and 19 (Table 4.2). The total coliforms analysis indicated that 12 of the ground water samples were deemed unsuitable for drinking purpose, while the remaining 10 groundwater samples were deemed satisfactory for drinking and exhibited no growth or detection of bacteria. Conversely, elevated concentrations of EC, TDS, sodium ion, chlorides, and sulfate have been identified as potential factors associated with microbial proliferation. The high levels of may be related to the absence of chlorination in most of collected water samples.

4.3.2. Escherichia coli

The Coliform Bacteria content in current study ranged from <2.2 to 16 CFU/100ml (Table 4.2). The lowest Coliform Bacteria value was <2.2 CFU/100ml in mostly samples and, while the maximum Coliform Bacteria value was 16 CFU/100ml recorded at S5, 12 and 19 (Table 4.2). Twelve water wells exhibited elevated levels of E. coli, rendering them unsuitable for consumption. The presence of E. coli in the water wells may be attributed to either the sampling procedure or the lack of chlorination.

4.4. Heavy Metal Parameters

4.4.1. Cadmium (Cd)

The hazardous heavy metal Cd is found organically in the crust of the Earth, but it can also enter the environment as a result of human activity, including mining, smelting, battery production, and the usage of phosphate fertilizers. The findings of current study indicated that the cadmium levels were below the detection threshold of IQS 2001 which are <0.0004 ppm (Table 4.3).

4.4.2. Arsenic (As)

The examined well water samples had an average Arsenic concentration of 0.251 mg/L, with a mean standard deviation of ± 0.5379 (Table 4.3). Nevertheless, its value varied between 0.0013 and 1.4820 mg/L. The highest recorded value was observed at the sampling site S1 throughout the duration of the investigation (Located inside the refinery border) (Table 4.3). The observations revealed a minimum value at sampling site S8. The findings of this study indicate that the amounts of arsenic in four sampling sites, namely S1, S11, S12, and S13, exceeded the Iraqi Guideline (2001) (Table 4.3 and Figure 4.12). Arsenic correlated positively with Ba and Pb. There was a negative association between Arsenic with Bo, Cr, Cu, Li, Mn, Vn and Zn (Table 4.4 and Figure 4.20).

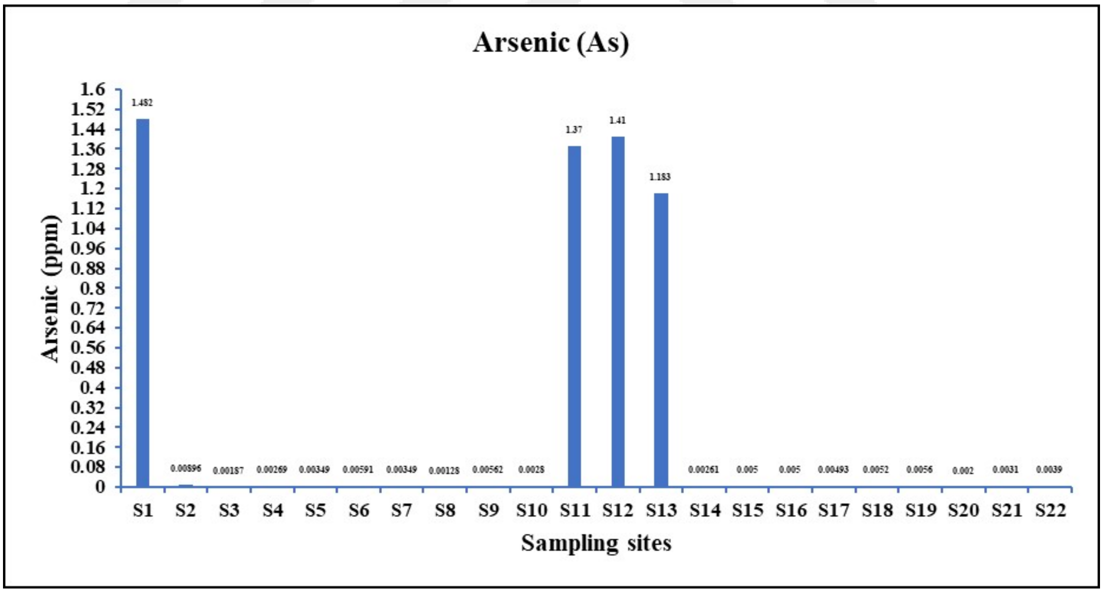


Figure 4.12. Arsenic (As) Heavy Metal Levels (mg/L) Shown in The Studied Sampling Sites

4.4.3. Copper (Cu)

The average copper concentration was reported as 0.1046 mg/L. Nevertheless, the observed range included a maximum value of 0.6269 mg/L in S17 and minimum value of 0.0089 mg/L in S9 and S14 (Table 4.3 and Figure 4.13). The statistical analysis findings indicated a significant negative correlation coefficient between copper and turbidity, as demonstrated in (Table 4.4 and Figure 4.20).

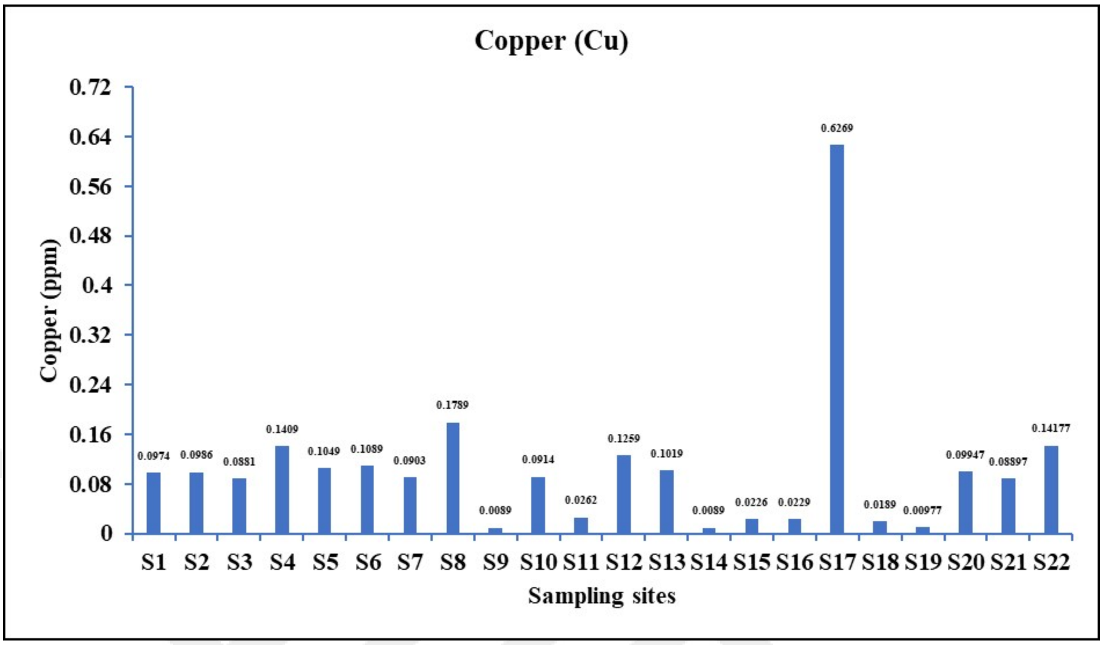


Figure 4.13. Copper (Cu) Heavy Metal Levels Shown in The Studied Sampling Sites

4.4.4. Chromium (Cr)

The chromium concentration measurements indicated a mean value of 0.0028 mg/L. The maximum chromium concentration observed at sampling site S14 was 0.0088 mg/L, whilst the minimum chromium concentration of 0.0010 mg/L was reported at sampling site S1 (Table 4.3 and Figure 4.14). The findings of the current study revealed a negative correlation coefficient between chromium concentration and several factors such as K, SO_4^{-2}, NO_3, Bo, and Mn in the sampling locations under investigation (Table 4.4 and Figure 4.20).

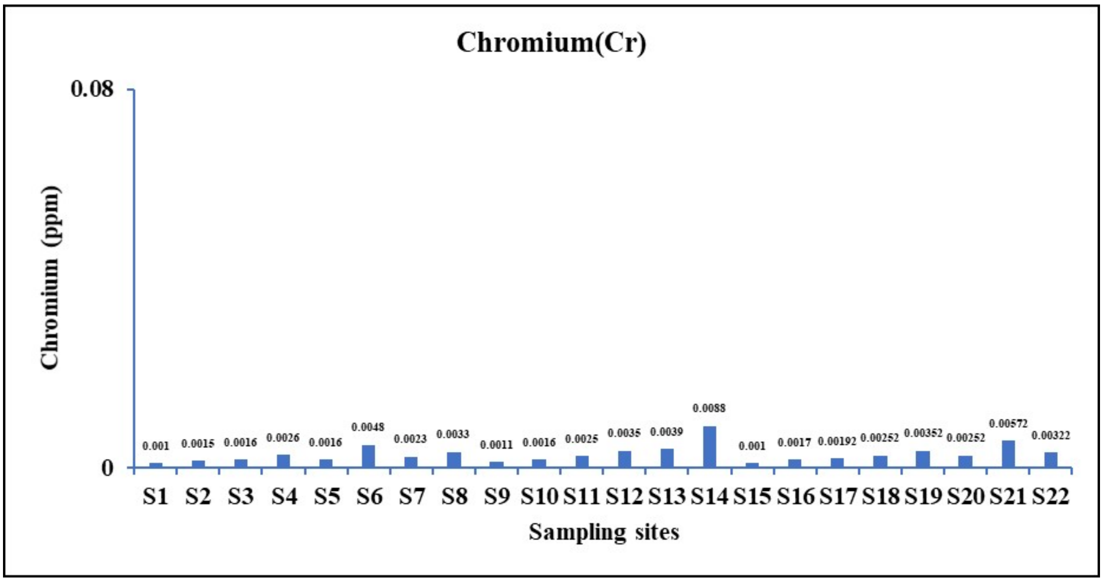


Figure 4.14. Chromium (Cr) Heavy Metal Levels in The Studied Sampling Sites

4.4.5. Zinc (Zn)

Mean value of zinc in the groundwater sampling sites is about 0.3346 mg/L. The zinc concentrations varied from a maximum value of 4.1300 mg/L at sampling site S16 to a low value of 0.0020 mg/L at sampling site S15 (Table 4.3 and Figure 4.15). A negative correlation coefficient was observed between DO, SO_4^{-2}, As, Ba, Bo, Cr, and other variables, as evidenced by the statistical analysis conducted (Table 4.4 and Figure 4.20)

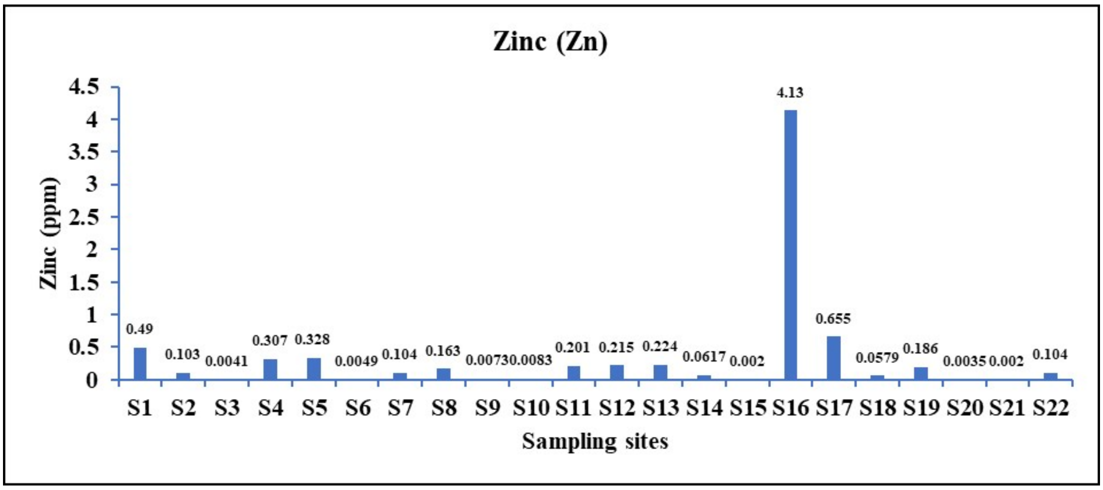


Figure 4.15. Zinc (Zn) Heavy Metal Levels Shown in The Studied Sampling Sites

4.4.6. Lead (Pb)

Lead concentration in current study revealed a mean value of 0.5269 mg/L. The maximum value of lead recorded at sampling site S1 was 3.2700 mg/L, whilst the minimum value found at S3 was 0.0022 mg/L (Table 4.3 and Figure 4.16). The statistical analysis results indicate a significant correlation coefficient ($P<0.01$) between turbidity and EC (Table 4.4 and Figure 4.20).

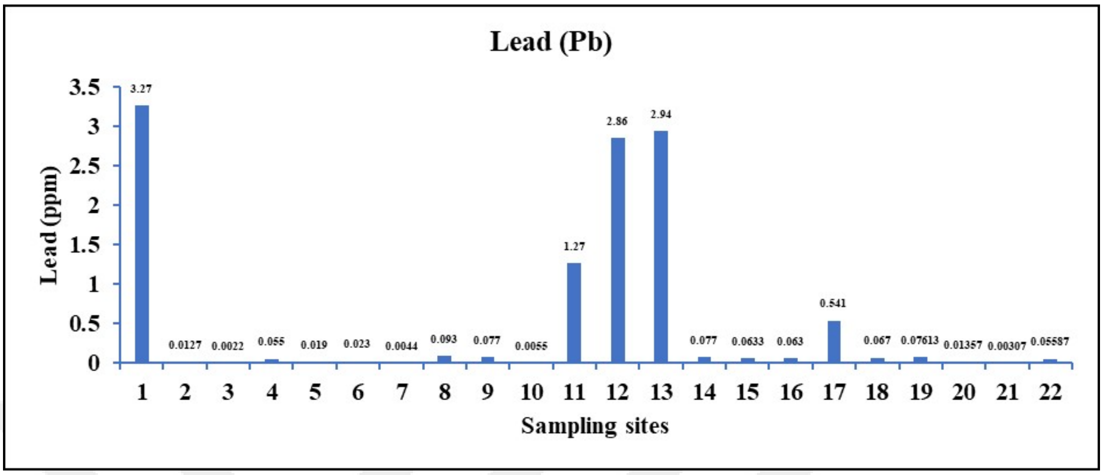


Figure 4.17. Lead (Pb) Heavy Metal Levels Shown in The Studied Sampling Sites

4.4.7. Other Heavy Metals

The concentration of Ba, Bo, Mn, and Li exhibited an average value of 0.0770, 0.1229, 0.0118, and 0.0107 mg/L, respectively. The maximum reported values for Ba and Mn were 0.6400 and 0.1800 mg/L, respectively, at sampling sites S11 and S9 (Table 4.3 and Figure 4.17). The statistical analysis indicated a significant correlation coefficient ($P<0.01$) between the parameter under investigation (Ba) and the concentrations of Na, K, and SO_4^{-2}, as presented in Conversely, a negative correlation was seen between Bo and the parameters of Turbidity, pH, EC, TDS, and Alkalinity (Table 4.4 and Figure 4.20).

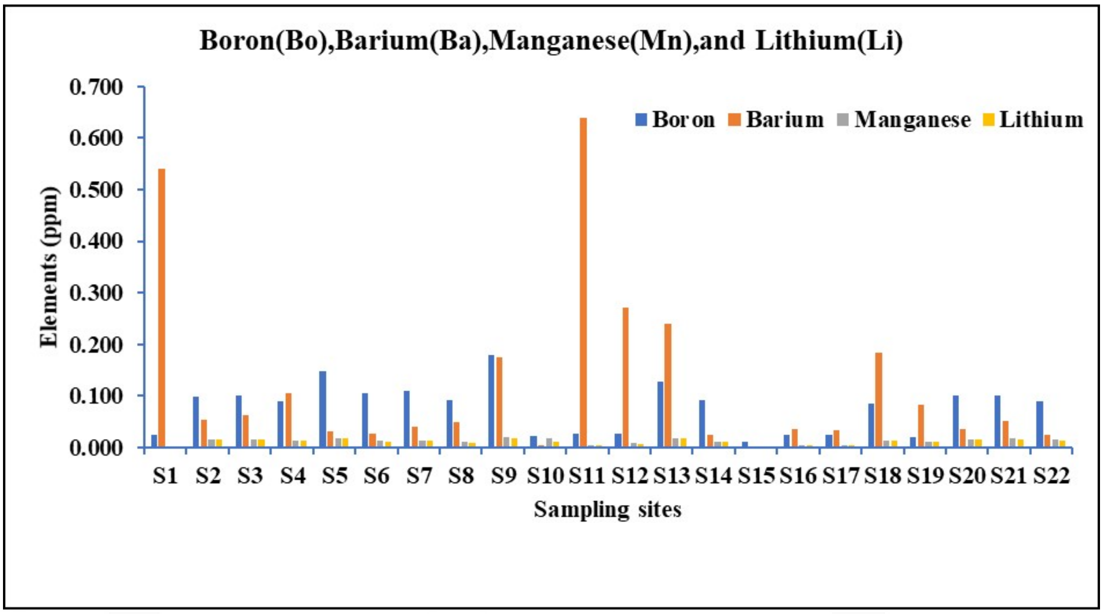


Figure 4.18. Boron, Barium, Manganese, And Lithium Heavy Metal Levels Shown in The Studied Sampling Sites

4.5. Total Petroleum Hydrocarbons (TPH)

Petroleum hydrocarbon components were examined in all collected water samples (22 well water samples). The maximum TPH is about 0.0062 in S11 and the minimum value is 0.000014 in S15 (Table 4.3 and Figure 4.18).

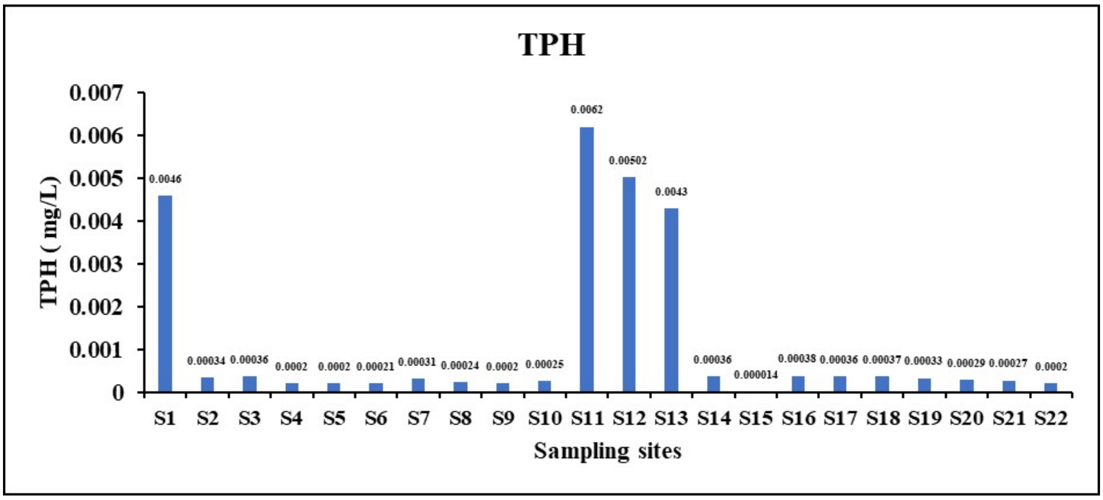


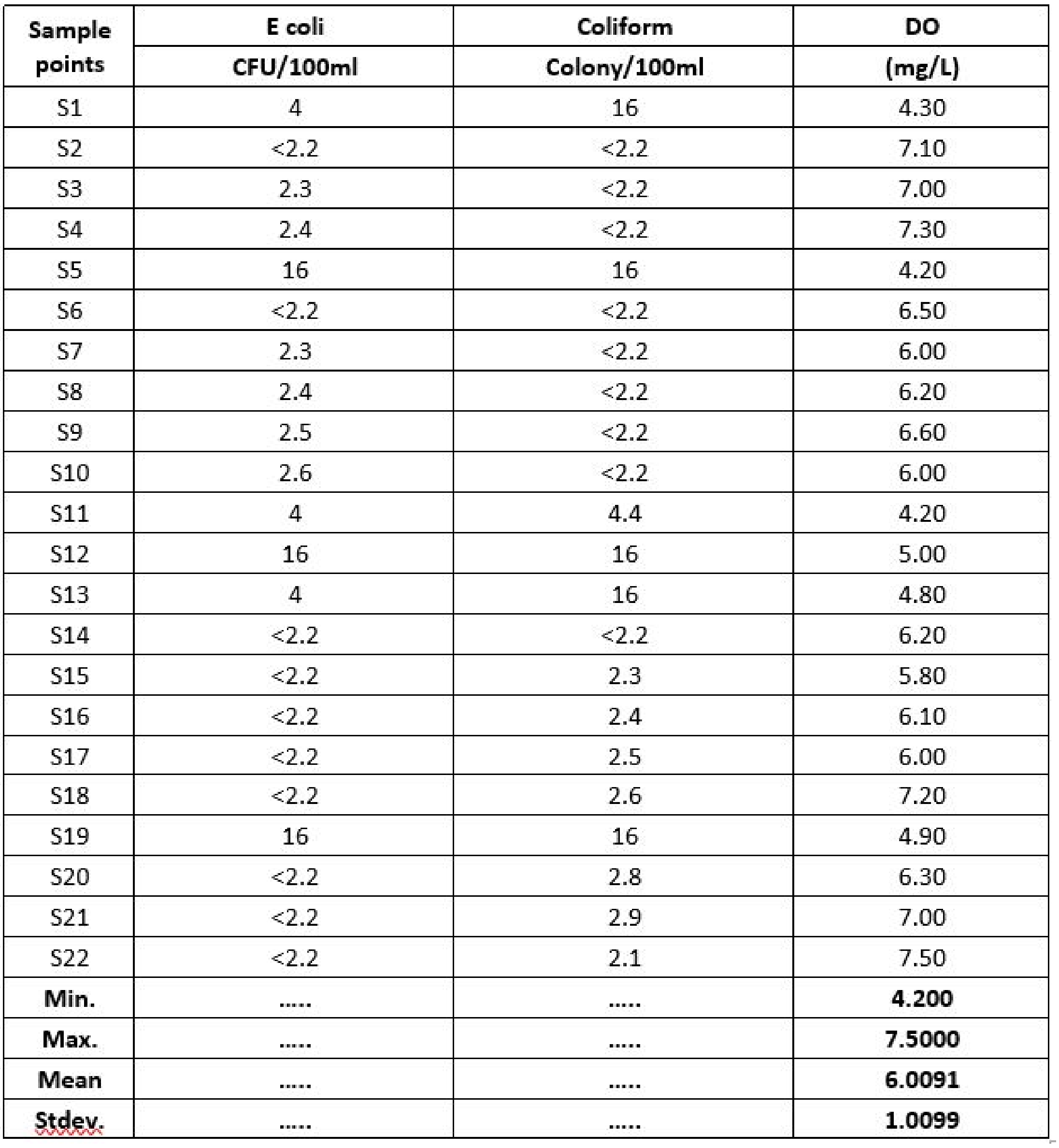
Figure 4.19. Total Petroleum Hydrocarbon (TPH) Levels Shown in The Studied Sampling Sites

Table 4.1. Physical And Chemical Elements of Water Quality Index Distribution in The Study Area

Sample points	Turb	PH	E.C	T.D.S	T.Alk.	T.H	Ca	Mg	Na	K	Cl	NO3	SO4	F
	NTU	-	µS/cm	mg/L	mg. CaCO3.L	mg. CaCO3.L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
IQS 2001*	5	8.5	-	1000	-	500	50	50	200	-	250	50	250	1.0
S1	3.1	7.1	533	266.5	235	678	87	32.625	194	3.2	19	83	47	0.89
S2	1.1	7	555	277.5	265	319	80	29.75	20	0.9	22	41	10	0.12
S3	2.7	7.1	325	162.5	161	236	59	22.125	5	0.7	17	37	40	0.71
S4	0.5	7.3	449	224.5	193	258	65	23.875	32	1.3	20	54	29	0.23
S5	3.1	7.3	348	174	168	261	65	24.625	5.4	0.8	23	74	38	0.88
S6	0.8	7.2	328	164	209	280	70	26.25	15	1	13	26	8	0.29
S7	0.4	7.2	325	162.5	181	232	58	21.75	12	0.9	18	35	14	0.54
S8	0.5	7.3	344	172	185	209	52	19.75	23	0.9	18	48	19	0.2
S9	0.9	7.1	333	166.5	190	210	53	19.375	21	1	15	24	28	0.23
S10	0.7	7.2	371	185.5	172	218	55	20.125	14	0.9	20	24	13	0.17
S11	1.2	7.6	417	208.5	199	476	69	25.875	87	0.8	14	24	35	0.04
S12	4.9	7.5	696	348	288	358	90	33.25	64	1.6	34	33	65	0.8
S13	0.5	7.6	686	343	221	368	92	34.5	102	1.8	46	36	58	0.07
S14	0.5	7.7	493	246.5	198	346	87	32.125	20	1	31	36	29	0.26
S15	0.3	7.6	513	256.5	223	324	81	30.375	13	0.9	35	39	16	0.41
S16	0.4	7.7	479	239.5	212	326	82	30.25	22	1	30	32	15	0.31
S17	0.6	7.8	458	229	203	358	90	33.25	21	0.9	34	34	15	0.09
S18	0.5	7.5	357	178.5	202	237	59	22.375	12	1	13	19	12	0.11
S19	1.1	7.2	408	204	202	269	67	25.375	22	1.1	18	97	19	1.21
S20	0.9	7.2	444	222	230	247	62	23	20	1	8	19	27	0.28
S21	1.1	7.2	405	202.5	214	319	80	29.75	8	1	29	28	20	0.3
S22	0.7	7.3	373	186.5	192	273	68	25.75	9	1	22	20	16	0.18
Min	**0.30**	**7.00**	**325.00**	**162.50**	**161.00**	**209.00**	**52.00**	**19.38**	**5.00**	**0.70**	**8.00**	**19.00**	**8.00**	**0.04**
Max	**4.90**	**7.80**	**696.00**	**348.00**	**288.00**	**678.00**	**92.00**	**34.50**	**194.00**	**3.20**	**46.00**	**97.00**	**65.00**	**1.21**
Mean	**1.20**	**7.35**	**438.18**	**219.09**	**206.50**	**309.18**	**71.41**	**26.64**	**33.70**	**1.12**	**22.68**	**39.23**	**26.05**	**0.38**
Stdev.	**1.17**	**0.23**	**108.01**	**54.00**	**29.85**	**104.98**	**13.16**	**4.85**	**43.86**	**0.53**	**9.20**	**20.83**	**15.58**	**0.32**

*IQS 2001:Iraq Water Quality Standards 2001

Table 4.2. Biological Elements of Water Quality Index Distribution in The Study Area



Sample points	E coli	Coliform	DO
	CFU/100ml	Colony/100ml	(mg/L)
S1	4	16	4.30
S2	<2.2	<2.2	7.10
S3	2.3	<2.2	7.00
S4	2.4	<2.2	7.30
S5	16	16	4.20
S6	<2.2	<2.2	6.50
S7	2.3	<2.2	6.00
S8	2.4	<2.2	6.20
S9	2.5	<2.2	6.60
S10	2.6	<2.2	6.00
S11	4	4.4	4.20
S12	16	16	5.00
S13	4	16	4.80
S14	<2.2	<2.2	6.20
S15	<2.2	2.3	5.80
S16	<2.2	2.4	6.10
S17	<2.2	2.5	6.00
S18	<2.2	2.6	7.20
S19	16	16	4.90
S20	<2.2	2.8	6.30
S21	<2.2	2.9	7.00
S22	<2.2	2.1	7.50
Min.	.....	.....	**4.200**
Max.	.....	.....	**7.5000**
Mean	.....	.....	**6.0091**
Stdev.	.....	.....	**1.0099**

Table 4.3. Heavy Metals of Water Quality Index Distribution in The Study Area

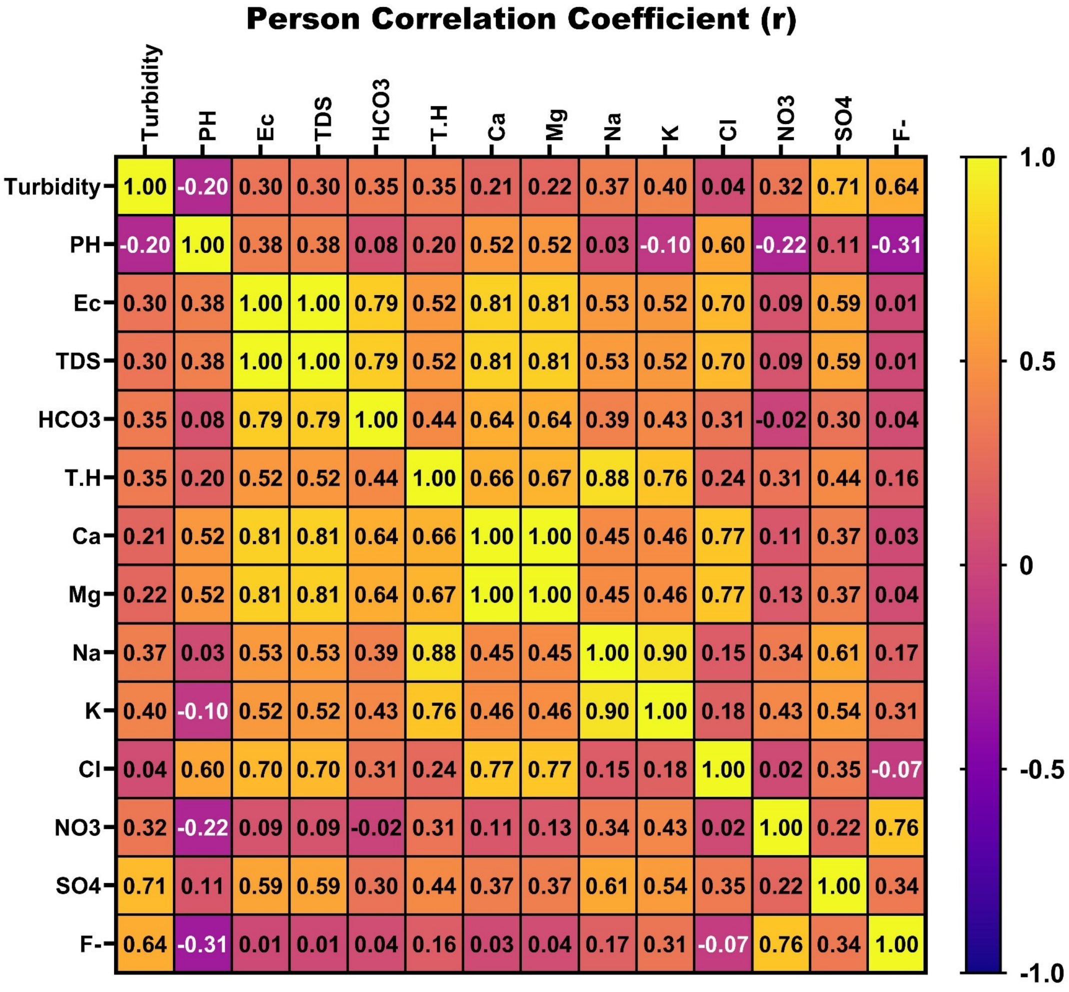
Sample points	Arsenic	Barium	Beryllium	Boron	Cadmium	Chromium	Cobalt	Copper	Lead	Lithium	Manganese	Molybdenum	Nickel	Selenium	Silver	Vanadium	Zinc	TPH
	Ppm	ppm	ppm	ppm	ppm	Ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
IQS 2001*	0.010	0.700	-	-	0.003	0.05	-	1	0.01	-	0.01	-	0.02	0.01	-	-	3	0.01
S1	1.482	0.540	<0.00020	0.024	<0.00040	0.001	0.002	0.0974	3.27	0.001	0.00187	<0.0020	0.002	0.01	0.001	0.001	0.49	0.0046
S2	0.009	0.053	<0.00020	0.099	<0.00040	0.0015	<0.0020	0.0986	0.0127	0.0142	0.01507	<0.0020	<0.0020	<0.0100	<0.0010	0.0048	0.103	0.00034
S3	0.002	0.063	<0.00020	0.100	<0.00040	0.0016	<0.0020	0.0881	0.0022	0.0153	0.01617	<0.0020	<0.0020	<0.0100	<0.0010	0.0038	0.0041	0.00036
S4	0.003	0.106	<0.00020	0.089	<0.00040	0.0026	<0.0020	0.1409	0.055	0.013	0.01387	<0.0020	<0.0020	<0.0100	<0.0010	0.0079	0.307	0.0002
S5	0.003	0.032	<0.00020	0.148	<0.00040	0.0016	<0.0020	0.1049	0.019	0.0176	0.01847	<0.0020	<0.0020	<0.0100	<0.0010	0.0027	0.328	0.0002
S6	0.006	0.027	<0.00020	0.106	<0.00040	0.0048	<0.0020	0.1089	0.023	0.0113	0.01217	<0.0020	<0.0020	<0.0100	<0.0010	0.0043	0.0049	0.00021
S7	0.003	0.040	<0.00020	0.110	<0.00040	0.0023	<0.0020	0.0903	0.0044	0.0119	0.01277	<0.0020	<0.0020	<0.0100	<0.0010	0.006	0.104	0.00031
S8	0.001	0.049	<0.00020	0.091	<0.00040	0.0033	<0.0020	0.1789	0.093	0.0093	0.01017	<0.0020	<0.0020	<0.0100	<0.0010	0.0084	0.163	0.00024
S9	0.006	0.174	<0.00020	0.180	<0.00040	0.0011	<0.0020	0.0089	0.077	0.0182	0.01907	<0.0020	0.0028	<0.0100	<0.0010	0.0043	0.0073	0.0002
S10	0.003	0.003	<0.00020	0.021	<0.00040	0.0016	<0.0020	0.0914	0.0055	0.01152	0.01744	<0.0020	<0.0020	<0.0100	<0.0010	0.005069	0.0083	0.00025
S11	1.370	0.640	<0.00020	0.026	<0.00040	0.0025	<0.0020	0.0262	1.27	0.004	0.00487	<0.0020	<0.0020	<0.0100	<0.0010	0.0099	0.201	0.0062
S12	1.410	0.270	<0.00020	0.027	<0.00040	0.0035	<0.0020	0.1259	2.86	0.0067	0.00757	<0.0020	<0.0020	<0.0100	<0.0010	0.0066	0.215	0.00502
S13	1.183	0.240	<0.00020	0.127	<0.00040	0.0039	<0.0020	0.1019	2.94	0.017	0.01787	<0.0020	<0.0020	<0.0100	<0.0010	0.0111	0.224	0.0043
S14	0.003	0.024	<0.00020	0.093	<0.00040	0.0088	<0.0020	0.0089	0.077	0.0102	0.01107	<0.0020	<0.0020	<0.0100	<0.0010	0.0092	0.0617	0.00036
S15	0.005	0.001	<0.00020	0.010	<0.00040	0.001	0.002	0.0226	0.0633	0.001	0.00187	<0.0020	0.002	0.01	0.001	0.001	0.002	0.00
S16	0.005	0.034	<0.00020	0.024	<0.00040	0.0017	<0.0020	0.0229	0.063	0.0035	0.00437	<0.0020	<0.0020	<0.0100	<0.0010	0.0094	4.13	0.00038
S17	0.005	0.032	<0.00020	0.024	<0.00040	0.00192	<0.0020	0.6269	0.541	0.0037	0.00457	<0.0020	<0.0020	<0.0100	<0.0010	0.0132	0.655	0.00036
S18	0.005	0.184	<0.00020	0.086	<0.00040	0.00252	<0.0020	0.0189	0.067	0.0122	0.01307	<0.0020	0.0033	<0.0100	<0.0010	0.0163	0.0579	0.00037
S19	0.006	0.083	<0.00020	0.020	<0.00040	0.00352	<0.0020	0.00977	0.07613	0.0107	0.01157	<0.0020	0.0068	<0.0100	<0.0010	0.0107	0.186	0.00033
S20	0.002	0.035	<0.00020	0.099	<0.00040	0.00252	<0.0020	0.09947	0.01357	0.01502	0.015886	<0.0020	<0.0020	<0.0100	<0.0010	0.0127	0.0035	0.00029
S21	0.003	0.051	<0.00020	0.101	<0.00040	0.00572	<0.0020	0.08897	0.00307	0.01612	0.016986	<0.0020	<0.0020	<0.0100	<0.0010	0.0144	0.002	0.00027
S22	0.004	0.024	<0.00020	0.090	<0.00040	0.00322	<0.0020	0.14177	0.05587	0.01382	0.014686	<0.0020	0.234	<0.0100	<0.0100	0.0168	0.104	0.0002
Min.	**0.00128**	**0.0005**	…..	**0.01**	…..	**0.001**	…..	**0.0089**	**0.0022**	**0.001**	**0.00187**	…..	…..	…..	…..	**0.001**	**0.002**	**0.000**
Max.	**1.482**	**0.64**	…..	**0.18**	…..	**0.0088**	…..	**0.6269**	**3.27**	**0.0182**	**0.01907**	…..	…..	…..	…..	**0.0168**	**4.13**	**0.0062**
Mean	**0.2508**	**0.1229**	…..	**0.077**	…..	**0.00283**	…..	**0.1047**	**0.5269**	**0.0108**	**0.0118845**	…..	…..	…..	…..	**0.008162**	**0.335**	**0.0011**
Stdev.	**0.5379**	**0.1692**	…..	**0.0475**	…..	**0.00181**	…..	**0.1266**	**1.0547**	**0.0053**	**0.0054701**	…..	…..	…..	…..	**0.004659**	**0.865**	**0.0019**

*IQS 2001:Iraq Water Quality Standards 2001

Table 4.4. Correlation Coefficient Between Elements of Water Quality Index of Water Wells in The Studied Area

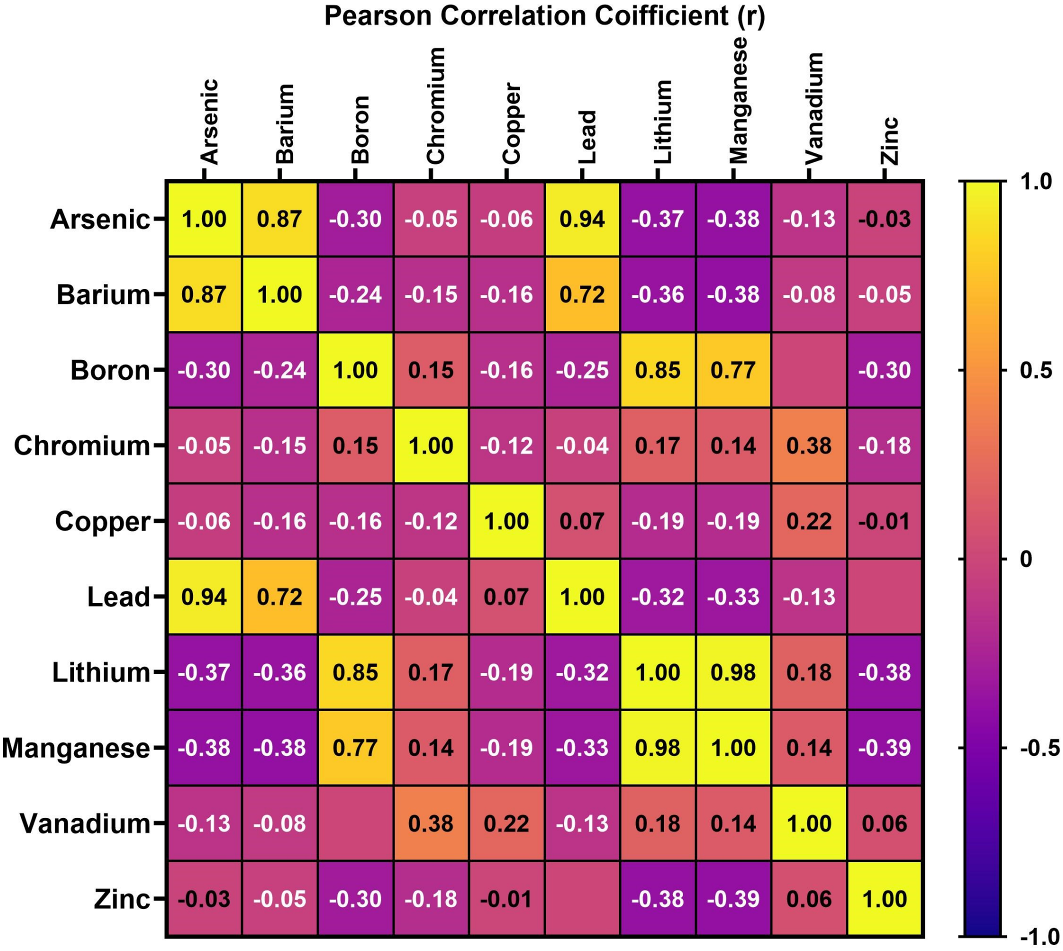
Parameters	Turbidity	pH	EC	TDS	T.Alk	Ca	Mg	Na	K	Cl	NO3	SO4	DO	As	Ba	Bo	Cr	Cu	Pb	Li	Mn	V	Zn	TPH	THARD	F-
Turbidity	1																									
pH	-0.202	1																								
EC	0.304	0.376	1																							
TDS	0.304	0.376	1.000**	1																						
TALKAL	0.348	0.081	.794**	.794**	1																					
Ca	0.213	.521*	.814**	.814**	.641**	1																				
Mg	0.217	.517*	.807**	.807**	.636**	.998**	1																			
Na	0.371	0.032	.529*	.529*	0.386	.445*	.455*	1																		
K	0.395	-0.099	.522*	.522*	.431*	.455*	.462*	.900**	1																	
Cl	0.039	.600**	.701**	.701**	0.31	.770**	.766**	0.148	0.18	1																
NO3	0.323	-0.225	0.087	0.087	-0.024	0.109	0.13	0.342	.427*	0.024	1															
SO4	.705**	0.111	.592**	.592**	0.3	0.369	0.371	.613**	.544**	0.353	0.217	1														
DO	-.442*	-0.236	-0.348	-0.348	-0.136	-0.308	-0.324	-.604**	-0.414	-0.22	-.508*	-.556**	1													
As	.540**	0.182	.628**	.628**	.487*	.473*	.482*	.874**	.688**	0.251	0.133	.770**	-.671**	1												
Ba	0.374	0.077	0.303	0.303	0.266	0.205	0.214	.828**	.576**	-0.096	0.137	.553**	-.568**	.873**	1											
Bo	-0.089	-0.391	-0.315	-0.315	-0.289	-0.368	-0.367	-0.278	-0.207	-0.191	-0.178	0.051	0.309	-0.296	-0.236	1										
Cr	-0.146	0.253	0.106	0.106	0.045	0.282	0.281	-0.128	-0.077	0.225	-0.122	0.041	0.12	-0.047	-0.155	0.151	1									
Cu	-0.014	0.272	0.056	0.056	0	0.254	0.246	-0.031	-0.022	0.248	-0.042	-0.08	0.054	-0.064	-0.161	-0.158	-0.118	1								
Pb	.539**	0.18	.727**	.727**	.534*	.580**	.587**	.887**	.816**	0.408	0.207	.798**	-.616**	.940**	.720**	-0.246	-0.04	0.066	1							
Li	-0.06	-.498*	-0.292	-0.292	-0.297	-.433*	-.434*	-0.416	-0.312	-0.197	-0.148	0.023	0.37	-0.368	-0.359	.847**	0.172	-0.191	-0.321	1						
Mn	-0.077	-.514*	-0.312	-0.312	-0.341	-.477*	-.482*	-.425*	-0.322	-0.205	-0.177	-0.015	0.36	-0.379	-0.381	.774**	0.138	-0.191	-0.334	.980**	1					
V	-0.371	0.337	-0.033	-0.033	-0.011	0.041	0.047	-0.218	-0.214	0.039	-0.365	-0.193	0.332	-0.132	-0.083	0	0.383	0.216	-0.134	0.178	0.145	1				
Zn	-0.099	0.392	0.141	0.141	0.061	0.262	0.25	0.04	0.04	0.231	0.019	-0.098	-0.071	-0.025	-0.047	-0.305	-0.18	-0.007	-0.003	-0.38	-0.387	0.059	1			
TPH	.489*	0.232	.581**	.581**	.440*	.431*	.439*	.814**	.571**	0.214	0.067	.733**	-.668**	.985**	.894**	-0.299	-0.023	-0.074	.879**	-0.358	-0.369	-0.07	-0.019	1		
THARD	0.348	0.195	.518*	.518*	.439*	.659**	.668**	.881**	.762**	0.238	0.307	.438*	-.563**	.769**	.750**	-.447*	-0.027	0.06	.743**	-.606**	-.629**	-0.175	0.141	.729**	1	
F-	.638**	-0.311	0.014	0.014	0.041	0.025	0.043	0.175	0.314	-0.072	.763**	0.339	-.462*	0.145	0.061	-0.174	-0.114	-0.204	0.194	-0.086	-0.112	-0.4	-0.013	0.076	0.159	1

* : means p-value < 0.05
** : means p-value < 0.01
*** : means p-value < 0.001



	Turbidity	PH	Ec	TDS	HCO3	T.H	Ca	Mg	Na	K	Cl	NO3	SO4	F-
Turbidity	1.00	-0.20	0.30	0.30	0.35	0.35	0.21	0.22	0.37	0.40	0.04	0.32	0.71	0.64
PH	-0.20	1.00	0.38	0.38	0.08	0.20	0.52	0.52	0.03	-0.10	0.60	-0.22	0.11	-0.31
Ec	0.30	0.38	1.00	1.00	0.79	0.52	0.81	0.81	0.53	0.52	0.70	0.09	0.59	0.01
TDS	0.30	0.38	1.00	1.00	0.79	0.52	0.81	0.81	0.53	0.52	0.70	0.09	0.59	0.01
HCO3	0.35	0.08	0.79	0.79	1.00	0.44	0.64	0.64	0.39	0.43	0.31	-0.02	0.30	0.04
T.H	0.35	0.20	0.52	0.52	0.44	1.00	0.66	0.67	0.88	0.76	0.24	0.31	0.44	0.16
Ca	0.21	0.52	0.81	0.81	0.64	0.66	1.00	1.00	0.45	0.46	0.77	0.11	0.37	0.03
Mg	0.22	0.52	0.81	0.81	0.64	0.67	1.00	1.00	0.45	0.46	0.77	0.13	0.37	0.04
Na	0.37	0.03	0.53	0.53	0.39	0.88	0.45	0.45	1.00	0.90	0.15	0.34	0.61	0.17
K	0.40	-0.10	0.52	0.52	0.43	0.76	0.46	0.46	0.90	1.00	0.18	0.43	0.54	0.31
Cl	0.04	0.60	0.70	0.70	0.31	0.24	0.77	0.77	0.15	0.18	1.00	0.02	0.35	-0.07
NO3	0.32	-0.22	0.09	0.09	-0.02	0.31	0.11	0.13	0.34	0.43	0.02	1.00	0.22	0.76
SO4	0.71	0.11	0.59	0.59	0.30	0.44	0.37	0.37	0.61	0.54	0.35	0.22	1.00	0.34
F-	0.64	-0.31	0.01	0.01	0.04	0.16	0.03	0.04	0.17	0.31	-0.07	0.76	0.34	1.00

Figure 4.20. Heatmap Was Showing The Pearson Correlation Coefficient For Physical And Chemical Elements



	Arsenic	Barium	Boron	Chromium	Copper	Lead	Lithium	Manganese	Vanadium	Zinc
Arsenic	1.00	0.87	-0.30	-0.05	-0.06	0.94	-0.37	-0.38	-0.13	-0.03
Barium	0.87	1.00	-0.24	-0.15	-0.16	0.72	-0.36	-0.38	-0.08	-0.05
Boron	-0.30	-0.24	1.00	0.15	-0.16	-0.25	0.85	0.77		-0.30
Chromium	-0.05	-0.15	0.15	1.00	-0.12	-0.04	0.17	0.14	0.38	-0.18
Copper	-0.06	-0.16	-0.16	-0.12	1.00	0.07	-0.19	-0.19	0.22	-0.01
Lead	0.94	0.72	-0.25	-0.04	0.07	1.00	-0.32	-0.33	-0.13	
Lithium	-0.37	-0.36	0.85	0.17	-0.19	-0.32	1.00	0.98	0.18	-0.38
Manganese	-0.38	-0.38	0.77	0.14	-0.19	-0.33	0.98	1.00	0.14	-0.39
Vanadium	-0.13	-0.08		0.38	0.22	-0.13	0.18	0.14	1.00	0.06
Zinc	-0.03	-0.05	-0.30	-0.18	-0.01		-0.38	-0.39	0.06	1.00

Figure 4.21. Heatmap Was Showing The Pearson Correlation Coefficient For Heavy Metals

4.6. Canadian Water Quality Index

These wells have subsequently been assessed for their water quality index using the Canadian guideline (CCWQI)for water quality index. The results were shown in the (Table 4.5 and Figure 4.21).

Table 4.5. Canadian Water Quality Index (CCWQI) For Study Water Well Samples

Sites	CWQI	Categories according to CCME WQI
S1	41.39	Poor
S2	87.81	Good
S3	91.94	Good
S4	77.37	Fair
S5	83.26	Good
S6	87.38	Good
S7	92.14	Good
S8	79.85	Good
S9	80.65	Good
S10	91.91	Good
S11	44.33	Poor
S12	43.75	Poor
S13	41.73	Poor
S14	78.18	Fair
S15	82.70	Good
S16	79.47	Fair
S17	56.84	Marginal
S18	82.43	Good
S19	77.69	Fair
S20	87.93	Good
S21	88.22	Good
S22	77.24	Fair
Mean	**75.19**	**Fair**

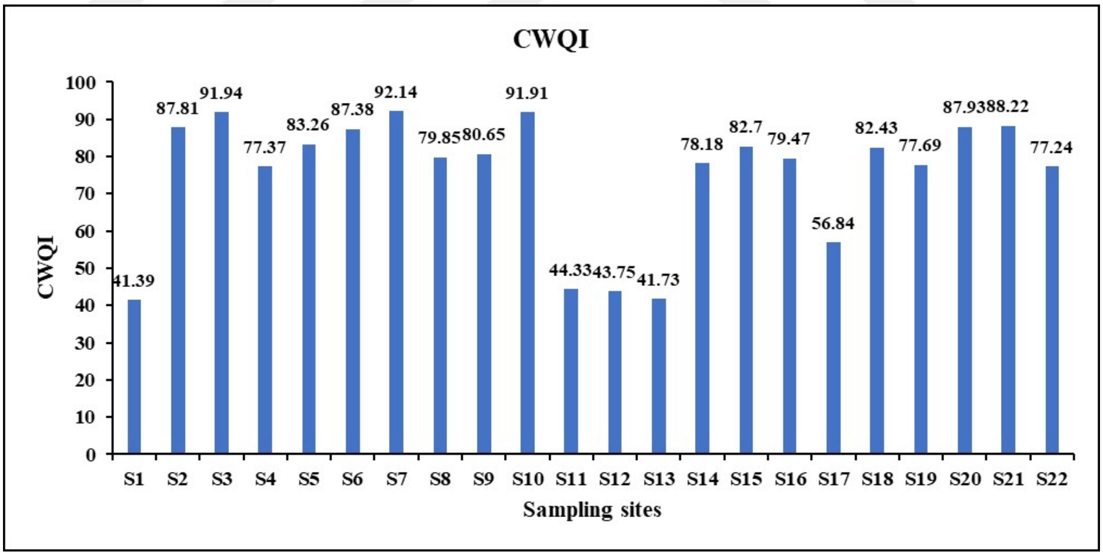


Figure 4.22. Canadian Water Quality Index (CCWQI) in Studied Sampling Sites

4.7. Mechanism Controlling Groundwater

A simplified chart Gibbs (1970) diagrams that compares TDS to the weight ratio of Na / (Na + Ca) would provide important information on the relative importance of the three main natural processes influencing the chemistry of groundwater such as Evaporation, Rock dominant, and Precipitation dominants.

Accordingly, the main mechanism for controlling groundwater is rock dominant in my study region (Figure 4.22). Rock dominance shows that the main ions in groundwater come from the weathering and dissolving of minerals in the rocks that make up the aquifer (Soro et al., 2019).

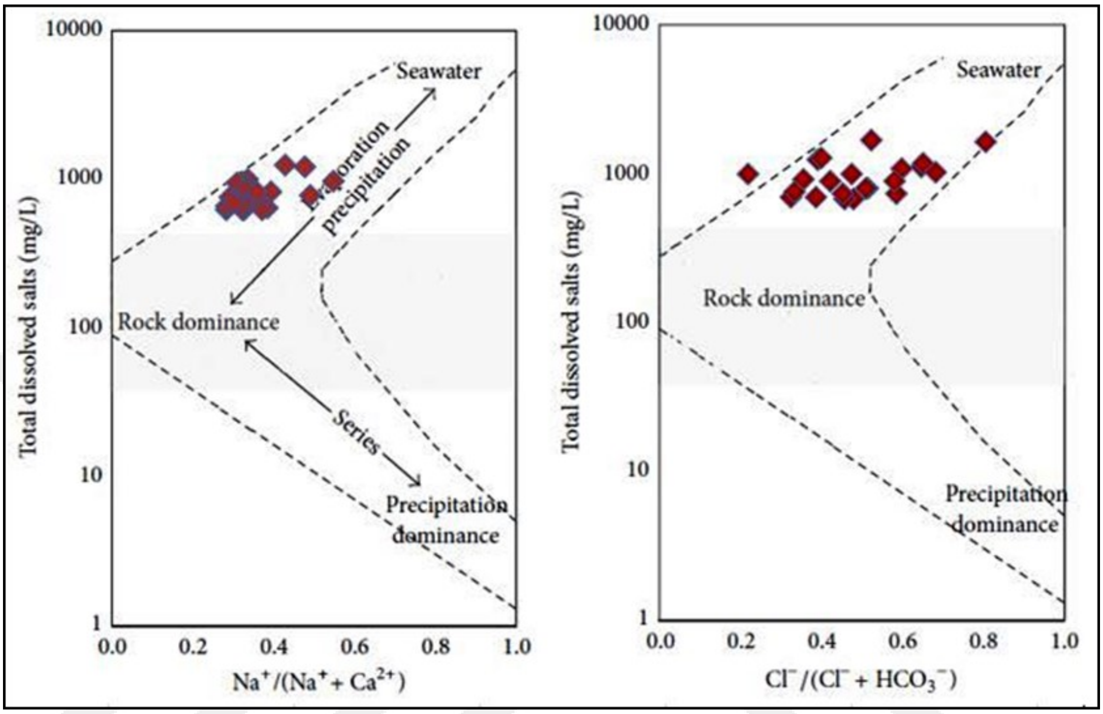


Figure 4.23. Gibbs Diagram, Dominant Type of Components in The Study Water Types

4.8. Groundwater Classification

Two types of classification show the groundwater types. First of all is Piper (1944) illustration was used to assess the quality of groundwater and surface water. Six categories of water are often shown on a diagram called a piper (Fetter, 1994). All samples were placed in area F (Calcium type), according to the cation trilinear findings, with the exception of S1, S11, S12 and S13, which were dispersed in region in area B (Sodium and Potassium). Similarly. area (Bicarbonate type), according to the anion trilinear. Also, Schoeller (1972) graphs the concentration of these ions in (epm) units on a semi-logarithmic paper to classify water according to its major cations and anions. we may visually compare the constituents of several waters in order of decreasing concentration (Fetter, 1994) (Table 4.6).Furthermore,According to the Schoeller graph, every variable in the examined region is moving in the same direction and is caused by lactogenic factors. Furthermore, the majority of stream water samples in the study area are of type F6, while S1, S11, S12, and S13 exhibit type B6. Given the high amounts of Ca, Mg, and HCO_3 ions, the water samples from the research location mostly display a calcium-magnesium-bicarbonate chemical signature. All samples had consistently low potassium levels, but modest quantities of sodium, sulfate, and chloride indicate little salinity and mineral effect. Minimal pollution from sewage or agricultural sources is indicated by the low nitrate contents. All things considered, the area's groundwater is fresh, naturally mineralized water that is mostly obtained from the dissolving of carbonate rocks, which makes it typically appropriate for use in homes and farms.

Table 4.6. Water Type According to Scholler (1972) Classification (Fetter, 1994)

Type	Cations	Types	Anions
A	r(Na+K) > rMg > rCa	1	rCl > rSO4 > rHCO3
B	r(Na+K) > rCa > rMg	2	rCl > rHCO3 > rSO4
C	rMg > r(Na+K) > rCa	3	rSO4 > rCl > rHCO3
D	rMg> rCa> r(Na+K)	4	rSO4 > rHCO3 > rCl
E	rCa > r(Na+K) > rMg	5	rHCO3 > rCl >rSO4
F	rCa > rMg > r(Na+K)	6	rHCO3 >rSO4 > rCl

5. DISCUSSION

According to the research results, representing the main discussions about each element distributions and illustrating all elements, indexes interpolation maps from IDW techniques by GIS-platform depending on the ranges of all parameters and indexes for Erbil Oil Refinery at Site 1 which representing the main sources of heavy metals and causes effecting the groundwater quality from S1 with surrounding sites in the area.

5.1. Physical Parameters

5.1.1. Turbidity

Turbidity is a quantitative assessment of the purity of water. The dispersion of light through water is influenced by many particles present in the water, including clay, silt, sand, algae, plankton, microorganisms, and other suspended substances reduction DO levels (Baird et al., 2017; Rump, 1999). The high value of turbidity level was shown in S12 (Figure 5.1) due to the leakage of hydrocarbon waste from the refinery, contamination has reached the groundwater, causing significant environmental harm. As the waste infiltrates the soil, it migrates downwards, eventually entering and polluting groundwater aquifers. This poses serious risks to water quality, rendering it unsafe for drinking, irrigation, and industrial use. The presence of hydrocarbons in groundwater not only threatens human health, as many of these substances are toxic, but also disrupts local ecosystems. Moreover, addressing this pollution is challenging, requiring complex and expensive remediation efforts to restore water safety and quality. The findings of this study were found to be lower than results reported by Jidauna et al. (2013) who studied water quality of water wells in Nigera. However, the current results consistent with the findings of Suleiman et al. (2022) in their study on water wells of Nigeria too.

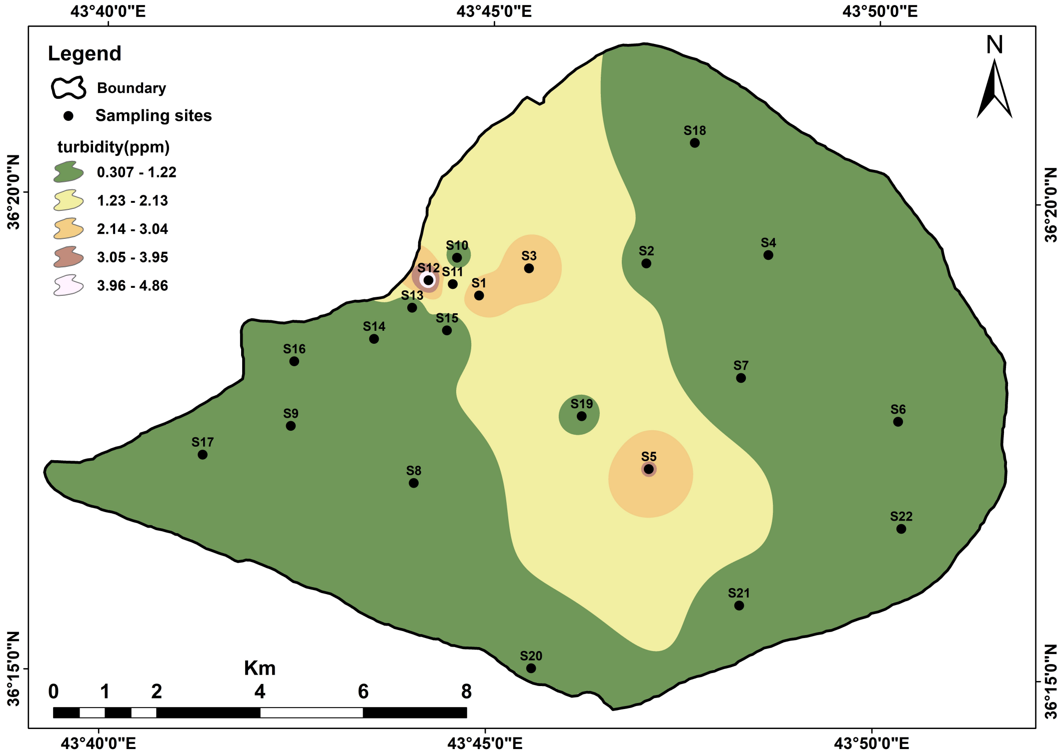


Figure 5.1. Interpolation Map Shows Turbidity Levels in The Studied Sampling Sites

5.1.2. Electrical Conductivity (EC)

According to the USEPA (2004) standard, all water wells examined in this study fell within the permissible ranges which is considered suitable for drinking purposes. On the other hand, in the Figure 5.2, sites S12 and S13 represent a higher result value than others due to differences in lithology and geological formations and depth of the water well. Also, the other factor is the leakage of hydrocarbon waste from the refinery, contamination has reached the groundwater, causing significant environmental harm. Muhammad (2004) made comparable observations in Sulaymaniyah province, whereas Trojan et al. (2003) made similar observations in Minnesota. Hassan (1998) observed in the well waters of Erbil city appear to validate the current findings. Bilbas (2004) findings about the EC levels in groundwater systems of Erbil, were between 150 to 3120 µS.cm-1. The observed levels of conductivity in the present study was found to be lower than findings reported by Abdel et al. (2018) in their study on shallow groundwater systems in El-Obour city, Egypt with values ranged from 574.8 and 15369.8 µ.S/cm.

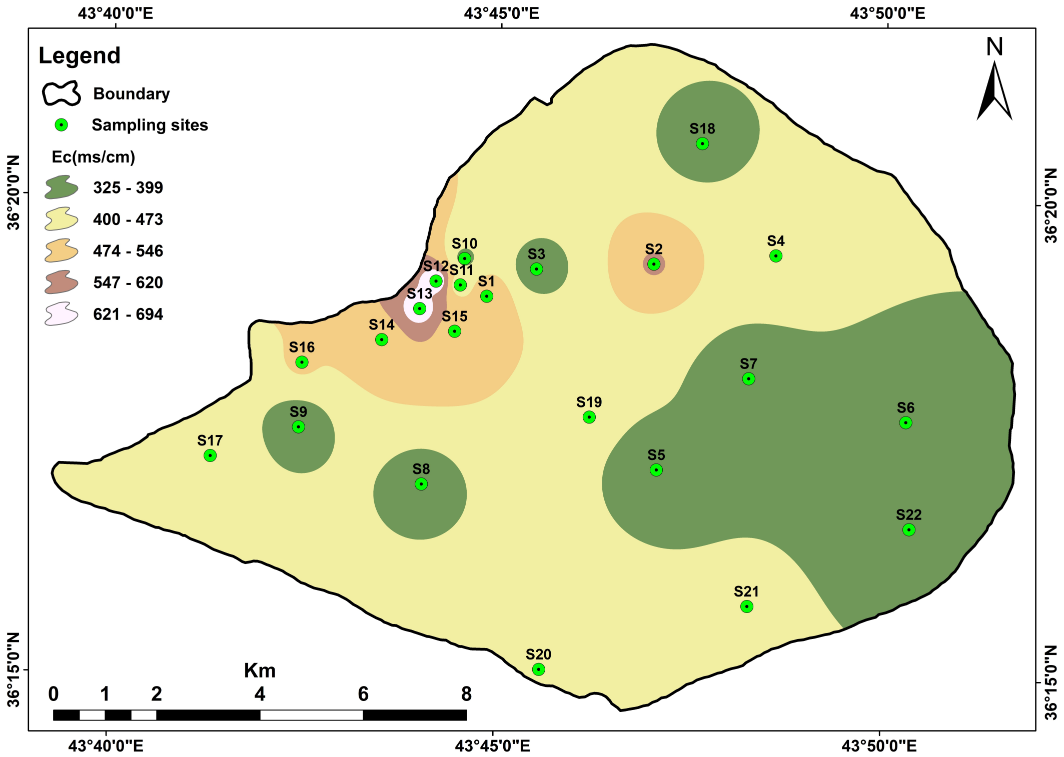


Figure 5.2. Interpolation Map Shows EC Levels in The Studied Sampling Sites

5.1.3. Total Dissolved Solids (TDS)

In the studied results are representing a strong correlation between the TDS values of water and its conductivity (Leggett et al., 2001). According to the Iraqi (2001) standard, all water wells examined in this study fell within the permissible ranges which is considered suitable for drinking purposes. While, in the Figure 5.3, sites S12 and S13 represent a higher result value than others due to differences in lithology and geological formations and disparities in mineral solubility in the water well sites (WHO, 2004). Also, the leakage of hydrocarbon waste from the refinery, contamination has reached the groundwater, causing significant environmental harm. The findings reported by El Baba et al. (2020) have TDS values fluctuated from 715 to 3598 mg/L were not consistent with the results of current study. The findings of the present study are incongruent with the results reported by Al-Shammary and Al-Mayyahi (2021) in the Ali Al-Gharbi District of Iraq with levels of 980 to 4736 mg/L, as well as Abdel et al. (2018) in their investigation of shallow groundwater in El-Obour city, Egypt with values of 420.6 to 7838.2 mg/L.

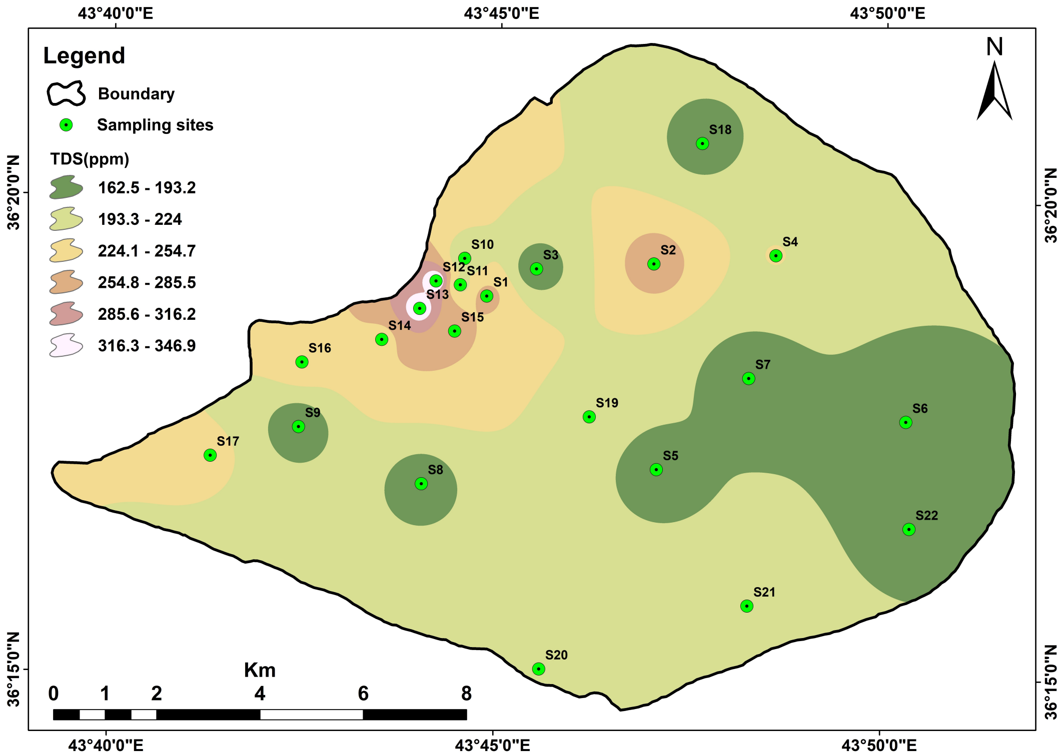


Figure 5.3. Interpolation Map Shows TDS Levels in The Studied Sampling Sites

5.2. Chemical Parameters

5.2.1. PH

The mean pH value in current study is 7.35 from the range of 7.0 in S2 to 7.8 in S17. The pH value of studied wells has a standard deviation of ± 0.232. Depending on comparing the current pH values with the suggested guideline values outlined in the Iraqi standard (2001) and USEPA (2004) for drinking water standards, it was seen that all water wells studied exhibited pH levels that fell within the acceptable range for consumption which is representing in (Figure 5.4). This fluctuation of pH can be ascribed to the geological formation of the area which is primarily constituted of $CaCO_3$ (Sawyer et al., 2003). However, pH has strongly correlation with turbidity in the area (Acheampong et al., 2013). Bilbas (2004), Ibrahim (1981) in Sulaimaniyah province, and Al-Nakshabandi (2002) in Dohuk province have the same findings and agreed with results of current study. The finding of this study was consistent with the results reported by El Baba et al. (2020) in the Dier al-Balah Governorate, Gaza Strip, Palestine with values fluctuated from 7.0 to 8.0, and slightly differs from that of Hui et al. (2020) in Hailun, China with values of 6.14 to 7.60.

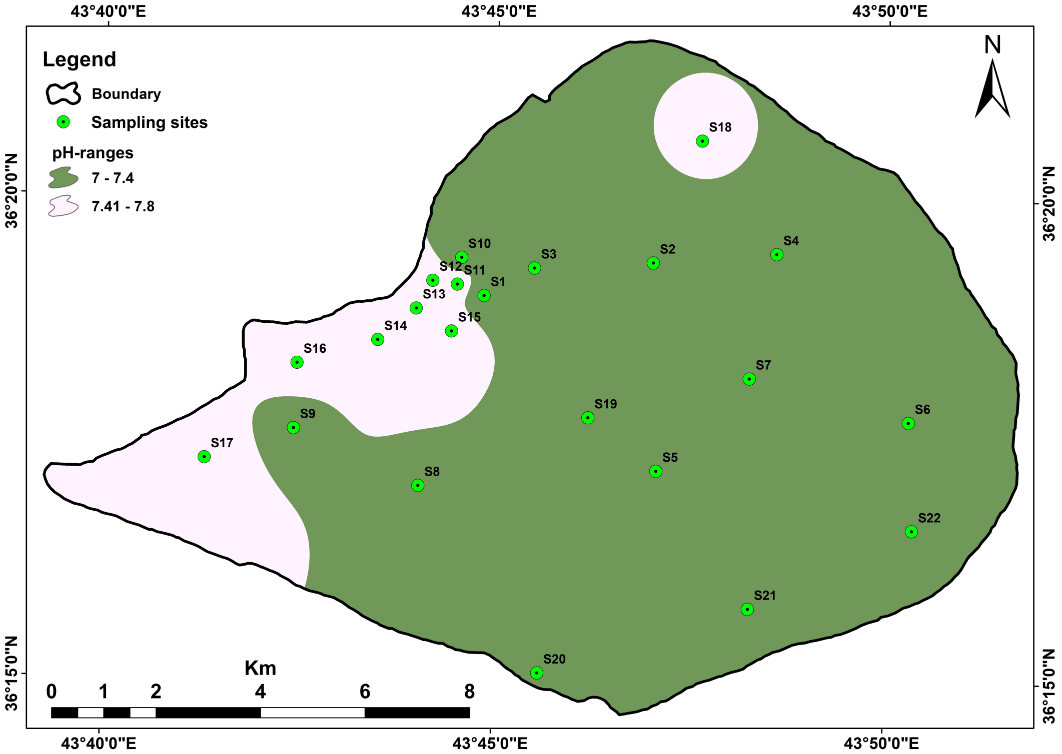


Figure 5.4. Interpolation Map Shows PH Levels in The Studied Sampling Sites

5.2.2. Total Hardness

The primary ions responsible for hardness in freshwater systems are calcium and magnesium, which are derived from sedimentary rocks, with limestone and chalk being the most prevalent (WHO, 1996). According to Iraqi Guideline (2001), all examined water wells were deemed safe for drinking water except S1 due to the direct leakage of hydrocarbons has permeated the soil, eventually seeping into the groundwater. Also, the average concentrations of calcium and magnesium are 71.41 mg/L and 26.64 mg/L in the study area (Figure 5.5,5.6,5.7). This pattern suggests that calcium, rather than magnesium, is the predominant component of total hardness in the studied area. This can be attributed to the geological composition of the Erbil governorate, which is primarily composed of Limestone (Hassan, 1998). Additionally, the solubility of calcite rock, which is abundant in the study area, occurs at a faster rate than that of dolomite(Chnaray, 2003). The findings of this study exhibit a strong correlation with the observations made by Shekha (2001) and Al-Nakshabandi (2002), in the groundwater samples collected in Erbil and Duhok, respectively. The current study yielded lower results compared to the findings of El Baba et al. (2020) in Dier al-Balah Governorate, Gaza Strip, Palestine. Additionally, the results were consistent with the results reported by Al-Barwary et al. (2018) in their study, which focused on water wells and natural spring samples collected from Soran District, Northern Erbil Governorate-Iraq 473.6 to 496.4 mg.$CaCO_3$/L.

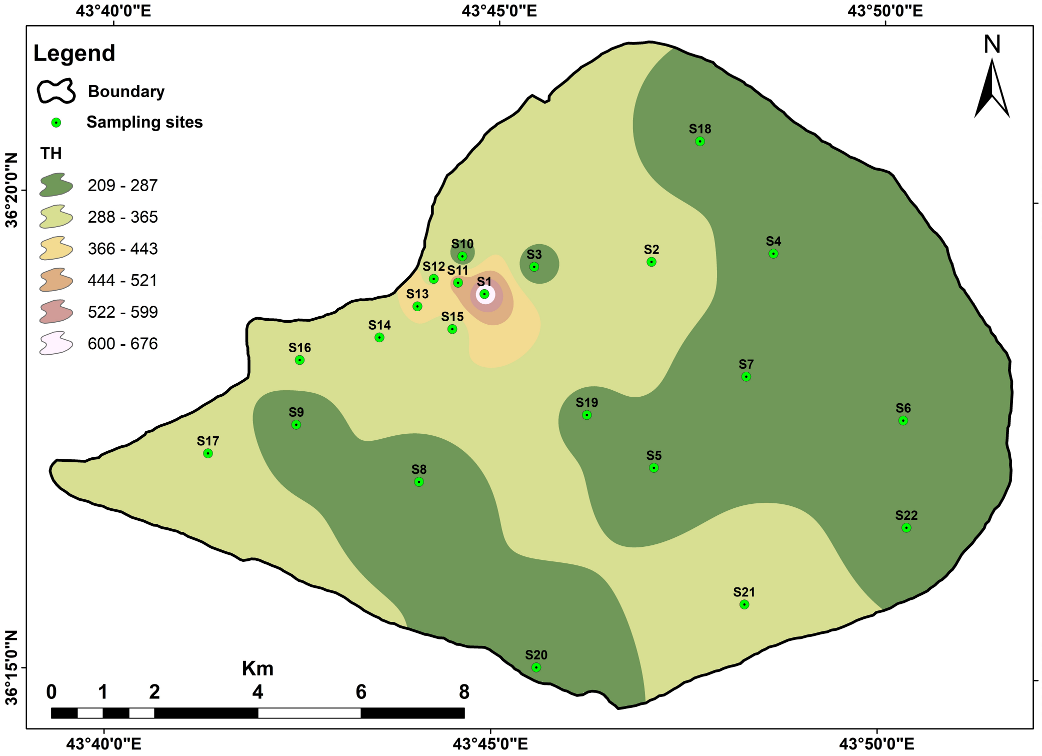


Figure 5.5. Interpolation Map Shows TH Levels in The Studied Sampling Sites

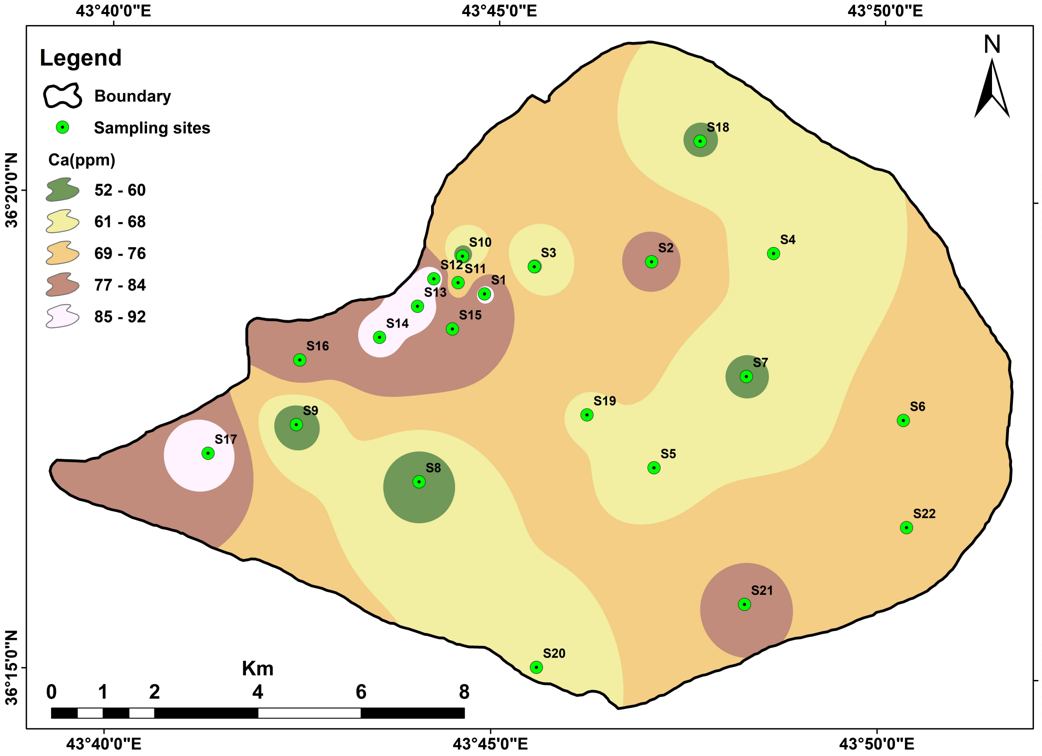


Figure 5.6. Interpolation Map Shows Calcium Levels in The Studied Sampling Sites

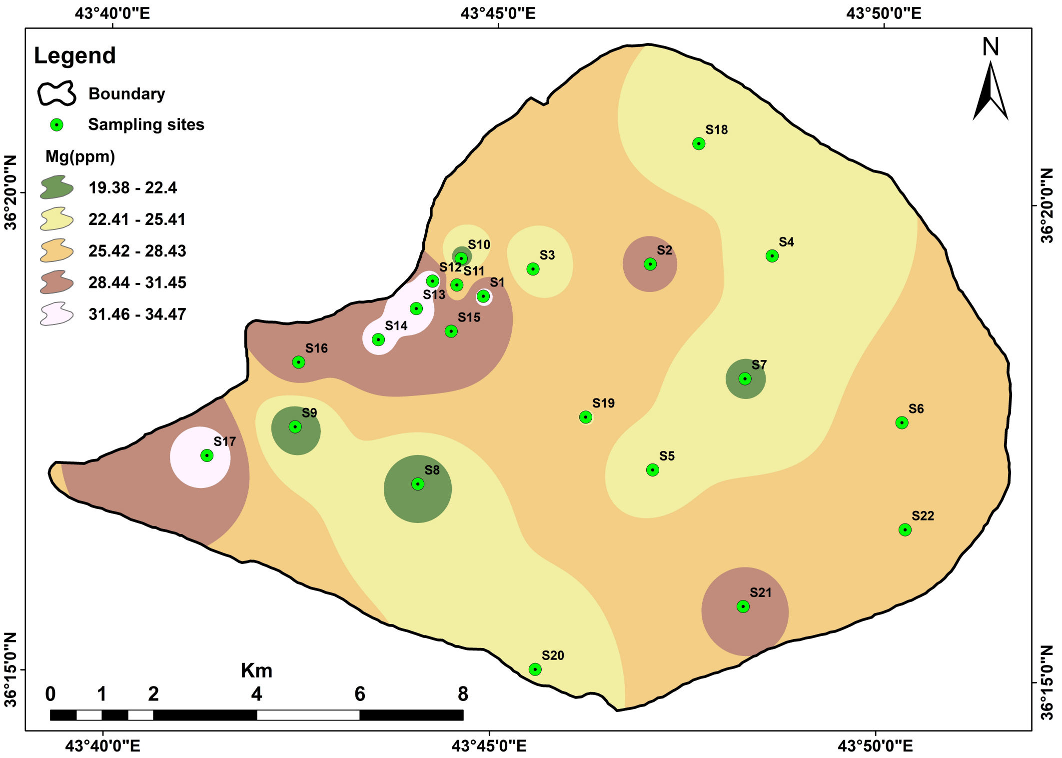


Figure 5.7. Interpolation Map Shows Magnesium Levels in The Studied Sampling Sites

5.2.3. Sodium (Na^+)

According to the (WHO 2004) , sodium salts exhibit a high solubility in water and are transported from the terrestrial environment to both groundwater and surface water. (Figure 5.8) shows the ground water samples of Sodium level in the area and site number one (S1) presented a very high concentration of sodium ions, which could serve as an indicator of pollution for these wells or to be attributed to the geological formation of the area and the direct leakage of hydrocarbons has permeated the soil, eventually seeping into the groundwater (Suleiman et al., 2022). The current findings are consistent and lower than results reported by Barzinji and Ganjo (2014) in the Halabja-Sulaimani-Iraq with levels of 1.59 to 2.83 mg/L. The findings of the present study were not consistent with the results reported by El Baba et al. (2020) in the Dier al-Balah Governorate, Gaza Strip, Palestine with levels of 310 to 780 mg/L. Additionally, the results of present investigation were significantly different and lower than findings of Al-Shammary and Al-Mayyahi (2021) in the Ali Al-Gharbi District, Iraq with levels of 50.4 to 870.9 mg/L, and Abdel et al. (2018) in the shallow groundwater of El-Obour city, Egypt with concentrations of 30 to 3641.9 mg/L.

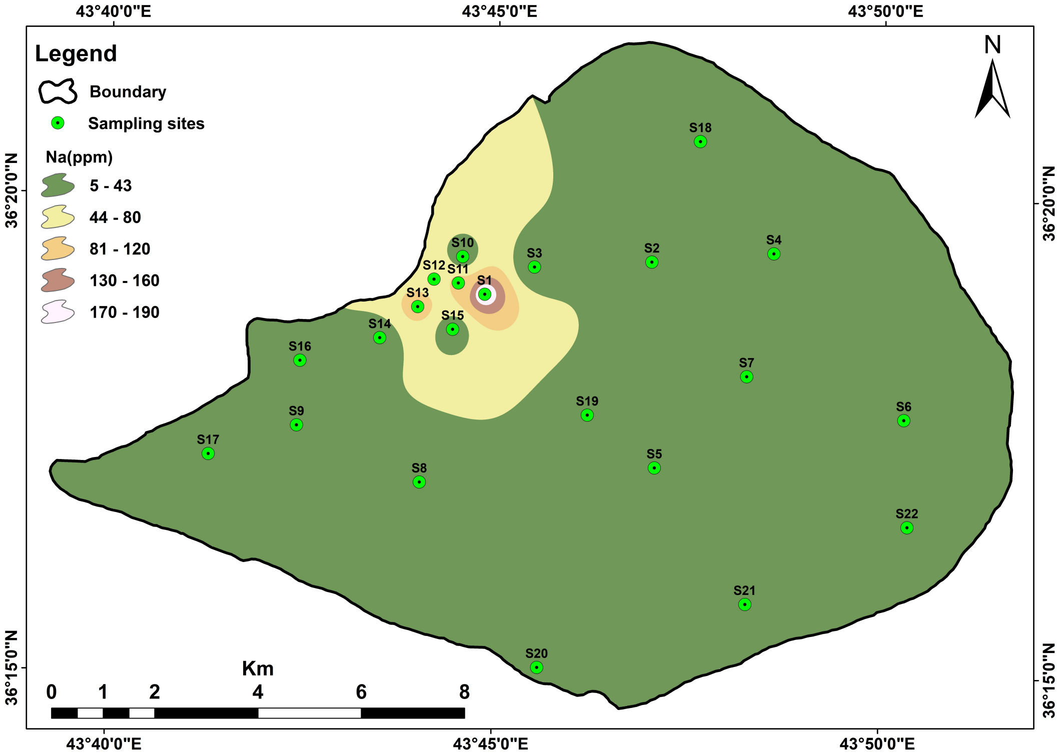


Figure 5.8. Interpolation Map Shows Sodium Levels in The Studied Sampling Sites

5.2.4. Potassium (K^+)

In soil, the concentration ranges from 0.1 % to 2.6 %, while in groundwater, it varies between 0.5 % and 10 %. The presence of potassium in groundwater systems can be attributed to the process of mineral dissolution, the decomposition of plant matter, and the discharge from agricultural activities (Baird et al., 2017). Figure 5.9 shows the ground water samples of Potassium levels in the area and site number one (S1) presented a very high concentration of Potassium ions due to the direct leakage of hydrocarbons has permeated the soil, eventually seeping into the groundwater and the process of mineral dissolution, the decomposition of plant matter, and the discharge from agricultural activities (Baird et al., 2017). This observation aligns with the findings of Muhammad (2004) in the Sarchnar spring with levels ranged from 0.18 to 10.10 mg/L. The findings of this study exhibit a lower magnitude compared to the results reported by Al-Shammary and Al-Mayyahi (2021) in the Ali Al-Gharbi District of Iraq with levels of 0.37 to 4.10 mg/L, primarily attributed to disparities in geological composition.

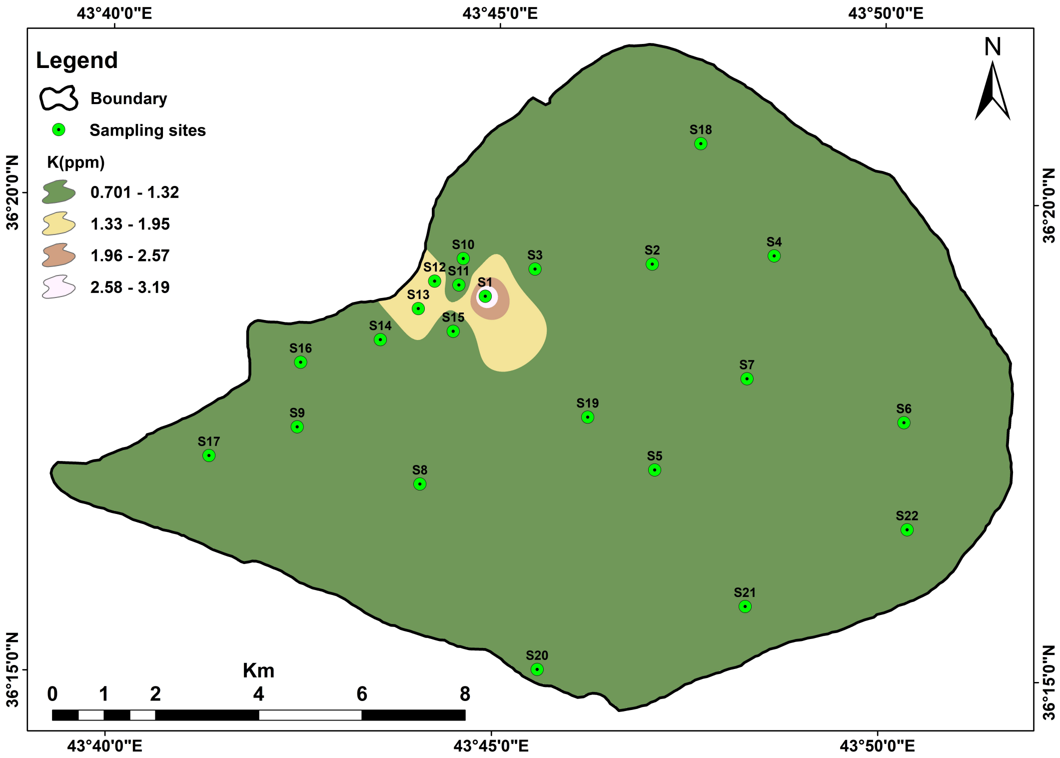


Figure 5.9. Interpolation Map Shows Potassium Levels in The Studied Sampling Sites

5.2.5. Alkalinity

Figure 5.10 demonstrated the alkalinity level in the study area and the predominant type of alkalinity in the study area was bicarbonate alkalinity. in the area and site (S12) presented a very high concentration of alkalinity, because the geological formation such as carbonate in the study area and the direct leakage of hydrocarbons has permeated the soil, eventually seeping into the groundwater ,This phenomenon may be attributed to the fact that elevated levels of calcium and bicarbonate in alkalinity can lead to an increase in TDS and electrical conductivity. This is due to the fact that these ions have a significant role in influencing the TDS values(WHO, 2004) .This observation aligns with the results presented by (Bilbas, 2004). The findings of the present study closely align with the results reported by Al-Barwary et al. (2018) in their study on well and spring samples collected from Soran District, located in the Northern Erbil Governorate-Iraq with concentrations ranged from 369. 9 to 395.6 mg/L.

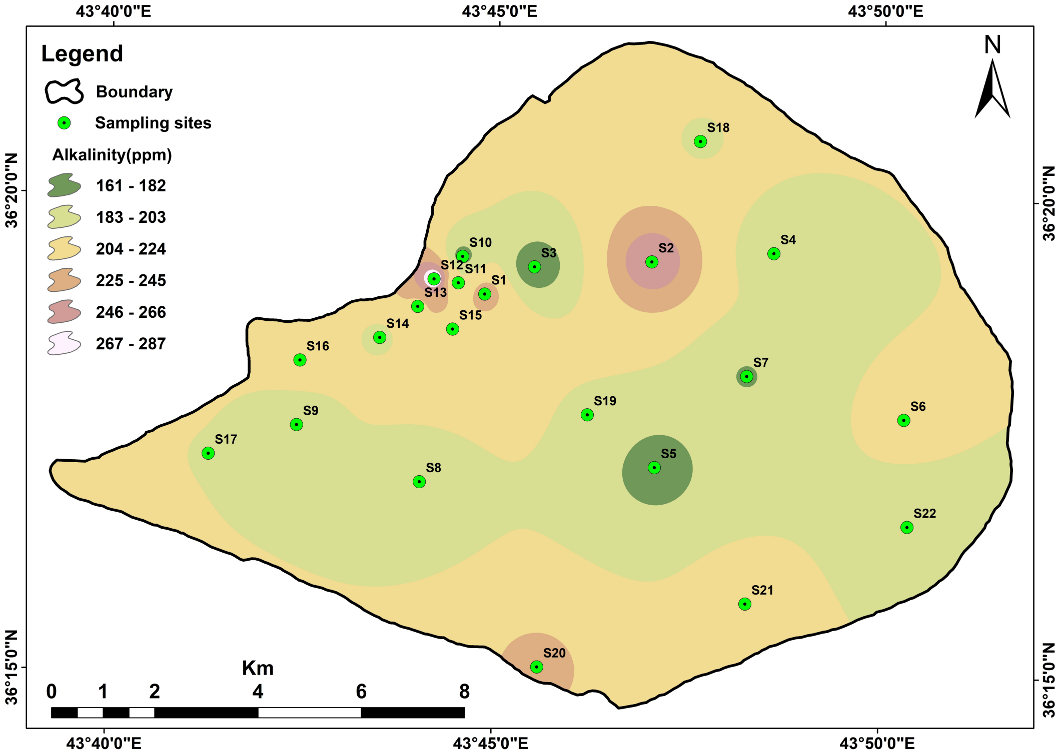


Figure 5.10. Interpolation Map Shows Alkalinity Levels in The Studied Sampling Sites

5.2.6. Sulphate (SO_4^{-2})

Sulphate is naturally present in groundwater under various mineral compositions, such as Barite ($BaSO_4$), Epsomite ($MgSO_4 . 7H_2O$), and Gypsum ($CaSO_4 . 2H_2O$) (WHO, 1996). However, the current study did not show significant health-based effects for sulphate according to WHO guideline and Iraqi guideline. However, due to the gastrointestinal effects caused by consuming drinking water with high sulphate levels, it is recommended that sulphate concentrations should not exceed 500 mg/L according to the (WHO, 2004). Similarly, the USEPA (2004) and Iraqi guideline (2001) stated that the allowable concentrations should not exceed 250 mg/L. The mean value of sulphate 26.05 and standard deviation of ±15.576 were reported in. Sulphate concentrations are relatively greater in sites S1, S12, and S13 if compared to other sites in the study area). Therefore, all sites examined were deemed suitable for drinking purpose. Results were agreed with results obtained by El Baba et al. (2020) in in the Dier al-Balah Governorate, Gaza Strip, Palestine with levels of 65 to 554 mg/L and Hui et al. (2020) in Hailun, China with values of 0.21 to 448.97 mg/L; moreover results were not agreed with that obtained by Al-Shammary and Al-Mayyahi (2021) in Ali Al-Gharbi District, Iraq with values of 379.5 to 934.3 mg/L, moreover its came in agreement with results of Al-Tameemi et al. (2020) in Kirkuk Governorate-Iraq with levels ranged from 23 to 1210 mg/L, moreover its came in agreement with results obtained by Al-Barwary et al. (2018) in water well and natural spring samples selected from Soran District, Northern of Erbil Governorate–Iraq with concentrations of 61.4 to 70.2 mg/L. Figure 5.11 shows the sulphate level in the study region.

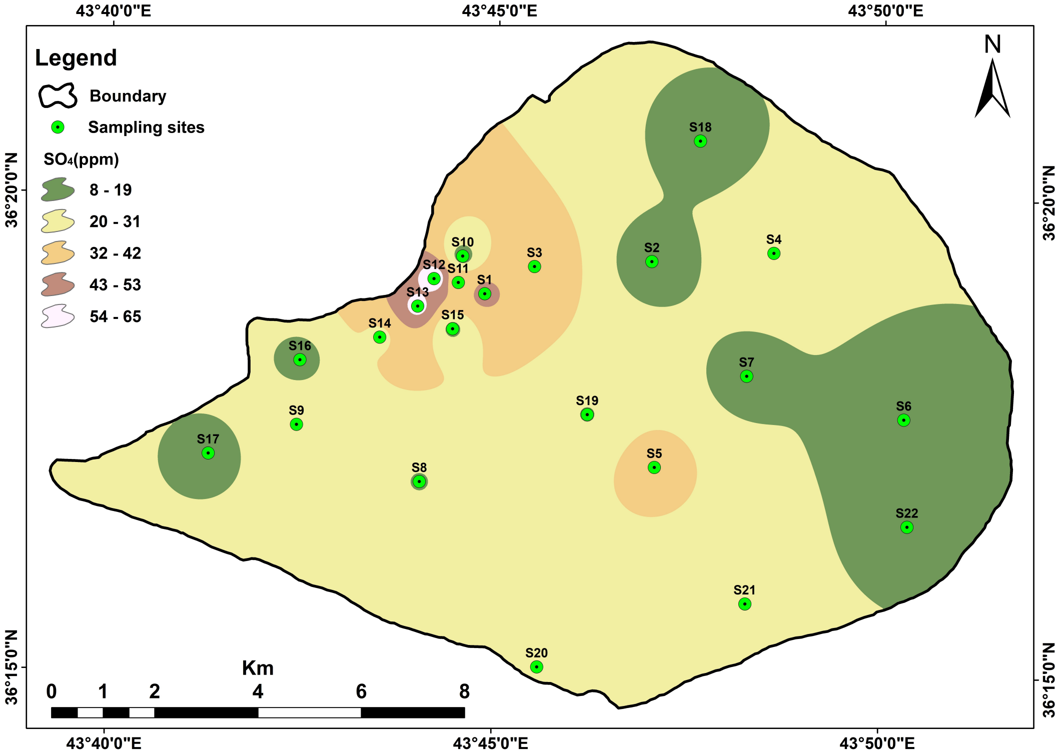


Figure 5.11. Interpolation Map Shows Sulphate Levels in The Studied Sampling Sites

5.2.7. Chloride (Cl^-)

Chloride anions are commonly found in natural aquatic environments. In accordance with the Iraqi Guideline (2001), the maximum permissible concentration of chlorides in drinking water is 250 mg/l. Therefore, the study focused on 22 wells that exhibited satisfactory chloride concentrations (Figure 5.12). The concentration of chloride ions in studied water wells exhibited an average value of 22.68 mg/L, accompanied by a mean standard deviation of ± 9.20. However, observed concentrations of chloride were varied between 8.0 to 46 mg/L. The lowest recorded chloride value was observed at S20, whilst the highest recorded chloride value observed at S13. Also, none of them surpassing the permissible levels of chloride. The findings of the present study exhibited a lower magnitude compared to the results reported by Al-Shammary and Al-Mayyahi (2021) in the Ali Al-Gharbi District of Iraq with values ranged from 128.7 to 962.2 mg/L, owing to inherent disparities. The study conducted by Abdel et al. (2018) focused on the geological formation and findings in the shallow groundwater of El-Obour city, Egypt with chloride levels of 26 to 4579.3 mg/L. The findings of present study were lower than results reported by Al-Barwary et al. (2018) in their study on well and spring samples collected from Soran District, Northern Erbil Governorate-Iraq with concentrations ranged from 79.8 to 102.5 mg/L, with the exception of one sampling site. Additionally, results of this study were lower than those reported by Al-Tameemi et al. (2020) in their study conducted in Kirkuk Governorate-Iraq with levels fluctuated from 12 to 430 mg/L.

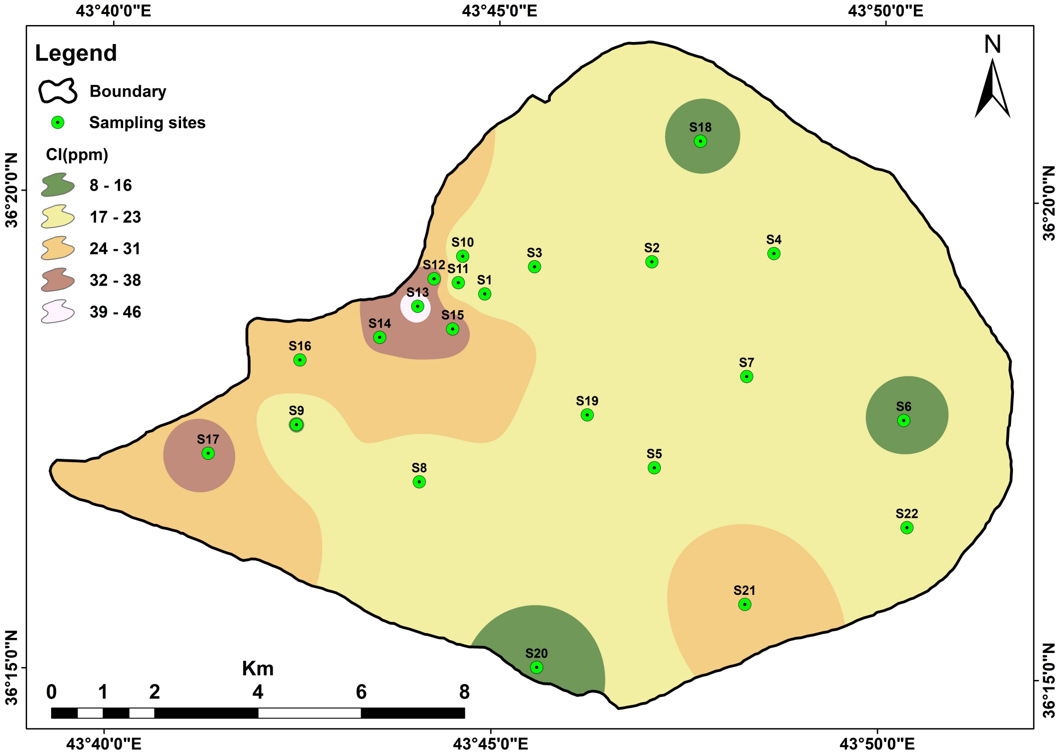


Figure 5.12. Interpolation Map Shows Chloride Levels in The Studied Sampling Sites

5.2.8. Nitrate (NO_3^-)

The Iraqi drinking water standards 2001 and the World Health Organization's guidelines from 2004 proposed that the maximum allowable level of nitrate in drinking water should not exceed 50 mg/L as Nitrate (10µg-at. N-NO_3/L as Nitrogen-Nitrate). Consequently, the majority of water wells examined have nitrate levels that fall within the permissible range, with the exception of wells S1, S5, and S19 close to the Erbil Refinery, which were deemed unsuitable for drinking purposes due to that the black water originating from household waste in Tobzawa camp has infiltrated the ground, ultimately reaching the groundwater. This infiltration has led to significant contamination of the groundwater, posing risks to water quality and public health. The polluted water is now unsuitable for consumption, agriculture, and other uses, as it may contain harmful pathogens and pollutants. If left untreated, this contamination can lead to long-term environmental damage and further compromise the safety of local water resources. The aforementioned phenomena have been documented by Chnaray (2003) in the groundwater systems of Erbil province and Nolan (2001) in the water systems of United States. The potential correlation between the elevated nitrate concentration and its proximity to the Jadeda collection is worth considering in addition to facilities at Erbil refinery. Several researchers in different places reached similar conclusions, including Hassan (1998) in Erbil city. The current findings are consistent with the results reported by Othman and Ibrahim (2021) in the Erbil region with levels of 10.2 and 101 mg/L. The results obtained in the present study were found to be greater than those obtained by Al-Shammary and Al-Mayyahi (2021) in the Ali Al-Gharbi District of Iraq with values of 0.05 to 29.1 mg/L and lower than results obtained by Hui et al. (2020) with values of 0.0 to 497.84 mg/L, while aligned with the findings of Al-Tameemi et al. (2020) in the Kirkuk Governorate of Iraq with concentrations ranged from 3.3 to 155 mg/L. Figure 5.13 shows the nitrate level in the study region.

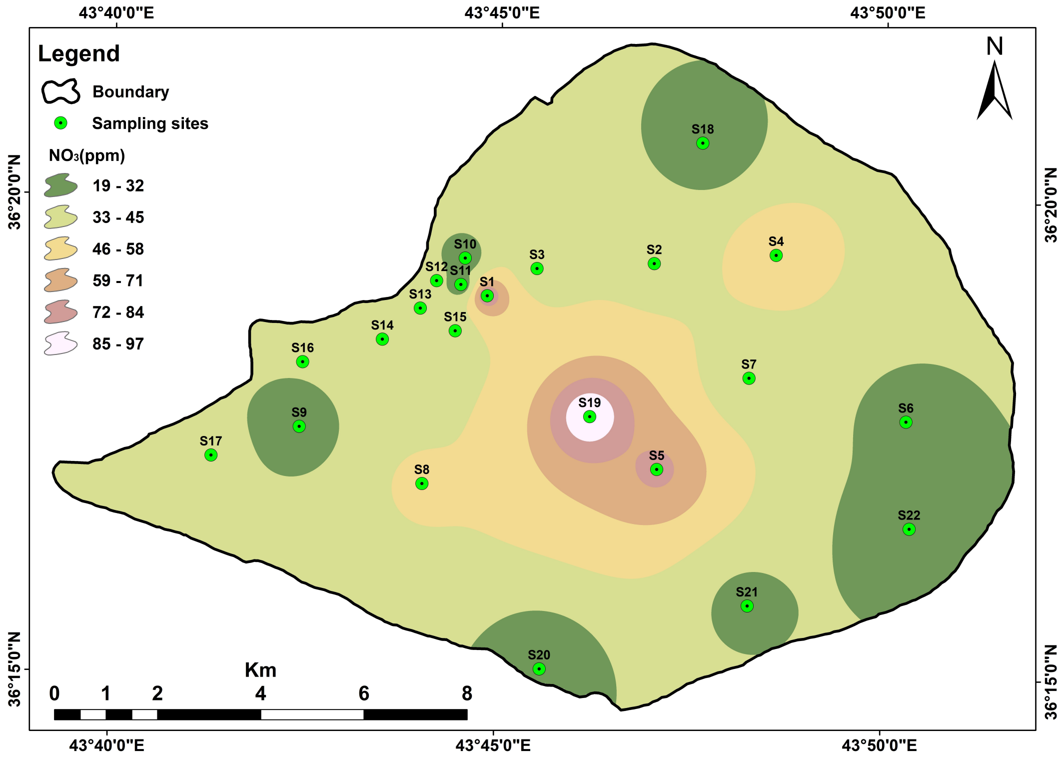


Figure 5.13. Interpolation Map Shows Nitrate Levels in The Studied Sampling Sites

5.2.9. Fluoride (F^-)

Fluoride levels in S19 were greater than other sites due to effect of village untreated wastewater and the leaching of fluoride-rich minerals such as apatite, fluorspar, fluorapatite, and biotite from the research area's main rocks, which included charnockite, calc, and granulite gneiss (Srinivasamoorthy et al., 2008). Also, the impact of dilution was clearly seen during POM. NO_3 levels were greater during POM (136 mg/L) and in predominantly agricultural regions, perhaps due to leaching from plant nutrients and nitrate fertilizers (Freeze & Cherry, 1979). Results of current study were less than that obtained by Mustafa et al. (2023) in Zagros Basin of Iraq with values ranged from 0.01 to 2.1 mg/L and of Al-Gadi et al. (2023) studied groundwater of Nineveh Governorate, Iraq with levels ranged from 0.158 to 2.179 mg/L. (Figure 5.14) shows the Fluoride level in the study region.

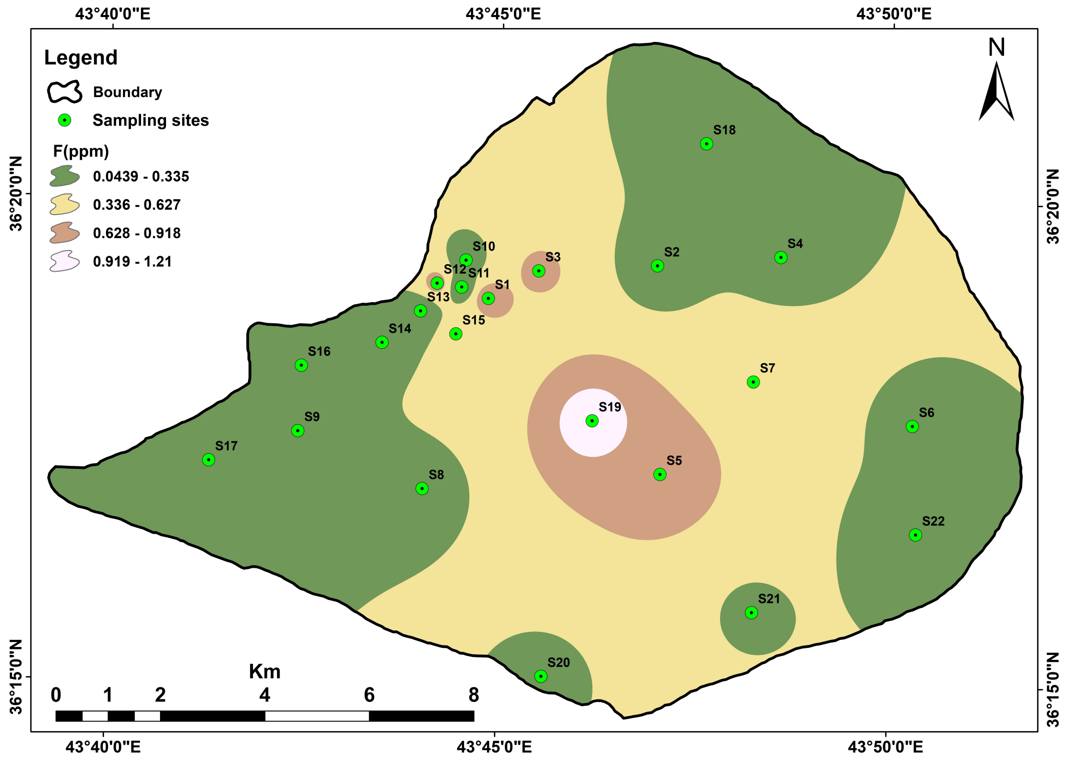


Figure 5.14. Interpolation Map Shows Fluoride Levels in The Studied Sampling Sites

5.3. Biological Parameters

5.3.1. Total Coliform Bacteria

The Coliform Bacteria content in current study ranged from <2.2 to 16 CFU/100ml. The phrase "total coliform" encompasses a broad assemblage of Gram-negative, rod-shaped bacteria that exhibit several shared traits. The findings of the present study were consistent with the results reported by Al-Tameemi et al. (2020) specifically in Kirkuk Governorate, Iraq with values ranged from 0.0 to 540 MPN/100ml. Escherichia coli is commonly selected as a primary organism for monitoring programs, as stated by the World Health Organization in 2004. Addisie (2022) achieved same outcomes in the highlands of Ethiopia. Coliforms are commonly associated with disease outbreaks caused by inadequate water quality, including diarrhoea, cholera, typhoid, and other illnesses. According to WHO (2019), around 485,000 individuals suffer from diarrhoea due to the inadequate water quality.

5.3.2. Escherichia coli

The Coliform Bacteria content in current study ranged from <2.2 to 16 CFU/100ml Escherichia coli is commonly selected as a primary organism for monitoring programs. It is widely regarded as the most appropriate indicator of fecal contamination, as stated by the World Health Organization in 2004 (WHO, 2004). Addisie (2022) achieved same outcomes in the highlands of Ethiopia. Coliforms are commonly associated with disease outbreaks caused by inadequate water quality, including diarrhea, cholera, typhoid, and other illnesses. According to WHO (2019), around 485,000 individuals suffer from diarrhea due to the inadequate water quality.

5.4. Heavy Metal Parameters

5.4.1. Cadmium (Cd)

The findings of current study indicated that the cadmium levels were below the detection threshold of IQS 2001 which are <0.0004 ppm. Cadmium is present in several substances such as soils, rocks, coal, and mineral fertilizers (Weast, 1989). According to Berglund et al. (1994), the consumption of water represents a relatively insignificant means of human exposure to cadmium. The cadmium concentration in the water wells under study is unlikely to have any adverse health impacts. Therefore, this water is considered safe for consumption, as recommended by the (USEPA, 2005). The present investigation demonstrates that the concentration of cadmium in the drinking water from water wells is within acceptable limits and does not exceed the detection threshold. This finding aligns with the results reported by

Muhammad (2004) in Sulaymaniyah spring with values fluctuated from 0.09 to 3.40 mg/L.

5.4.2. Arsenic (As)

Arsenic is present in all soils and rocks and these compounds are solid substances that have the ability to dissolve in water without undergoing evaporation or removal from the surrounding environment (Weast, 1989). The majority of sampling sites were found to be safe and within the boundaries specified by the Iraqi Guideline 2001 except S1, S11, and S12 have a high value due to the direct leakage of hydrocarbons has permeated the soil, eventually seeping into the groundwater (Figure 5.15) shows the Arsenic level in the study region.

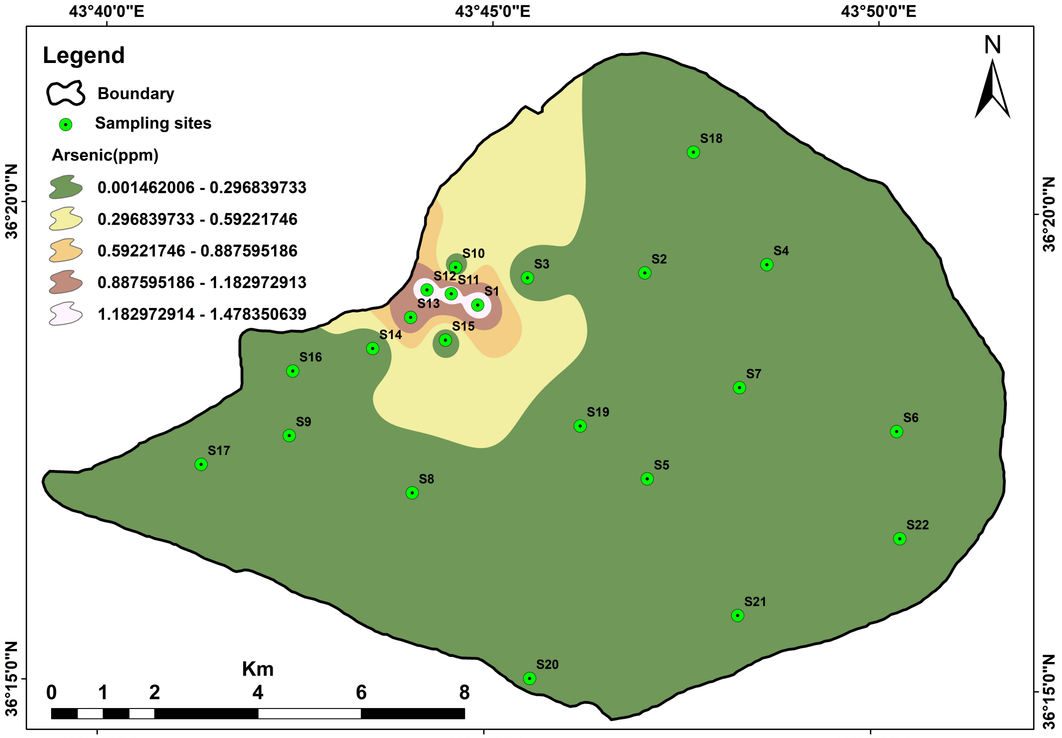


Figure 5.15. Interpolation Map Shows Arsenic Heavy Metal Levels in The Studied Sampling Sites

5.4.3. Copper (Cu)

The current analysis demonstrates that the copper content varied from a high value of 0.6269 mg/L at S17 to a minimum value of 0.0089 mg/L at S9. The High value of copper due to the variability of copper concentration in drinking water is influenced by factors such as pH levels, mineral content (hardness), and the availability of copper within the distribution system. The most common reason for copper pollution is the corrosion of copper pipes. Also, discharge of untreated waste water from illegal refinery effected the copper pollution. Studies conducted in the United States, Europe, and Canada have shown that copper concentrations in drinking water can vary from less than 0.005 to over 30 mg/L. The copper concentration in the current study falls within the acceptable range recommended by the Iraqi Standard (2001), USEPA (2003b), and Granholm (2006) for drinking water. Therefore, it does not have any adverse impacts on human health. Figure 5.16 shows copper heavy metal levels in the study region.

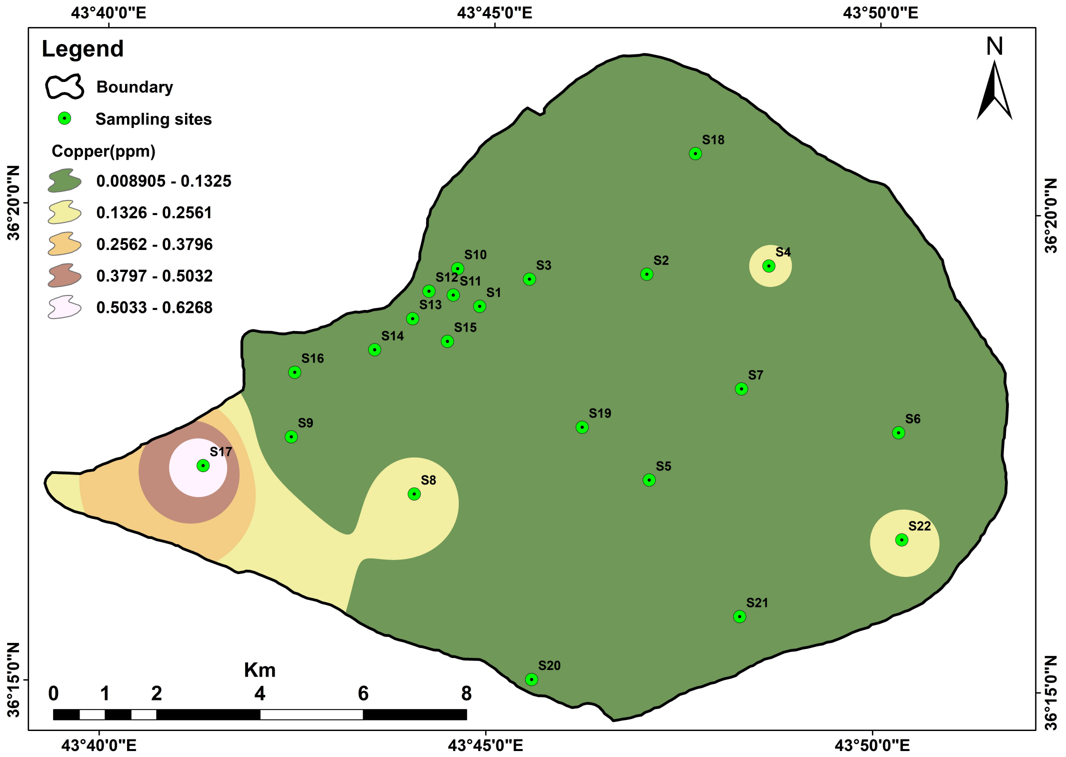


Figure 5.16. Interpolation Map Shows Copper Heavy Metal Levels in The Studied Sampling Sites

5.4.4. Chromium (Cr)

The findings of the present investigation indicate that the maximum recorded chromium concentration was 0.088 mg/L, whereas the minimum recorded value of Cr in S1,S15 was 0.0010 mg/L. According to Colter and Mahler (2006), the high value of Cr in S14 might be attributed to either natural geological processes or the corrosion of pipes. The chromium concentration in the current study falls within the acceptable range recommended by the Iraqi Standard (2001), USEPA (2003b), and Granholm (2006)for drinking water. Therefore, it does not have any adverse impacts on human health. The findings align with the results reported by Hui et al. (2020) in

Hailun, China with levels ranged from 0.0 to 0.08388 mg/L. Figure 5.17 interprets Chromium heavy metal levels in the study region.

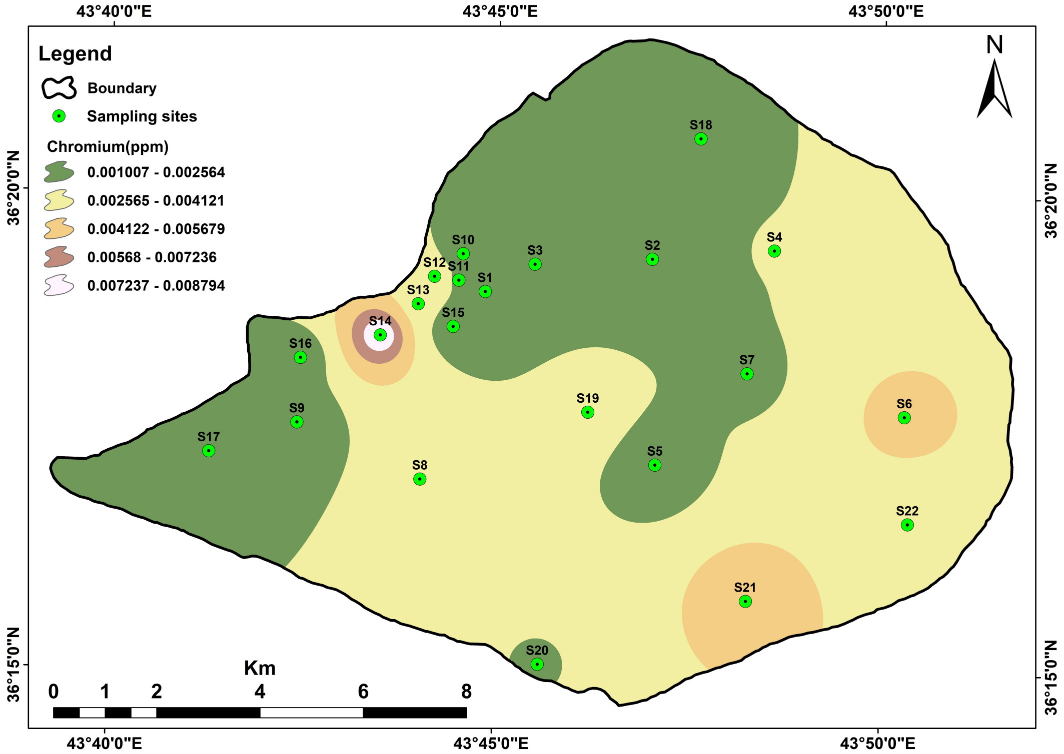


Figure 5.17. Interpolation Map Shows Chromium Heavy Metal Levels in The Studied Sampling Sites

5.4.5. Zinc (Zn)

The Zinc concentration in ground water systems typically falls within the range of 10 to 40 mg/L. The concentration of zinc in tap water can be significantly elevated due to the leaching of zinc from pipelines, fittings, or the erosion of natural deposits (WHO, 2004). These values fall within the normal range for zinc concentrations in drinking water, with the exception of S16, which surpassed the Iraqi Guideline 2001 (3 ppm), as supported by the Environmental Protection Agency USEPA (2003a) and Anton et al. (2008). Figure 5.18 shows Zinc heavy metal levels in the study region.

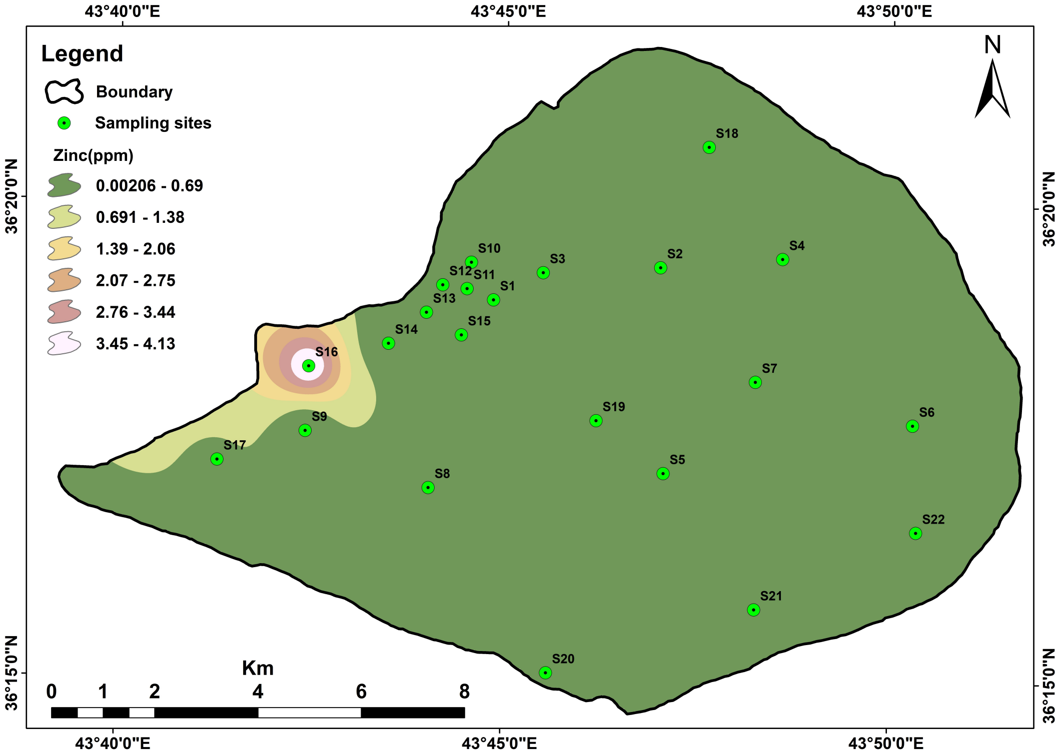


Figure 5.18. Interpolation Map Shows Zinc Heavy Metal Levels in The Studied Sampling Sites

5.4.6. Lead (Pb)

The high lead concentration was recorded at sampling site S1 and S13 which are located inside the boundary of Refinery. The observed variations in results may not be attributed to precipitation, but rather to the geological formation of water wells and the other effective factor was direct leakage of hydrocarbons has permeated the soil, eventually seeping into the groundwater (Ahmed, 2003; Bartram, 2002). The findings were consistent with the results reported by Hui et al. (2020) in Hailun, China with levels of 0.0 to 0.08388 mg/L.The current investigation demonstrated that the content of lead exceeded the established Iraqi criteria (3 mg/L) that might potentially be found in the potable water. Figure 5.19 shows Lead heavy metal levels in the study region.

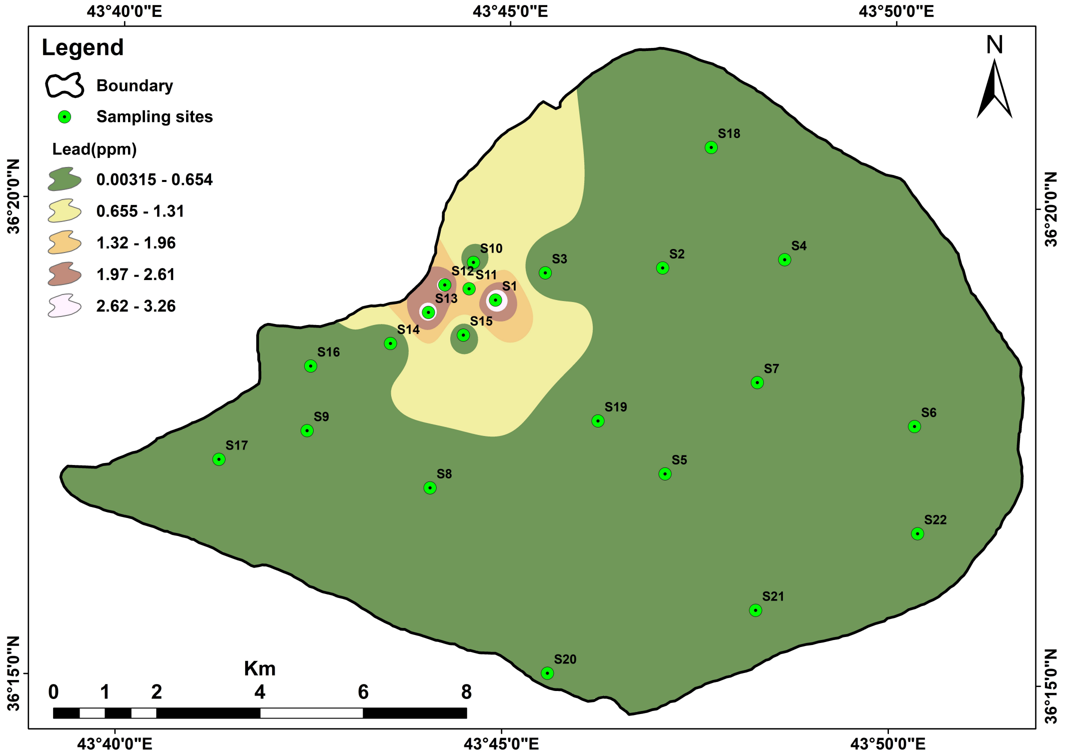


Figure 5.19. Interpolation Map Shows Lead Heavy Metal Levels in The Studied Sampling Sites

5.4.7. Other Heavy Metals

Elevated concentrations in aerobic waters are commonly linked to the presence of industrial pollutants. In acidic water, the reducing condition in groundwater and certain reservoirs may lead to elevated levels of conductivity, reaching up to 1.3 mg/L (Dowdeswell, 1984). Several locations in current study including S2, S3, S4, S5, S6, S7, S8, S9, surpassed the Iraqi (2001) Standard due to direct leakage of hydrocarbons has permeated the soil, eventually seeping into the groundwater. In Germany, the manganese content in the drinking water provided to 90% of households was found to be below 0.02 mg/L. AL-Saddi (2006) and Motavalli and Miles (2002) have provided evidence indicating that manganese is a naturally occurring metal that is present in various rock formations. The findings of present study do not align with the findings reported by Addisie (2022) with a manganese concentration of 0.2 to 5.3 mg/L.

5.5. Total Petroleum Hydrocarbons (TPH)

In the majority of the samples gathered, TPH results for all sampling sites were below the maximum levels allowed by Iraqi standard 2001 and were deemed safe for consumption, moreover no values of TPH has been identified to be more than Iraqi guideline 2001. As a result, all samples of water were deemed to be safe.

5.6. Canadian Water Quality Index

The average CWQI values indicated a fair level of water quality across all sampling sites throughout the study period. Throughout the study period, the water quality at the Erbil Refinery generally fell within the range of "Poor to good" for groundwater systems from S1 to S22, with a CWQI range of 42.39 - 92.14. The results from the CWQI analysis indicate that the water quality in areas with a distance away from the Erbil Refinery, as well as in collectives and villages such as S5, S6, 7, S20, S21, S18, and S2, was found to be satisfactory and good (Figure 5.20). The degradation of water quality has been seen at various sites in close proximity to the Erbil Refinery, including S1 (Inside the Refinery boundary), S14, and S16, as well as in areas near settlements such as S4 and S8. The observed phenomenon could potentially be attributed to the escalating contamination of untreated water sources, including urban trash, precipitation, and human-induced activities and might be the refinery effect (Olowe et al., 2016; Ramakrishnaiah et al., 2009). There are still certain places, namely S2, S3, and S15, that have a favorable water quality index and are in close proximity to facilities. The findings of the present study are consistent with the results reported by Ibe et al. (2019) in their Study on the Assessment of Water Quality Index for Groundwater Systems in Ado Ekiti, Nigeria. The decrease in the Water Quality Index (WQI) may be attributed to the impact of aridity in the region during the previous year(Abbasi & Abbasi, 2012). The findings of the present study are consistent with the results reported by Addisie (2022) in Palestine and Hui et al. (2020) in Hailun, China.

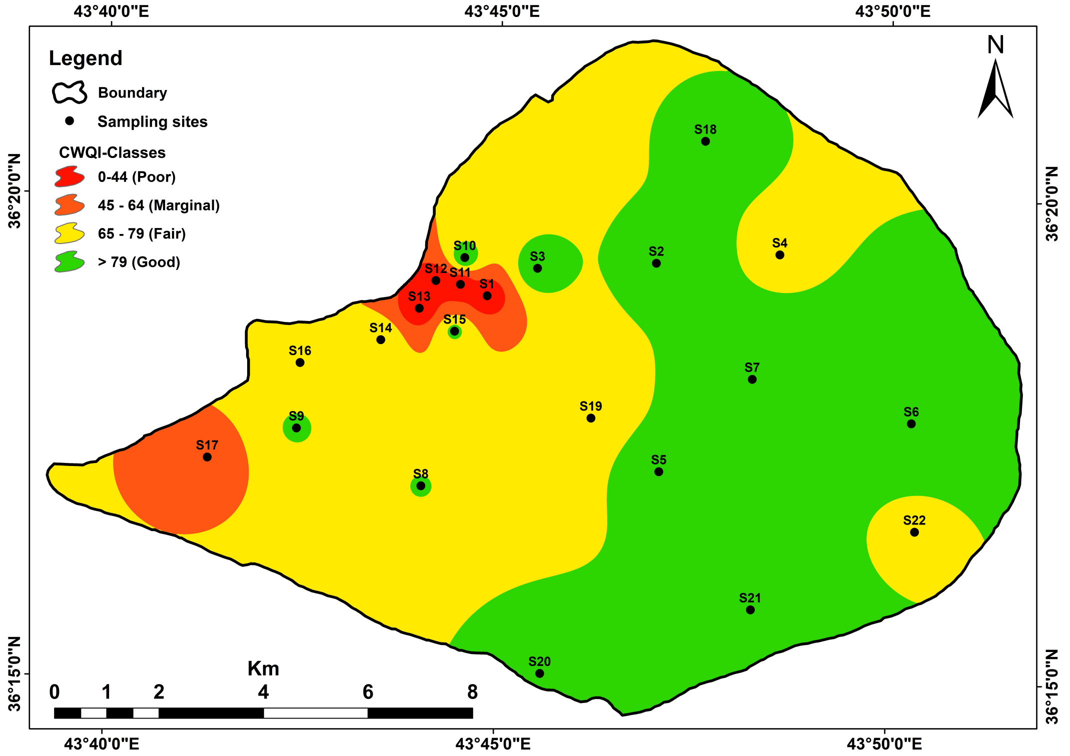


Figure 5.20. Interpolation Map Shows WQI Categories in The Studied Sampling Sites

5.7. Mechanism Controlling Groundwater Quality

Most surface waters, groundwater may have a wide range of Na/ (Na + Ca) ratios (from 0.2 to 0.6) at moderate levels of total dissolved solids (TDS) and we demonstrate the extensive variation in groundwater chemistry (Qi and Harris, 2017). If carbonate minerals are predominant, the chemistry of groundwater is likely to be influenced towards lower Na/ (Na + Ca) ratios. In some silicate-dominated regions, the Na/ (Na + Ca) ratios may be greater, as observed by Banks and Frengstad (2006). The well water examined samples are classified by Gibbs (1970) as belonging to the "Rock dominant mechanism" from carbonate lithology and formations.

5.8. Groundwater Classification

The piper (1944) diagram used to assess the quality of groundwater and surface water. All samples were placed in area F (Calcium type), according to the cation trilinear findings, with the exception of S1, S11, S12 and S13, which were dispersed in region area B (Sodium and Potassium). Similarly. area (Bicarbonate type) showed the distribution of all anions. In the research region, every groundwater sample contains the (Ca-Mg--bicarbonate water type), only S1 is mixed type (Ca-Mg--bicarbonate type and NA-K-- bicarbonate type),(Figure 5.21). The Schoeller graph indicates that all variables in the analyzed area have the same direction and are driven by lactogenic causes. Additionally, most stream water samples in the research region contain the type F6 the type B6 is seen in S1,S11,S12 and S13, (Figure 5.22). Results of current study concomitant with results of Al-Aboodi (2008) in ground water of Buhairat Al-Najaf area in Iraq in which sulfate are sulfate sodium and sulfate calcium too. Results of this study agree with results of Berhe et al. (2015) in groundwater of Kütahya plain of Turkey in which Five hydro chemical facies have been identified based on the major ion chemistry of the surface and groundwater of this area. However, based on hydro chemical facies in this area of Turkey, the type of water that predominates in the study area is Ca-Mg/Mg-Ca- HCO_3 type during both December 2013 and June 2014.

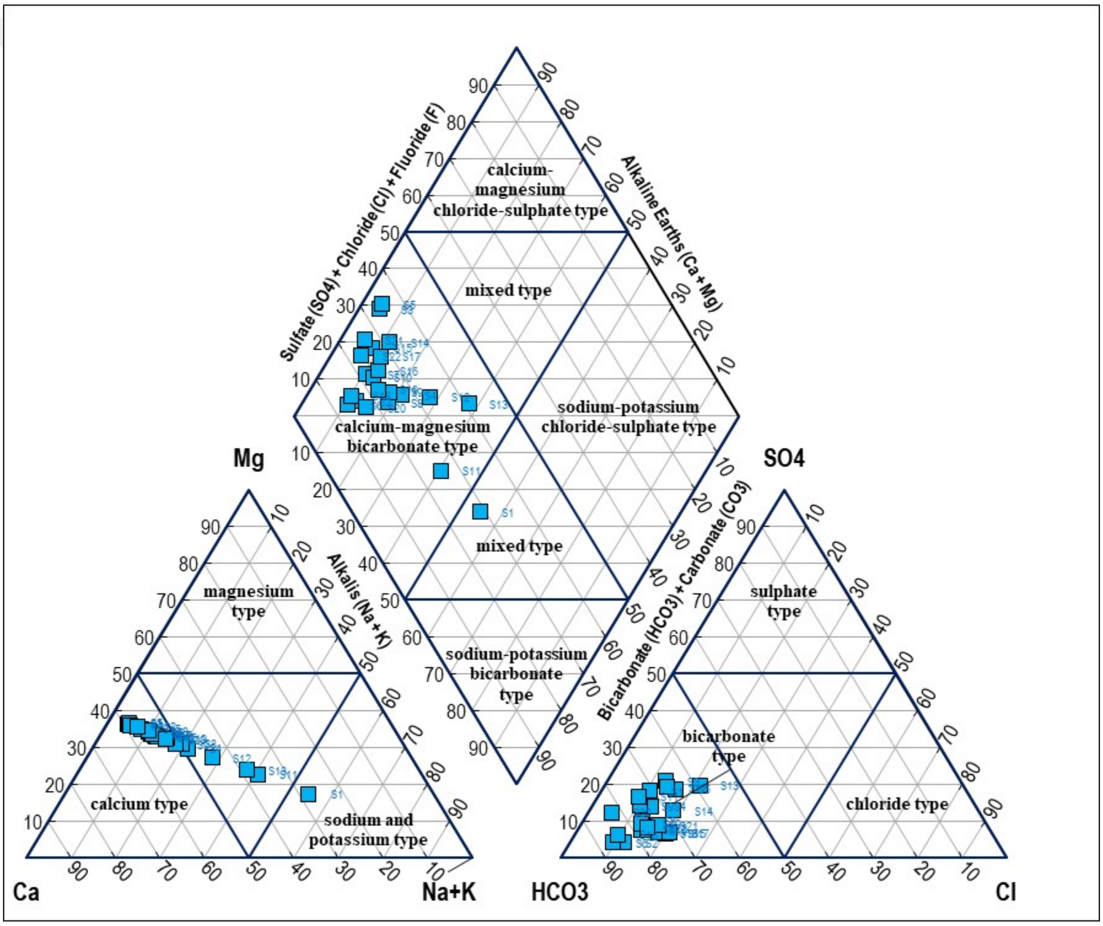


Figure 5.21. Piper Classification of Water Type in Study Region

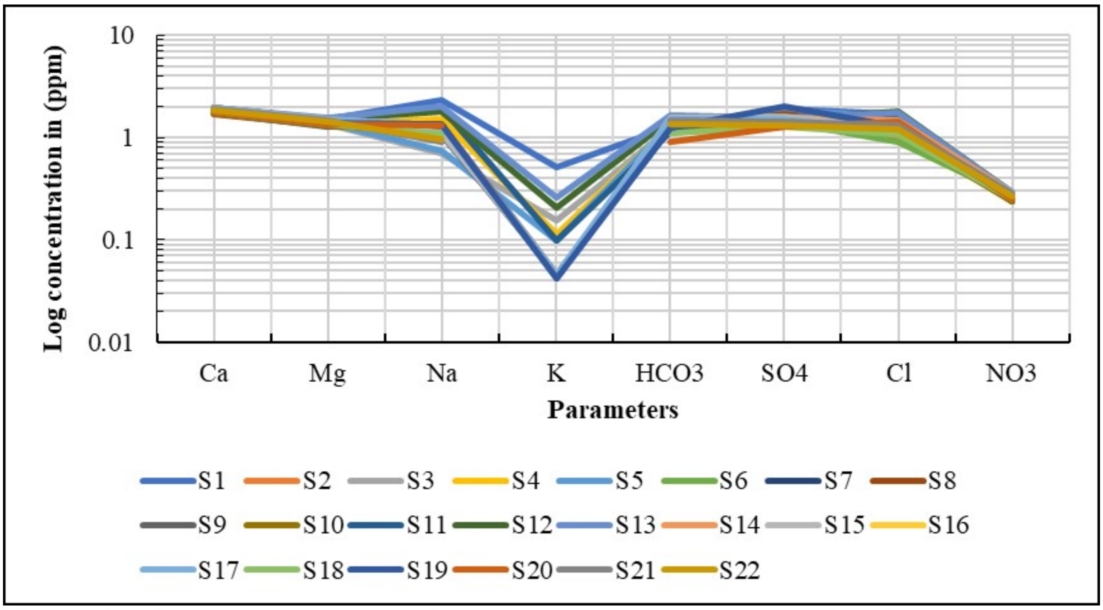


Figure 5.22. Scholler Classification of Water Type in Study Region

6. CONCLUSION

This study provided a spatially explicit assessment of groundwater quality around the Erbil Oil Refinery through extensive field sampling, standard laboratory analyses, and GIS-based spatial modeling. The results demonstrated that the aquifer system is predominantly characterized by a Ca–Mg–HCO_3 hydrochemical facies, reflecting the influence of carbonate-dominated lithology and water–rock interactions, with a mixed facies observed in certain locations near the refinery. The CWQI values ranged from approximately 42.4 to 92.1, indicating conditions from “poor” to “good.” Sites located farther from the refinery, such as S5, S6, S7, S18, S20, S21, and S2, generally scored in the good category, whereas locations within or close to the facility, such as S1, S14, and S16, as well as nearby settlements like S4 and S8, showed lower quality scores. These findings point to a groundwater system that remains broadly suitable for drinking purposes but with clear, localized vulnerabilities.

Across most locations, general water quality parameters including pH, EC, TDS, alkalinity, total hardness, and major ion concentrations fell within both Iraqi and international standards, with pH values showing slight alkalinity likely linked to geological conditions. Turbidity levels were typically low, although a few sites, notably S12, exhibited elevated readings possibly associated with hydrocarbon-related particulates. Chloride and sulfate concentrations were consistent with natural geogenic sources, though slightly elevated near industrial zones. Nitrate levels displayed greater variability, with several shallow wells, particularly S19, exceeding the WHO limit of 50 mg/L, suggesting anthropogenic influences such as agricultural runoff and septic leakage. Biological analyses revealed the intermittent presence of total coliform bacteria, indicating potential microbial contamination risks. Heavy metal concentrations were generally low, though arsenic levels were locally elevated at sites close to the refinery, possibly due to geochemical mobilization or industrial inputs.Overall, the combination of hydrochemical, spatial, and microbiological evidence suggests that while the groundwater is generally safe, targeted interventions are necessary to address specific contamination hotspots and prevent further degradation.

7. RECOMMENDATIONS

In order to guarantee the provision of safe and clean drinking water to the residents living in close proximity to the Erbil Oil Refinery, a variety of measures are recommended to address concerns regarding groundwater quality. It is essential to monitor and test groundwater sources, especially well water, regularly. It is recommended to conduct these tests at least four times a year in order to monitor for bacteriological contaminants and other physical and chemical parameters, such as heavy metals, hydrocarbons, nitrates, and pollutants associated with oil refining activities. This routine testing will guarantee the prompt detection of any contamination and aid in addressing pollution concerns before they pose significant health hazards.

In addition to testing, it is essential to diversify the water sources available to the local population. Reducing the dependence on potentially contaminated groundwater by enhancing the existing surface water delivery systems, such as utilizing water from the Greater Zab River, would provide safer alternatives for drinking water. This requires investments in infrastructure improvements such as pipelines and advanced filtration systems, which will ensure that the community has a reliable and safe water supply.

For wells that have already been polluted, immediate action is necessary. Contaminated wells should be modified or replaced using advanced well-building techniques that provide better protection against future pollution. This includes ensuring proper sealing, lining, and placement of wells away from industrial activities. Additionally, implementing standard water treatment techniques, such as chlorination for all drinking water wells, can help to disinfect the water. In cases where contamination levels are higher, boiling the water before consumption is recommended as an added precaution to ensure its safety.

Furthermore, it is imperative to enhance the prevailing water treatment systems. Many chlorine flashers, which are responsible for mixing chlorine with water to disinfect it, are outdated and frequently experience maintenance issues. It is imperative to conduct regular maintenance and promptly replace parts for these systems in order to safeguard their efficacy in purifying water.

Local planning and development agencies ought to adopt a proactive approach in taking into account the entire spectrum of land use activities surrounding the refinery and their potential implications on groundwater quality. It is imperative that appropriate zoning and land-use regulations are strictly enforced in order to safeguard future contamination from industrial, agricultural, or residential activities. Lastly, it is highly recommended that you establish a dedicated water research facility at or near the Erbil Oil Refinery. A such facility would be responsible for planning, monitoring, and conserving water resources in the region, providing essential data to inform future policies and ensure the long-term protection of water quality in the area.

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