A MODIFIED ANALYTICAL HIERARCHY PROCESS METHOD TO SELECT SITES FOR GROUNDWATER RECHARGE IN JORDAN

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ABSTRACT

The aim of this study was to identify potential sites for groundwater recharge in the Azraq basin in Jordan. Several research questions were answered in this study including how to utilize the views and opinions of multiple experts in the field of groundwater recharge within a spatial analysis framework to identify the suitable sites for groundwater recharge in the study area and check the consistency in these opinions and their spatial representation.

The Analytic Hierarchy Process (AHP) was modified in a novel approach to identify the potential sites for the groundwater recharge in the study area. First, the physical criteria that affect the groundwater recharge were identified based on an extensive literature review. Seventeen experts were then asked to evaluate the importance of each criterion. The consistency ratio between the experts opinions were evaluated using the pairwise comparison method and a final weight was computed for each criterion. A groundwater recharge suitability map was then generated following the weighted linear combination (WLC) method. The sites that are not suitable for groundwater recharge within the study area were identified and eliminated following the Boolean method, and a final groundwater recharge suitability map was generated. The outcome of the GIS analysis of this study was evaluated against field investigations carried out in the study area. Time Domain Electromagnetic (TDEM) and Soil Texture Analysis were used on sixteen locations distributed in eight sites within the study area.

The results acquired by the field investigation agreed well with the GIS acquired results. The knowledge generated by this analysis may provide information on potential recharge zones. Finally, the findings of this research can be used to assist in the efficient planning of the groundwater management to ensure a sustainable development of the groundwater in Jordan and in other areas suffering from water shortages.

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1 Introduction

The analysis of spatial data sets within a Geographical Information System are often used to address environmental issues that are driven by a number of social, economic and physical factors. Arguably, there is no greater issue that the provision of safe, clean water that can be used for consumption or for the irrigation of crops. However, water use needs to be monitored and moderated. Over extraction of particularly ground water resources need to be determined so that mitigation measures can be put in place. As water sitting under the ground is spatially distributed and extraction takes place at certain points, we can resolve issues regarding ground water recharge by utilising methods of spatial data analysis. In this thesis, a novel spatial data analysis approach to determine where siting of groundwater recharging facilities are best located will be presented.

This study is undertaken within the framework of an Analytic Hierarchy Process (AHP) as a multi-criteria evaluation approach by integrating it with the Geographic Information System (GIS). The analytical hierarchy process (AHP) is one of the multi-criteria decision-analysis (MCDA) tools developed by Saaty (1980). AHP is used to calculate the weights based on Expert opinions, a novel approach. Computed composite weights are inserted into the spatial analysis functions of GIS to produce the final map. Hence, based on the analysis and findings that are made in this research, finding suitable sites for groundwater recharge using the sites selection model. It is hoped that the results can be useful in the planning and sustainability of groundwater resources and future planning for groundwater recharge in the Azraq basin of Jordan by the Jordanian Government.

Specifically, this research presents a new method of determining relative weights to the selection criteria based on individual expert opinion and confirming the consistency ratio of the mean, the median and the mode of individual opinion weights to an overall weight for each criterion. Field investigation methods were used to verify the results of the spatial analysis.

In this chapter the motivation and context of the study is presented. focuses on the groundwater resources in Jordan, the focus being on the groundwater recharge for supplying drinking and irrigation water. This chapter is split into five sections. The first section gives a general overview of the conducted research. The second section reviews the global water resources, the water resources in the arid and the semi-arid countries, highlighting the water resources in Jordan. It also inspects the available surface, groundwater and water resources of the study area. The third section focuses on the description of the problem of water resources in the study area (the Azraq basin). The fourth section demonstrates the aim and objectives of this research, and the last section illustrates the structure of this thesis.

1.1 The Availability of Water

Since the beginning of the human settlement, major civilizations were mainly scattered around the banks of rivers and around the shores of lakes. This indicates that water was the major factor in the initiation of these civilisations (Al-Ayash and Al-Adamat, 2012). Human history can be written in terms of the interaction with water, which has been considered throughout time as a natural resource critical to human survival (Biswas, 1997). Water is a very important requirement for humans. It is required for home consumption, agriculture, industry and energy generation (Biswas, 1997). There is about $1{,}360\times10^{6}$ km^3 of water available on Earth, of which more than 97% is in the oceans. The remaining water (around 37×10^{6} km^3) is fresh (Biswas, 1997).The majority of this fresh water is of little use because it is located in icecaps and glaciers (Biswas, 1997). The development of the world economy has put increasing pressure on global water resources due to the growth of the industrial, the expansion of the irrigated areas, and the water consumption of heat power-engineering (Shiklomanov, 1999). While much of the world's irrigation water is fed from rivers, lakes, and reservoirs, an increasing proportion is now pumped from the groundwater (Biswas, 1997).

In many countries and regions of the world, water resources are being depleted (Heathcote, 1983). It is, therefore, almost impossible to meet the ever-increasing water demands of the growing population worldwide. Water is particularly important in the arid and the semi-arid regions of the world because it is such an important resource (Allison et al., 1998). Africa, the Middle East and South Asia are the three areas of the world that suffer from a severe water shortage: These regions, together with parts of Australia, the southern part of North America and limited areas of South America form the arid and the semi-arid areas of the world (Clarke, 1991).

Water scarcity has traditionally restricted the development of Countries as their development relies on sufficient, reliable and lasting water supplies in terms of quantity and quality (Dottridge *et al*., 1998, Heathcote, 1983). Thousands of years ago, water management received much emphasis in major civilisations developed in countries such as Egypt, and India (arid and semi-arid) .This indicates the importance of this resource in the development of nations in such regions (Biswas, 1997). Surface waters in the arid lands can be subdivided into permanent and temporary supplies. Permanent provisions include major rivers like the Yellow river in China and the river Nile in Egypt and Sudan. The temporary supplies include the precipitation (rain and snow). The concentration of these inputs into surface watercourses or groundwater recharge provides an important temporary resource of water (Heathcote, 1983).

In the Middle East, water resources are limited and are currently decreasing, while demand for water is increasing to support the industrial, the agricultural, and the population growth (Baban and Al-Ansari, 2001). Population growth in the Middle East, combined with the economic development, have exhausted usable water resources in the last 30 to 40 years (Baban and Al-Ansari, 2001). In several countries, water scarcity, aggravated by declining water quality and the lack of efficient water management, has become a major problem (Van-Tuijl, 1993). Over the past three decades, all Middle Eastern and North African countries have rapidly depleted their groundwater resources, which might eventually lead to a limited food supply as the ability to produce enough food for their population is disturbed (Seckler *et al*., 1999).

Groundwater is a major source of water supply throughout the world. It comprises about two thirds of the world's fresh water (Chapman, 1996). It is a major source for irrigation, industry and municipalities (Todd, 1980). The use of groundwater has gradually increased due to the growth of the worlds' population and increased demand of water and rapid industrialisation (Ahn and Chon, 1999). Groundwater resources in the arid lands can be separated into living and archaic waters, depending upon whether the aquifer is being actively recharged. Living aquifers are constantly recharged from the surface and their waters have a recent age. Archaic aquifers, on the other hand, are formed thousands of years ago and have no current recharge (Heathcote, 1983).

1.2 Water Resources Issues in Jordan

Jordan is a developing country located to the east of the Mediterranean Sea between the longitudes 35° and 39° east and the latitudes 29° and 33° north. Jordan is bordered by Syria on the North, Saudi Arabia on the South, Iraq and Saudi Arabia on the East, and Palestine and Israel on the West (Figure 1.1).

Jordan's total area is about 90,000 km^2. It is located in an arid to a semi-arid region where about 90% of its land receives an average precipitation of less than 100 mm/year, and only 3% of its land receives an average annual precipitation of 300 mm (Tarawneh *et al*., 2008). This area consists of a variety of characteristic topographic units such as the high lands, the rift valley and the arid lands desert area. The annual population growth rate in Jordan is estimated to be about 2.8% and is expected to be around 10 million by 2020 (Nortcliff *et al*., 2008). This will increase the pressure on the existing water resources in the country, and significantly decrease the average ability to 90 $m^3 capita^{-1} year^{-1}$ by 2025 (Al-Adamat *et al*., 2010).

Figure 1.1. The location of Jordan in the Middle East, adapted from Nation Map (2004)

Water resources are gradually becoming scarce in Jordan. This is mainly due to the increase of population and urbanisation, which imposes excessive pressure on these resources. The challenge in the next decades is to ensure an increase in food production for the survival of the growing population. This will impose more pressure on water resources, which may result in water quality degradation, particularly in countries with scarce water resources such as the Hashemite Kingdom of Jordan. Groundwater recharge is an important policy in the developing countries, which aims to increase the available resources of water in order to assist in tackling water shortage and help preventing water quality degradation. This emphasises the significance of selecting appropriate sites for current and future groundwater recharge.

Jordan can be classified as a semi-desert area. It is considered to be one of the poorest countries in the region in terms of water resources (Al-Ansari and Baban, 2001).The limited amounts of rainfall and, therefore, the limited water surface and groundwater resources have resulted in the naturally imposed semi-aridity nature of Jordan (Salameh, 2001). The aridity of the country combined with the population growth, which is due to the high birth rate or due to the influx of refugees, has imposed increasing pressure on the water resources in Jordan (Al-Adamat *et al.*, 2010, and Salameh and Bannayan, 1993). Figure 1.2 shows that a Jordanian citizen uses, on average, about 150 m^3 $year^{-1}$ of water, whereas a global citizen average consumption of water is about 1000 m^3 $year^{-1}$ (Jordan Ministry of Water and Irrigation, 2011). In summary, water consumption strategies under an increasing population needs to be carefully planned.

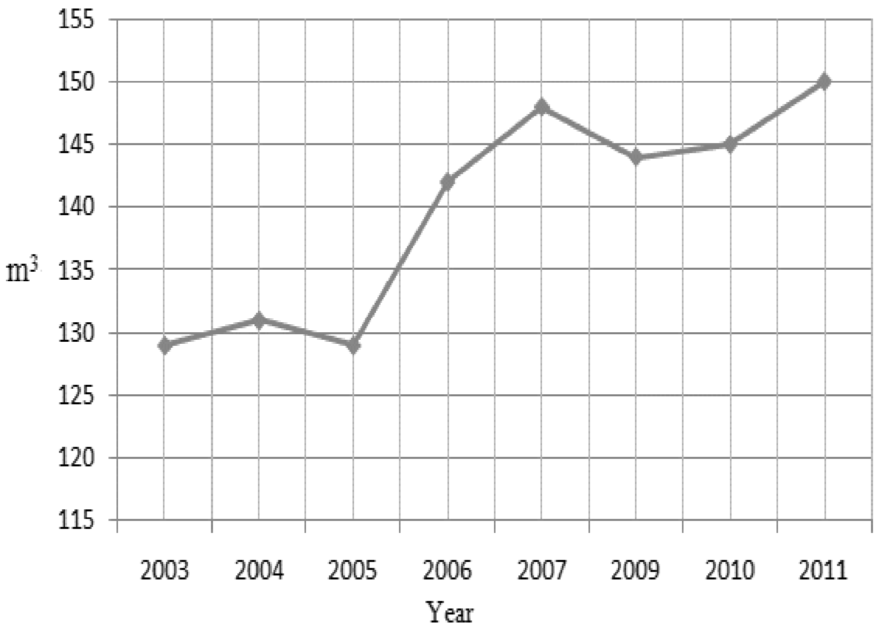


Figure 1.2. Average consumption of water of an individual in Jordan between 2003 and 2011. Adapted from Jordan Ministry of Water and Irrigation (2011)

1.3 Groundwater in Jordan

Groundwater has been considered the main water supply in many areas and the only source of water in some other areas in Jordan. Jordanian groundwater resources are found in twelve basins as shown in Figure 1.3. These basins vary by area and importance in terms of the amount of annual recharge, storage, water quality, and safe yield (Salameh and Bannayan, 1993). Groundwater resources are presently exploited at maximum capacity and in some cases is exploited beyond the safe yield. The safe yield in the Azraq Basin was estimated by the Jordanian Ministry of Water and Irrigation based on the annual rainfall, the evaporation rates, and the runoff volume measured at various Wadies in the Basin. Groundwater can be divided into two types as shown in Table 1.1 being renewable and non-renewable groundwater resources (Salameh and Bannayan, 1993).

Table 1.1. Groundwater basins in Jordan and their estimated safe yields. Adapted from Jordan Ministry of Water and Irrigation (2011)

No	Groundwater Basin	Safe yield (m^3 x10^6)
	Renewable Groundwater resources	
1	Amman – Zarqa	87.5
2	Azraq	24
3	Yarmouk	40
4	Jordan River Side Wadis (North Jordan Valley basin inallison *et al*., 1998)	15
5	Jordan Valley	21
6	Dead Sea (Mujib in Allison *et al*., 1998)	57
7	North Wadi Araba	3.5
8	South Wadi Araba	5.5
9	Sirhan	5
10	Hammad	8
	Non-Renewable Groundwater resources	
1	Jafer	18
2	Disi Mudawwara	125
Total (non-renewable groundwater)		143
Total (renewable groundwater)		266.5
Total		409.5

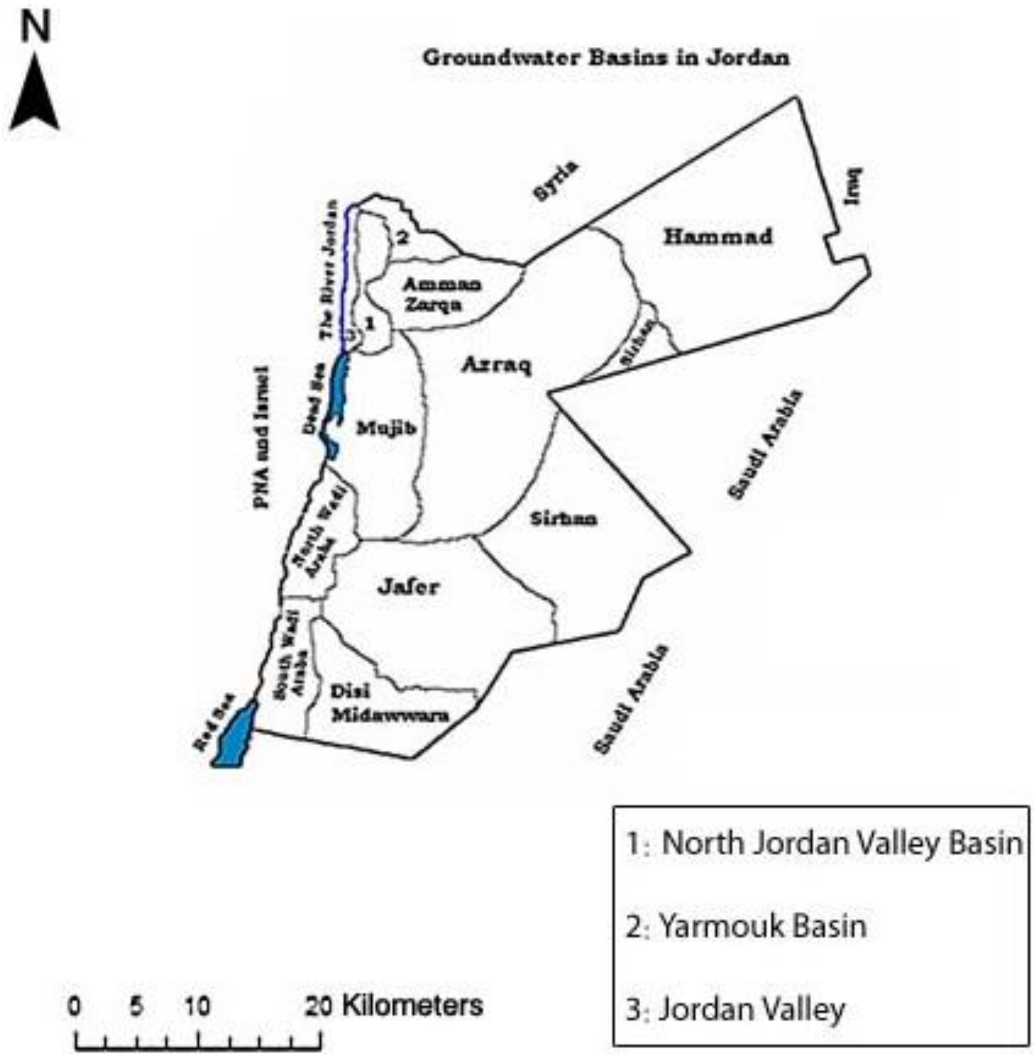


Figure 1.3. Groundwater basins in Jordan. Adapted from Allison *et al*. (1998), Salameh and Bannayan (1993), and USGS (2000)

Critical to this study is that natural or artificial recharging of the water tables is considered an efficient ways to combat the deficit in groundwater resources (Reid and Dreiss, 1990). The importance of the groundwater recharge within the study area comes from the following rationale:

- The groundwater is an important and major source of water in this region, and thus, determining potential sites for groundwater recharge is important. We cannot see the groundwater directly, rather have evidence of levels from point measurements coming from deep wells.

- It is important to consider avenues for enhancing groundwater recharge. The groundwater recharge will minimise the impact of evaporation and will eventually lead to increase the available water resources.
- Artificial recharge takes place at certain locations that maximise the opportunity to recharge and minimise waste. Optimisation of these locations is a spatial problem.
- The study area is characterised by flash floods that generate large quantities of runoff water in a short period. Such quantities are generally lost due to high evaporation rates in the area. Identifying water collection zones in relation to recharge zones is of great importance.
- There is a range of local opinion on the strategies to mitigate future water shortages.

1.4 Aim of the Study

The aim of this research is to identify potential sites for groundwater recharge in an aquifer in Jordan using an adapted AHP method that utilises the opinions of local experts. The knowledge generated by this analysis may provide information on potential recharge zones.

1.5 Thesis Structure

The research is presented in the following chapters.

Chapter 2 focuses on understanding relevant concepts of AHP and MCDA from an extensive review of the literature. The research questions are presented in this chapter.

Chapter 3 describes the study area and the data collection process.

Chapter 4 focuses on the selection criteria, development and pairwise comparison of primary data collected from experts.

Chapter 5 focuses on the data analysis and techniques applied to identify the groundwater recharge sites.

Chapter 6 focuses on the validation of results derived in Chapter 5.

Chapter 7 provides the conclusions, and the recommendations extracted from the outcomes of this research.

2 LITERATURE REVIEW

It is necessary to evaluate existing approaches and methods when addressing the aim of this piece of research. In the first section, we resolve the groundwater recharge issues into a spatial problem that can be tackled with methods of spatial analysis. The second section focuses on spatial mapping approaches that can be explored and developed to define the suitable sites of the groundwater recharge. The third section considers the spatial factors that determine groundwater recharge potential. Section four summarises the literature and presents a justification for the approach taken and where the original contribution of this study is contained. The final section sets out the spatial analysis problem that is addressed in this thesis as a set of research questions and further describes the objectives that will need to be answered if the aim of the study is to be met.

2.1 Groundwater Recharge Resolved as a Spatial Problem

Bear (1979) defined the groundwater as all the water found beneath the surface of the ground. However, the groundwater hydrologist is primarily concerned with the water within the zone of saturation and uses the term groundwater to denote the water in this zone. In agronomy, the term groundwater is sometimes used to denote the water above the water table in the unsaturated layers. Porosity and permeability of the aquifer are factors that affect the existence of groundwater. The porosity of the aquifer is defined as those portions of a soil or rock that are not occupied by solid material and can be occupied by groundwater. The permeability, on the other hand, is a measure of the contained interstices or voids. The permeability is expressed as the ratio of the volume of voids or interstices to the total volume (Todd, 1980). A rock that has one or two open cracks but no voids may have a low porosity and may be poor at storing water. However, as water may pass easily through the cracks, the permeability may be high (Price, 1996). Thus, there is no correlation between the porosity of the material and its permeability. Some rocks might be porous but impermeable, either because the pores are so small, water cannot pass through without difficulty, or because the pores are not connected (Price, 1996). Aquifers can be classified into two types, confined or unconfined aquifers. Confined aquifers are bounded on their upper surface by an aquitard, which is a less permeable formation that transmits water more slowly than the aquifer. Unconfined aquifers, on the other hand, are the aquifers that have the water table as their upper boundaries (Bear, 1979, Gorelick *et al*., 1993, Ward and Robinson., 2000). Therefore, Aquifers may be considered to be 3-D polygons where their attributes can be modified by a number of factors.

Osborn and Cook (1997) stated that the groundwater recharge is the quantity of water passing into the aquifer through the unsaturated zone during a specific period. There are several sources of groundwater recharge. A representative list of such sources include precipitation, lakes and stream flow, excess irrigation, reservoirs, seepage from canals, and water that is deliberately introduced into the ground. Recharge sources have been classified as direct recharge from percolation of precipitation and indirect recharge from runoff ponds. Direct recharge is a direct vertical percolation of precipitation through the unsaturated zone to the saturated zone. Indirect recharge, on the other hand, is a percolation of the runoff and localisation in joints by means of ponds in low-lying areas and lakes to the water table (Sophocleous. 2004).

Groundwater flow pattern is regulated by the distribution of the hydraulic conductivity of the rocks and the arrangement of the water table. The water table is, in turn, influenced by the topography and is regulated by the climate of the time. Thus, flow pattern of groundwater is a function of the topography, the geology, and the climate (Gupta, 1997). The factors that control groundwater recharge are:

- The topography: areas with a low slope have a greater opportunity for recharge than those with a high slope.
- Soil permeability: Soil with high level of permeability has a greater opportunity for water to infiltrate into its saturated zone.
- Rainfall: areas that receive more rainfall potentially have more opportunity for recharge than those with low rainfall. (Piscopo, 2001, Scanlon *et al*., 2002, and Sophocleous, 2004).

Artificial recharge is the process through which excess surface water moves by non-natural systems from the surface of the earth to the underground aquifer to be stored for future use (NRC, 1993). Artificial groundwater recharge can be used for a number of reasons including:

- The use of aquifers for storing and distributing water.

- The removal of the contaminants that occurs as a polluted rain (Spandre, 2009).
- Emergency storage or strategic water reserve.
- Enhancement of well field production.
- Restoration of groundwater levels.
- The improvement of the groundwater quality to the agricultural or the municipal standards (Raju *et al*., 1994).

It appears that responsible recharge strategies can be developed at certain locations that are favourable to maximise the recharge potential. These locations are point sources that need to take into account the absolute and relative importance of a number of factors. Those factors may have spatial dimensions or be of a single dimension. In the next section, existing spatial mapping tools and methods are presented.

2.2 Spatial Analysis Tools to Address Groundwater Recharge Issues

The use of Geographical Information System (GIS) technology has a wide range of applications such as agriculture, land use planning, municipal applications, and global scale applications (Ahn and Chon, 1999) as well as the modelling and the management of the natural environment. According to Mitasova and Mitas (2002), for a time efficient and cost-effective analysis, GIS are best suited for dealing with a widespread range of criteria data from various sources. The use of GIS for environmental modelling has increased over the last few years, shifting from research to routine applications. A number of spatial-based multi-criteria evaluation methods were applied in a GIS environment (Boroushaki and Malczewski, 2008, Carver, 1991, Chen *et al*., 2008, Chen *et al*., 2010, Jankowski, 1995, Malczewski, 1999). The combination of GIS functions and map algebra operations facilitates the use of simple models within GIS.

GIS has been used in many parts of water resource management (Merchant, 1994, Tkach and Simonovic, 1997, Wang *et al*., 2011), land use and catchment planning (Burrough. 1986, Chen *et al*., 2008, Chen *et al*.,2011, Dai *et al*., 2001, Giap *et al*., 2003, Yu *et al*., 2011,Zerger *et al*., 2011), and land suitability assessment (Bojorquez-Tapia *et al*., 2001, Chen *et al*., 2009,Joerin*et al*., 2001, Malczewski. 2004, Malczewski, 2006, Pereira and Duckstein, 1993, Yu *et al*., 2011b).GIS is a tool that reduces the time required and the cost of selecting sites and providing a digital data bank for future monitoring programs of the selected sites (Malczewski, 2004). It has been widely used for site selection in many applications including dumpsites, water harvesting schemes, and infrastructure (Al-Adamat *et al*., 2010, Al-Adamat, 2008, Baban and Wan-Yusof, 2003, El-Awar *et al*., 2000, Gupta *et al*., 1997, Shatnawi, 2006, Srivastava, 1996).

The use of GIS for identifying the optimum sites for groundwater recharge projects have been addressed in many studies (Anbazhagan*et al*., 2005, Balachandar *et al*., 2010, Bhattacharya, 2010, Chenin and Ben Mammou, 2010, Chenini *et al*., 2010, Chowdhury *et al*., 2010, Ghayoumian *et al*., 2005, Ghayoumian *et al*., 2007, Juaidi., 2008, Machiwal *et al*., 2011, Mahdavi *et al*., 2010, Naseri *et al*., 2009, Rahman *et al*., 2012, Riad *et al*., 2011, Saraf and Choudhury. 1998, Sargaonkar *et al*., 2011, Scanlon *et al*., 2002, Shaban *et al*., 2006, Shankar and Mohan, 2005, Shirahatti *et al*. 2010, Srivastava and Bhattacharya., 2006, Tweed *et al*., 2007). In this chapter, a number of these studies will be discussed in more detail.

In the process of selecting sites within the GIS environment, decision rules are used for the combination of a group of criteria maps according to some preferences with respect to the evaluation criteria. This advancement in GIS has made it possible for several research projects to identify the optimum sites for groundwater recharge (Al-Adamat *et al*., 2010). There is a relationship between groundwater recharge and groundwater vulnerability. If there were a potential site for recharge, this would mean that this area has a high vulnerability. Therefore, the groundwater vulnerability maps can be used as an indication of groundwater recharge. Chenini and Ben Mammou (2010) implemented an approach coupling GIS techniques and the numerical hydrogeological modelling for the demarcation of suitable sites for the artificial recharge of groundwater aquifers. A Hydrogeological Information System was used to prepare thematic maps and to integrate these layers. GIS-based hydrological assessments were used to identify potential sites for locating groundwater recharge structures.

Vulnerability maps can be produced with the help of a GIS (Burrough and mcdonnell, 1998). Several methods are used worldwide to assess the groundwater vulnerability including process-based mathematical models, statistical methods and using overlay and indexing methods. Each of these approaches is discussed.

Process-based mathematical models: the process based mathematical models involve the analytical or numerical solutions of mathematical equations, which represent coupled processes governing the contaminant transport (NCB, 2003). These mathematical models include the following methods:

- Indices based on simple transport models.
- Analytical solutions for one-dimensional transport of contaminants through the unsaturated zone.
- Coupled, unsaturated-saturated, multiple phase, two-dimensional or three-dimensional models.

The process-based models have been established and primarily used by research scientists rather than regulators (Almasri, 2007). Many of these methods attempt to predict the contaminant transport in both space and time, which distinguish them from the other methods (NRC, 1993). Evans and Maidment (1995) argued that the fundamental physical principles of the process-based mathematical models can predict the fate and the transport of contaminants from known sources with remarkable accuracy in a localised area by predicting the flow of water in porous media and the behaviour of the chemical constituents carried by that water. Examples of such models include the Pesticide Root Zone Model (PRZM), the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS), and the Leaching Estimation and Chemistry Model (LEACHM). Evans and Maidment (1995) also claimed that although process models are considered to provide the most sophisticated and precise predictions of water quality, they are not broadly utilised for regional groundwater vulnerability investigation. The process-based methods use simulation models to approximate the contaminant migration. However, they are constrained by the lack of data and the computational difficulties (Barbash and Resek, 1996, Rao and Alley, 1993).

Statistical methods: The statistical models are usually used in evaluating, determining, and quantifying the association between measures of vulnerability and various types of information that could be related to vulnerability (NCB. 2003) Statistical methods are flexible since they can deal with qualitative, numerical, or mixed data sets. Examples of statistical methods include simple and multiple regression analysis for single and multiple variables and analysis of variance.

A possible application of the statistical methods in groundwater vulnerability assessments includes the estimation of the possibility that a pollutant will contaminate the underlying aquifers. These methods are based on using the following data:

- The frequency of contaminant occurrence,
- Contaminant concentration or contamination probability as a response variable.

The use of statistical methods is limited by the requirement for high quality data, cost and time constrains (Evans and Maidment, 1995).

Overlay and index methods: The overlay and index methods are used for combining maps of parameters considered to be important in contaminant transport (geology, soil, depth to groundwater table), where each attribute is assigned a numerical score based on its perceived importance (Evans and Maidment., 1995, NRC, 1993). The simplest method is to assign an equal score to each parameter regardless of its importance, while more quantitative methods tend to have different numerical scores and weights for each parameter to indicate the degree to which that parameter might have an influence on groundwater vulnerability in a region (Evans and Maidment, 1995). The overlay and indexing methods primarily rely on qualitative or semi-quantitative compilation and interpretation of mapped data (NRC, 1993).Their major negative aspect is the fact that assigning numerical values to the descriptive entities and relative weights for the different attributes is subjective. The overlay and index methods rely on simple mathematical representations of expert opinion rather than process representation or empirical data.

Examples of the developed overlay and Index methods include the following:

- DRASTIC (Al-Adamat *et al*., 2003, Aller *et al*., 1987, Evans and Mayers, 1990, Fritch *et al*., 2000, Fortin *et al*., 1997, Page, 1993, Piscopo, 2001, Stark *et al*., 1999).
- GOD (Foster, 1987, Gogu*et al*., 2003, Neukum and Hotzl, 2007).
- EPIK (Doerfliger*et al*., 1999, Neukum and Hotzl, 2007, Vias *et al*., 2005).
- AVI (Stempvoort *et al*., 1993).
- SINTACS (Civita and De Maio, 2000, Civita, 1994, Corniello *et al*., 2004).
- PI (Goldscheider *et al*., 2000).
- COP (Daly *et al*., 2002, Goldscheider and Popescu, 2004).

There are several advantages and disadvantages for each method. DRASTIC, EPIK, PI, and COP were designed to be applied to carbonate or karstic aquifers. They provide reasonable results and are highly logical with karstic and hydrogeological features. The

COP appears to be easier to apply and more flexible when considering the role of climatic parameters. The GOD and AVI are useful for mapping large areas with high vulnerability contrasts (Polemio *et al*., 2009).

2.2.1 Utilising Information from Satellite Remote Sensing

Remote sensing is one of the main sources of data for GIS. Satellite data can be defined as a process of gathering data about the surface of the earth and the environment from a distance, usually by aircraft or space sensors (Malczewski, 1999). Remote sensing is defined as a method of collecting information about certain phenomena or objects, without being in contact with these phenomena or objects (Campell, 2002). It can provide objective information without modifying their nature (Baban and Luke, 2001). Remote sensing is capable of providing spatial data that can quantitatively describe an environmental process with some degree of accuracy (Varma, 2002).

There are several benefits of using remotely sensed data including access to free data, the synoptic view, uniformity of the collected information, repetitive and sometimes frequent coverage, and the cost effectiveness (Baban and Luke, 2001). However, the disadvantages of remote sensing data include the need to possibly geometrically and georeferenced data and confusion in spectral signatures that may lead to a classification error. An example of such phenomena is the artificial and the natural grass in green light (Baban and Luke, 2001). Environmental applications could benefit from the integration of GIS and remote sensing (Varma, 2002). Urban, population, precision farming, and agriculture are applications that have benefited from the integration of GIS and remote sensing (Varma, 2002). For about three decades, the application of remote sensing technology in groundwater resources evaluation has been practised. It is the general experience that satellite data must be used in conjunction with the available ancillary information in the application of remote sensing to groundwater hydrology (Meijerink, 2000). Satellite data provide quick and beneficial baseline information about numerous factors that directly or indirectly control the occurrence and movement of groundwater such as geomorphology, soil types, slope, land use/land cover, drainage patterns, lineaments, etc. (Engman and Gurney, 1991, Jha and Peiffer, 2006, Jha *et al*., 2007, Meijerink, 1996, Waters *et al*., 1990). The integration of GIS and remote sensing to study groundwater recharge has been looked at in many research projects. For example, this integration has served in assessing soil and groundwater in Stratum, the Netherlands (Thunnissen *et al*., 1992) and in selecting suitable sites for groundwater recharge in a hard rock area in Pardesh, India (Saraf and Choudhury, 1998). In addition, GIS and remote sensing were used to map a groundwater salinity in alluvial terrain of the Ganges in India (Srivastava, 1996). Even though remote sensing has proved to be a useful tool in providing data for GIS to study various environmental aspects including the groundwater, a number of factors must be considered before using this data in GIS. Among these factors are those summarised by Baban and Luke (2001), which include the spatial resolution, the spectral resolution and the temporal resolution. In summary, satellite data can provide reliable up-to-date information on land cover, land use, geology, vegetation etc. that may be of relevance to a number of important factors.

2.2.2 Multi Criteria Decision Analysis (MCDA)

In a GIS framework, MCDA is used to combine layers of spatial data representing the criteria and to specify how the layers are combined. MCDA was designed in the 1960 to help decision-makers to integrate the numerous choices, reflecting the opinions of the actors involved, into a potential or retrospective framework. MCDA approaches tackle real world problems that are multi-dimensional in nature. Decision-making is a systematic procedure for analysing and choosing between alternatives. The strategy is to split a problem into small parts, analysing each part and aggregating them to achieve a meaningful solution. Geographers are often involved in connecting spatial components with decisions. For this reason, GIS and MCDA complements each other.

The general aim of MCDA tools is to help decision makers in selecting the best feasible option from a set of possible alternatives using user-defined priorities such as the problem definition, the searching for alternatives, the selection criteria, and the selection and the evaluation of the alternatives (Jankowski, 1995). The subdivision structures of decision problems into individual and group decision making applies to two main groups of methods: Multi-Attribute Decision Analysis (MADA) and Multi-Objective Decision Analysis (MODA). If the problem is to assess a limited possible set of alternatives and to choose the best one according to the scores of a set of criteria, it is an MADA problem. MODA deals with the choice of the greatest alternative based on a series of opposing objectives (Malczewski, 1999; Massam, 1988).

Many researchers have found that MCDA provides an effective tool for water management by adding structure, auditability, transparency and rigor to decisions (Dunning *et al*., 2000, Joubert *et al*., 2003). Hajkowicz and Higgins (2008) suggested that as the selection of a MCDA technique is important for water resources management, more emphasis is required on the initial structuring of a decision problem, which involves choosing criteria and decision options. Several methods of MCDA have been implemented in the GIS environment. The following is a general introduction to some these methods

Boolean technique

In this method, the variables are crisp (true or false), and site selection is based on three basic operators as shown in Figure 2.1: Intersection (the logical term AND), Union (the logical term OR) and complement (the logical term NOT). These Boolean operators use integers. Boolean maps are produced with a raster cell value of one for every area that covers the criteria of appropriateness (suitable in all the maps of the area) and zero for all areas that are not considered as appropriate for that particular alternative. This approach then combines all the criteria through one or more logical operators such as intersection (AND) or union (OR). The results are then used to create constraint maps. (Bonham-Carter, 1996, Malczewski, 1999).

AND (A*B)

A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

OR (A+B)

A	B	C
0	0	0
0	1	1
1	0	1
1	1	1

NOT

A	B
0	1
1	0

Figure 2.1. Basic operation of the Boolean technique, adapted from Malczewski (1999)

Thus, the Boolean method is mostly employed as a technique when the parameter maps have been classified into Boolean suitable (Yes) and Boolean unsuitable (No) categories. The use of the Boolean method for site selection for groundwater recharge has taken root over the last twenty-five years or so and many researchers have made progress in developing methods of site selection for groundwater recharge using the Boolean technique as shown in Table 2.1. Most of the studies shown in Table 2.1 used Boolean analysis in a GIS environment. All these studies used the AND (INTERSECTION) operation for selecting site for groundwater recharge with the

Boolean technique to derive the suitability map for the groundwater recharge. This indicates that no weights are assigned to the groundwater recharge that has a major effect on the final suitability results. The following physical factors are used to select the optimum sites for groundwater recharge using the Boolean operation: the slope, the infiltration rate, the depth to the groundwater, the quality of alluvial sediments and the land use. These studies reported that for the "highly suitable" class, all the selected sites for groundwater recharge affecting the suitability should have a value "highly suitable". This means that if one factor was assigned as moderately suitable, the overall suitability will be moderately suitable. In addition, most of these studies showed that the results in the Boolean classification are based upon the rules that are applied to derive the groundwater recharge suitability maps.

Table 2.1. Boolean mapping studies relevant to groundwater recharge applications

Author and date	Country of Application
Al-Adamat *et al*.(2010)	Jordan
Chang *et al*.(2008)	China
Ghayoumian *et al*.(2007)	Iran
Juaidi (2008)	West Bank, Palestine
Madrucci *et al*.(2008)	Brazil.
Shirahatti *et al*.(2010)	India.
Mahdavi *et al*.(2010)	Iran
Anane *et al*.(2008)	Tunisia

Fuzzy logic

Fuzzy logic is used as an alternative to the strict Boolean concepts of (True or False), and it is considered to be a generalisation of the Boolean method. This method has been applied to modelling many processes that are complex and not clear, for example, Fuzzy set theory is an extension of the ordinary (Crisp or Boolean) set theory, which is assigned to each element partial and or multiple membership of the set (i.e. Degree of membership, uncertainty, or truth). This grade can be any real number between 0 and 1, where 0 indicates absence (no membership) and 1 indicates complete membership (Bonham-Carter, 1996, Zadeh, 1965). There are three basic fuzzy operators as shown in Figure 2.2 similar to that of the Boolean operation

- Intersection: MIN. The fuzzy MIN operator determines the degree to which x belongs to both A and B and is equal to the smaller of the individual degree of membership.
- Union: MAX. The fuzzy MAX operator determines the degree of x belonging to either A or B and is equal to the larger of the individual degree of membership.
- Complement: The logical NOT. The fuzzy NOT operator determines the degree to which x does not belong to A, that is, 1 minus the degree to which x belongs to A (Malczewski, 1999).

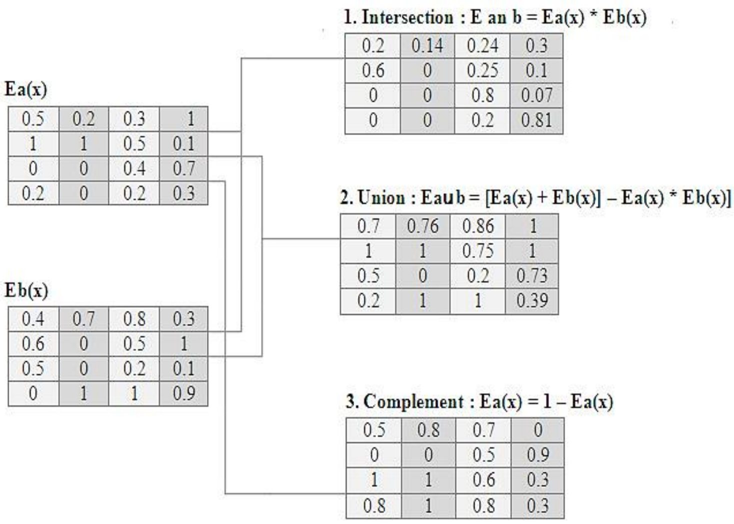


Figure 2.2. Basic operation of the Fuzzy technique, adapted from Malczewski (1999)

Weighted linear combination

The weighted linear combination (WLC) technique is a modification of the index overlay technique. It involves standardisation of the suitability maps because the criteria are measured on different scales. It is necessary that factors be standardised before combination, so that all factor maps are positively correlated with the suitability. Weights are assigned of relative importance to the suitability maps, and then the weights and standardised suitability maps are combined to obtain an overall suitability score. The WLC technique is based on some processes including standardising the suitability maps, assigning weights of relative importance to the suitability maps, combining the weights and the standardised suitability maps and obtaining a suitability score. With WLC, factors are combined by employing a weight to each criteria followed by a summation of the results yielding a suitability map. The total weight of each map of the final integrated layer is computed using the following equation:

$$Si = \sum Wi.Ri \tag{2.1}$$

Where Si is the suitability index, Wi is the weight of the criteria, and Ri is the rating of the criteria.

The use of the WLC method for the selection of potential sites for groundwater recharge has been widely used over the last years. A representative list of such studies is shown in Table 2.2.

Table 2.2. WLC mapping studies relevant to groundwater recharge applications

Author and date	Country of Application
Al-Adamat *et al*.(2010)	Jordan
Ayalew and Yamagishi. (2005)	Japan
Baban and Wan-Yusof. (2003)	India.
Eastman.(2001)	Switzerland
Shatnawi.(2006)	Jordan
Yalcin. (2008)	Turkey
Shirahatti *et al*.(2010)	India.
Rahman *et al*.(2012)	Portugal

Many of the studies shown in Table 2.2 use a WLC method in a GIS environment. They used the following physical factors to select the optimum sites for the groundwater recharge: the geology, the soil, the land use/cover, the water table fluctuation, the depth to the bedrock, the slope, the drainage density, the lineament density and the geo morphology. The generated thematic layers were integrated in order to produce a map depicting the suitable areas for artificial groundwater recharge.

Ordered weighted averaging

Ordered Weighted Averaging (OWA) is an easy and direct method for a combined analysis of multi class maps. OWA analysis involves two sets of weights: criterion, or importance weights and order weights (Saraf and Choudhury, 1998). This method is effective because it allows human judgment to be incorporated into the analysis. The OWA methodology takes into account the relative importance of the parameters and the classes that belong to each parameter. The factors are ranked from low to high order. To control the final result, the decision maker can manipulate the weights. There is no standard scale for a simple OWA method. For this reason, the criteria for the study are defined and each parameter has an assigned importance (Saraf and Choudhury, 1998).

The computation of OWA involves three main steps: defining the order weights, sorting the weighted standardised criteria values of each alternative in descending order, and multiplying the values by corresponding order weights and find the sum to achieve an evaluation score for a given location (Saraf and Choudhury, 1998). To classify OWA operators with respect to their position between AND, and OR, measures of andness, orness, and Trade-Off associated with any set of ordered weights can be introduced (Jiang and Eastman, 2000, Malczewski, 1999, Saraf and Choudhury, 1998, Yager, 1988).

Analytical hierarchy process

The Analytical Hierarchy Process (AHP) is an interactive process where decision-makers confer their preferences to the analyst and who can confer or debate opinions and outcomes individually or as a group (Proctor, 2000). The AHP is based on the assembly of a Pair-Wise Comparison Matrices (PCMs) series, comparing all the criteria to one another. AHP is a method of MCDA that is implemented within GIS, which defines weights for criteria. AHP was initially developed by Saaty (1980). AHP is an effective method for dealing with the framework of the decision making process that allows the decision-makers to know the relationship between the goals, criteria, sub-objectives and alternatives.

AHP has been applied in many environmental applications, for example: choosing a design solution in building construction and ranking priority for maintenance programs (Wong, 1999). AHP was also used in farmland appraisals (Aznar Bellver and Caballermellado, 2005), applications within the natural resources, and environmental management and planning (Chen *et al*., 2001, Chowdhury *et al*., 2009, Eastman., 2003, Jha *et al*., 2010, Kolat *et al*., 2006, Madrucci*et al*., 2008, Mendoza and Martins, 2006, Pereira and Duckstein., 1993, Saaty., 1980, Sipahi and Timor., 2010, Thirumalaivasan *et al*., 2003). In addition, several studies have been carried out for the determination of areas most suitable for artificial recharge using AHP (Anane *et al*., 2008, Han., 2003, Krishnamurthy and Srinivas., 1995, Krishnamurthy *et al*., 1996, Rahman *et al*., 2012, Rolland and Rangarajan, 2013, Saraf and Choudhury, 1998).

The major advantage derived from the application of the AHP method to the site selection process for groundwater recharge is that the AHP allows the decision-makers to know the relationship between the criteria that effect the groundwater recharge. The disadvantage of the use of the AHP, however, is the difficulty of using the AHP method to compare attributes. If too many criteria are used, the pairwise comparisons analysis must be run for a number of times (Malczewski, 1999).

The AHP approach can be used as a set of tools for deriving weights of criteria. The AHP has the ability to deal with inconsistent judgments. (Saaty, 1980, Voogd, 1983, Malczewski, 1999). Table 2.3 shows some of the studies that used the AHP as an MCDA method to select site for groundwater recharge.

Table 2.3. MCDA mapping studies relevant to groundwater recharge applications

Study	Country of Application	MCDA
Rahman *et al*. (2012)	Portugal	AHP, WLC and OWA
Chowdhury *et al*. (2010)	West Bengal	AHP
Sargaonkar *et al*. (2011)	India	AHP
Srivastava and Bhattacharya (2006)	India	AHP
Machiwal and Mal (2001)	India (Rajasthan)	AHP
Anane *et al*. (2008)	Tunisia	AHP and Boolean

As shown in Table 2.3, AHP approach has been widely used for the processes of selecting sites for groundwater recharge. For example, the AHP approach was used by Chowdhury *et al.* (2010), and Srivastava and Bhattacharya (2006) for deriving criteria weights, whilst Rahman *et al.* (2012), Machiwal and Mal. (2001), Anane *et al*. (2008) used an AHP approach to support decision making, incorporating AHP to identify site for groundwater recharge.

2.2.3 Pairwise Comparison Method (PCM)

The multi criteria decision analysis (MCDA) problems involve criteria of varying importance in the opinions of experts. Determining the weights of the selected criteria is a central problem in the MCDA. Weights are used to express the relative importance of the selected criteria in MCDA (Alfares and Duffuaa, 2008, Malczewski, 1999). Thus, information concerning the relative importance of the criteria is necessary, which is to allocate weights to the individual criteria.

The derivation of these weights is, therefore, a crucial step in producing the decision maker’s preferences. A weight can be expressed as a value given to an evaluation criterion that represents its importance compared to other criteria. As the value of the weight increases, the criterions importance in the overall utility also increases. The Pairwise Comparison Matrices PCMs involves comparing all the possible pairs of criteria in order to determine which of all the criteria is of a higher priority. The AHP method is based upon the construction of a series of PCMs, which compare all the criteria to one another. Saaty (1980) suggests a scale from 1 to 9 (Table 2.4) for PCM elements, where the value of 1 indicates that the criteria are equally important and a value of 9 indicates that the criterion under consideration is extremely important compared to the other criteria. PCM includes a consistency check where judgement errors are identified and a consistency ratio is calculated.

Table 2.4. Scales for the pairwise comparisons method, adapted from Saaty (1980)

Intensity of Importance	Definition	Explanation
1	Equal importance in a pair	Two criteria contribute equally to the objective
3	Moderate importance	Judgment and Experience slightly favour one criterion over another
5	Strong importance	Judgment and Experience strongly favour one criterion over another
7	Very strong importance	Judgment and Experience very strongly favour one criterion over another
9	Extreme importance	The evidence favouring one criterion over another is of highest possible validity
2, 4, 6, 8	Intermediate values	When compromise is needed
Reciprocals	Values for inverse comparison	If criterion i had one of the above numbers assigned to it when compared with criterion j , then j has the reciprocal value when compared with i

The main stages to make decisions based on PCMs in the AHP approach are:

- The determination of the important criteria in the problem.
- The assessment of the relative importance of each criterion to each other. This is usually done by experts using a scale from 1 to 9.
- The assessment of the consistency through pairwise comparisons to assign the Consistency Ratio (CR).

According to Malczewski (1999), for a good decision there must be a CR of less than or equal to 0.1. A consistency ratio of 0.1 shows that the comparisons of the criteria are consistent, and the relative weights are appropriate for applying the AHP approach. However, if CR is greater than 0.1, then the experts should revise the pairwise weights.

Constructing the pairwise comparison matrix

This stage is to develop the pairwise comparison matrix by taking relative importance for each element. In this research, this was taken from the experts opinions by using scale range from 1 to 9. Figure 2.3 shows the determination of the criteria weights from experts' opinions. The criteria {C1, C2,.......,Cn} (where n is the number of the compared criteria, n= 9 in this case study), their current weights$[w_1, w_2, \ldots\ldots, w_n]$are extracted fromthe experts opinions [E].The weights are usually normalized to the sum to

1, and the matrix of the ratios of all weights is represented as follows (Malczewski, 1999):

	C_1	C_2	C_3	C_n
E_1	W_{11}	W_{21}	W_{31}	W_n
E_2	W_{12}	W_{22}	W_{32}	W_n
E_m	W_{13}	W_{23}	W_{33}	W_n

Figure 2.3. The structure of the experts' opinions in the matrix

The computation of the criterion weights

This step includes three main operations (Malczewski, 1999, Saaty, 1990):

- The summation of the values in each column of the pairwise comparison matrix.
- The division of each element in the pairwise comparison matrix by its column total.
- The calculation of the average of the elements in each row of the pairwise comparison matrix (normalising inputs).

The estimation of the consistency ratio

This stage involves the following operations (Malczewski., 1999; Saaty., 1990):

- Calculating the priority vector for a criterion.
- Computing λ_{max} (The Principal Eigenvalue).
- Computing the Consistency index (CI).
- Determining the appropriate value of the random consistency ratio (RI)).
- Calculating CR.

The computation of the weighted sum vector is done by multiplying the weight of each criterion by the sum of its associated column of the pairwise comparison matrix,then summing the acquired values of each rows.

The value of λ_{max} is the average number of the consistency vector (Malczewski, 1999; Saaty, 1990). The calculation of λ_{max} is the sum of the consistency vectors divided by the number of the consistency vectors.

$$\lambda_{max} = 1/n\sum_{i=1}^{n}(A.W/W) \qquad (2.2)$$

Where A is known as the judgment matrix and n is the order of the matrix.$A.W$ isthe sum of the weight vectors and the $A.W/W$ isthe consistency vector. The eigenvalue (λ_{max}) must always be greater than or equal to the number of the criteria (n) for a positive value and λ_{max} = n if the pairwise comparison matrix is a consistent matrix. If there is any inconsistency in the experts' opinions, a difference between n and λ_{max} is indicated. Therefore, λ_{max} – n can be classed as a measure of the degree of inconsistency.

The calculation of CI is based on the observation of λ_{max}, as shown in equation 2.3 (Saaty., 1990; Malczewski., 1999):

$$CI = (\lambda_{max} - n)/ (n-1) \qquad (2.3)$$

The random index (RI) is the consistency index of a randomly generated pairwise comparison matrix (Saaty, 1977, Saaty, 1990). RI depends on the number of the criteria being compared as shown in Table 2.5 (Saaty, 1980).

The consistency ratio is given in Equation 2.4:

$$CR = CI/RI \qquad (2.4)$$

Table 2.5. Average random consistency indices (RI) for different number of criteria, adapted from Saaty (1980)

Number of criteria (N)	Random consistency indices (RI)
1	0.0
2	0.0
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.54
13	1.56
14	1.57
15	1.59

2.3 Spatial Factors Influencing Recharge Site Selection

In recent years, many methods have applied to identify sites potential for groundwater recharge reflecting in a large number of studies being published. Table 2.6 shows a summary of a number of these studies that used GIS, integrated with RS and MCDA for the selection of potential sites for groundwater recharge. In their quest to find the optimum sites, a set of weights for the different themes and their individual features were decided based on personal judgments, considering their relative importance for recharge. they applied GIS techniques on various criteria including: the geology, the vadose zone, the rainfall, the soil (hydraulic conductivity/texture/ clay contents), the land use/land cover, the aquifer hydraulic conductivity, the geomorphology, the aquifer media, the lineament density, the static water level, the drainage density, the slope, and the aquifer transitivity.

Table 2.6. Studies that have used GIS integrated with RS and MCDA for selecting suitable sites for groundwater recharge

Study	Methods	Criteria
Al-Adam *et al*. (2012)	GIS, Google Earth	Lineament density, drainage density, slope, land use/land cover
Anane, Makram *et al*. (2008), and	RS, GIS (AHP)	Aquifer depth, geology, soil texture, groundwater salinity, soil salinity, slope
Anbazhagan *et al*. (2005)	GIS, RS	Land use / land cover, geomorphology, Soils, geology, rainfall, hydrogeology, subsurface geology
Balachandar *et al*. (2010)	GIS, RS	Drainage density, Lineament density, geomorphology and land use/ land cover
Chenini and Ben Mammou (2010),	GIS	Drainage density, lithology, lineament density
Chowdhury *et al*. (2010)	GIS, RS, MCDM (AHP)	Geology, geomorphology, drainage density, slope, aquifer transmissivity
Ghayoumian *et al*. (2005)	GIS and DSS	Slope, transmissivity, Infiltration rate, Water table and aquifer thickness
Ghayoumian *et al*. (2007)	RS, GIS (Boolean and Fuzzy logic)	Slope, infiltration rate, depth to groundwater, quality of alluvial sediments and land use
Machiwal *et al*. (2010)	GIS, RS, MCDA (AHP and WLC)	Slope, soil, geology, geomorphology, surface water body, rainfall, groundwater depth
Mahdavi *et al*. (2010)	GIS (Fuzzy)	Slope, thickness of unsaturated zone, land use, soil texture
Mostafa *et al*. (2013)	GIS(Fuzzy Logic)	Slope, Infiltration rate, dry alluvial thickness, electrical conductivity, land use
Rahman *et al*. (2012)	WLC,OWA,AHP	Land use, slope, soil, sub-surface impermeable layer thickness, groundwater depth, , aquifer thickness,
Riad *et al*. (2011)	GIS (Boolean and overlay weighted model)	Land slope, distance to the Residential (urban) areas, distance to the Supply wells, distance to the treatment plants, distance to the roads land use, Pollution risk and depth to groundwater
Rolland and Rangarajan (2013)	GIS(AHP), RS	Land use/land cover, geomorphology, surface water bodies, lineament density, drainage density, soil
Choudhury (1998)	GIS, RS	Geology, geomorphology, lineaments, slope, depth to water level, land use and drainage
Sargaonkar *et al*. (2010)	GIS, AHP	Lineament density, depth to bedrock And soil cover, drainage density, slope, landforms, Land use/land cover and water table level
Shaban *et al*. (2006)	GIS, RS	Lineament density and drainage density, lithological character, karstic domains and land cover/land use.
Shankar and Mohan (2005)	GIS	Geomorphology, slope, lineament density, drainage density

Shirahatti *et al*. (2010)	RS,GIS(WLC)	Geomorphology, geology, soil, land use/cover, slope, lineament density, static water table, depth to bed rock
Srivastava and Bhattacharya (2006),	RS, GIS (Fuzzy and AHP)	Geomorphology, lithology, land use, lineament density, soil , drainage density, slope
Tweed *et al*. (2007)	GIS, RS,	Depth to groundwater, slope, soil

A review of this literature indicated that nine criteria (factors) were mostly considered and subsequently taken into consideration when identifying optimal sites for groundwater recharge. They include:

Rainfall: One of the most important criterion that has a major role in identifying suitable sites for groundwater recharge. It determines the amount of water that falls, and thus, the movement of groundwater. Regions that receive more rainfall have more opportunity of infiltration than those with low precipitation.

Materials of the Vadose zone: An important criterion used to determine sites for groundwater recharge based on the materials of the zone above the water table where the infiltrated water has to pass through it.

Static Water Level (Depth of groundwater): An important criterion to be considered because it represents the depth from the ground surface to the water table. Hence, it determines the time taken by the water to reach the groundwater.

Soil Texture: Suitable soils should have a very low clay portion, where it represents the uppermost portion of the vadose zone and controls the amount of recharge that can infiltrate to the aquifer.

Slope: Indicates the slope of the land surface. A good suitability for a groundwater recharge should be in low slope (flat).

Aquifer media: A useful criterion to identify the speed at which water would travel to the aquifer and the amount of recharge that could be expected in the aquifer. The characteristic of this zone material controls the pass of the water. It determines the rate at which the groundwater flows, and controls the rate at which it enters the aquifer.

Land use/land cover: An important characteristic of the runoff that affects the recharge process and evapotranspiration. It includes natural, man-made population density. In addition, the existing land use/land cover provides information about the land availability for artificial groundwater recharge projects. For example, areas that are under use are inappropriate areas for artificial groundwater recharge projects implementation.

Drainage density: Draining density is a reverse function of permeability. Hence, the less permeable a rock is, the less the recharge of rainfall. It can indirectly indicate the suitability for groundwater recharge of an area because of the relationship between the surface runoff and the permeability.

Lineament density: Lineament density is one of the important criteria that affect the groundwater recharge. Groundwater exploration in basaltic land has a considerable importance. The fractures and joints serve as channels for movement of water to the groundwater.

Previous studies that have used the GIS, RS and MCDA methods to select the most suitable sites for groundwater recharge (either artificial or natural). Modifications to the AHP method has the capacity for addressing and exploring the uncertainties associated with the selection of the criteria and identifying weights. Those ideas are developed in the study.

2.4 Summary

Sites selection for potential groundwater recharge requires a variety of criteria that affect the selection of these sites. While GIS has been a powerful tool to handle spatial data in selecting optimal sites, application of this tool alone could not overcome the issue of inconsistency in expert opinions when trying to assign relative importance to each of the criteria considered in selecting sites suitable for groundwater recharge. This issue is addressed in this thesis. Since, it is extremely difficult to assign importance of weights to the different criteria involved in making a decision on sites selection for groundwater recharge. It is necessary to adopt a method that allows an estimation of the weights. The Analytical Hierarchy Process (AHP) method was adopted in this research due its superiority compared to other methods (Duc, 2006). The AHP methods can deal with inconsistent judgments and provides a measure of the inconsistency of the judgment of the respondents (Duc, 2006). The AHP will be selected because it allows assigning different weights of importance to the different criteria involved in site selection for groundwater recharge based on individual expert opinion. Weights for the criteria have been obtained through the pairwise comparison analysis, based on gathering of experts, this a main requirement for the application of the analytical hierarchy process (AHP).

The original contribution of this research will be the development of an AHP method for the determine importance of weights for selection criteria based on the multiple individual opinions of local experts, and the assessment of the consistency between these opinions through the pairwise comparisons method. The context for this analysis will be to address the location of proposed sites for groundwater recharge. It is argued that WLC together with AHP implemented within a GIS environment, are the most suitable combination of methods to select optimal sites for groundwater recharge in the study area. AHP will be used to determine weights for selected criteria while WLC will be used to integrate between all criteria that affect sites selection for groundwater recharge.

2.5 Research Questions & Objectives

From the review of the literature, this study addresses the following research questions.

- Can we utilise the views and opinions of multiple experts in the field of groundwater recharge with a spatial analysis framework to identify the suitable site for groundwater recharge in the study area?
- What is the consistency in these opinions and can they be represented spatially?
- What novel adaptations to existing approaches can be made to support the merge of physical criteria and social factors to locate suitable sites for groundwater recharge potential?
- Do these adaptations yield results that add value to existing knowledge and yield sites that are appropriate for groundwater recharge locations?

To answer these research questions, we need to solve the following objectives.

- It is necessary to identify a range of local experts from which to gather their opinion.
- It is necessary to determine the importance of each criterion from the experts in the context of groundwater recharge.
- To gather data in a format that can be analysed by the spatial analysis techniques discussed in this chapter.

- To combine the selected criteria and social factors that affect the suitability of sites for groundwater recharge in the study area in a GIS environment to allow for the selection the optimal sites for groundwater recharge in the study area.
- Verify the outcomes of this analysis by making representative field measurements relevant to groundwater recharge that includes Time Domain Electromagnetic Methods (TDEM) and soil texture analysis.

3 METHODOLOGY

This chapter provides an overview of the methodology used in this study to address the research questions described in the previous chapter. An appropriate study area located in a hydrological basin in eastern Jordan is selected and described. The methods used to collect the secondary data (the digital maps for the study area, the DEM and the satellite imagery) and the primary data (the interviews, criteria selection and the fieldwork) collected. The approach used to validate the output products is described in detail.

3.1 Study Site Selection Criteria

The basic underpinning properties of a study site that can be used to answer the research questions posed in the previous chapter are as follows:

- A large enough groundwater reservoir where continued over-extraction would lead to serious water shortages.
- Where recharge activities were a serious consideration and that the locations for these recharge experiments were potentially multiple and unknown at the time of the study.
- Where there was uncertainty or dis-agreement as to where to deploy the recharge activities within the expert community.
- Where the cost of getting it wrong would be high.

From the data perspective, the study site should also have available:

- Data on important hydrological and geological information that, according to the literature, are to be considered when developing groundwater recharge strategies.
- Ideally these data sets would be available for a number of points or regions across the study area or spatially interpolated.
- These data should be accurate.
- If not available then they can be created from other sources of data, e.g. satellite data and used.
- The data sets should cover the whole of the study site.

Finally, the study area should be fully accessible for the purpose of validation and not present any material risks whilst conducting fieldwork. One such country in the Middle East where resourcing water for a number of uses continues to present challenges is Jordan.

3.2 Water Resource in Jordan

Jordan has an annual volume of surface water resulted from precipitation of around 8500 x 10^6 m^3. Between 85% and 92% of this water which is lost through evaporation. Furthermore, around 5% - 11% of the surface water in Jordan disappears through infiltration, and 2% - 4% generates a runoff (Allison *et al.*, 1998, and Allison *et al.*, 2000). Table 3.1 lists the annual precipitation in Jordan for the years 1951 to 2010 as reported by the Jordan Ministry of Water and Irrigation (2011). This table shows that the annual precipitation varies from one year to another with a minimum of 3915×10^6 m^3 recorded in 1959/1960 and a maximum of up to 17979×10^6 m^3recorded in 1966/1967.The rainfall months (winter season) in Jordan are between September and April. Thus, data in Table 3.1 represents the amount of rainfall in the period between the winter season of 1959/1960 to the winter season of 2009/2010.

Jordan's surface water resources are distributed over fifteen surface water basins. These basins vary in rainfall quantities, as well as on the runoff and on the evaporation rates as shown previously in Figure 1.3 and Table 1.1 (Salameh and Bannayan, 1993). Jordan lacks the surface water bodies such as lakes or large rivers, although it has two small rivers, which contribute to its water resources. These two rivers are the Zarqa River, which originates within Jordan, and the Yarmouk River, which originates from the southern part of Syria and the North Western part of Jordan as shown in Figure 1.3. At present, the Jordan River is of no use to Jordan because of the currently ongoing development of its upper catchment conducted by Israel, which prevents any fresh water flowing from Lake Tiberius to the Dead Sea (Salameh and Bannayan, 1993).

Table 3.1. Annual precipitation in Jordan (1951 – 2010). Adapted from Jordan Ministry of Water and Irrigation (2011)

Year	Volume (10^6 m^3)	mm	Year	Volume (10^6 m^3)	mm	Year	Volume (10^6 m^3)	mm
1951/1952	11627	130.6	71/72	11563	129.9	1992/1993	5898	66.3
1952/1953	8675	97.5	72/73	4536	51	1993/1994	8440	94.8
1953/1954	8504	95.6	73/74	11896	133.7	1994/1995	8524	95.8
1954/1955	6725	75.6	74/75	9476	106.5	1995/1996	6046	67.9
1955/1956	8553	96.1	75/76	7556	84.9	1996/1997	8746	98.3
1956/1957	9879	111	76/77	6070	68.2	1997/1998	5798	65.3
1957/1958	4855	54.6	77/78	5886	66.1	1998/1999	4636	52
1958/1959	6386	71.8	78/79	5912	66.4	1999/2000	7089	80
1959/1960	3915	44	79/80	10873	122.2	2000/2001	8566	96.1
1960/1961	8496	95.5	80/81	8466	95.1	2001/2002	7489	82.8
1961/1962	7495	84.2	81/82	5590	62.8	2002/2003	9504	104.4
1962/1963	5497	61.8	82/83	9204	103.4	2003/2004	7856	85
1963/1964	11679	131.2	83/84	5407	60.8	2004/2005	5980	66.6
1964/1965	10857	122	84/85	7189	80.8	2005/2006	7680	85.7
1965/1966	6936	77.9	86/87	7650	86	2006/2007	8652	96.1
1966/1967	17797	200	87/88	12262	137.8	2007/2008	7858	85.9
1967/1968	8421	94.6	88/89	10205	114.7	2008/2009	9320	103.6
1968/1969	8542	96	89/90	7609	85.5	2009/2010	9873	106.9
1969/1970	8534	95.9	90/91	8379	94.1			
1970/1971	10006	112.4	91/92	10429	117.2			

Based on the data supplied from the Jordanian Ministry of Water and Irrigation, 2011, the Azraq Basin has been suffering from over pumping of groundwater, with an abstraction rate of about 222% of the safe yield in 2010. Water in the Azraq Basin is mainly used for irrigation and drinking purposes.

Jordan is one of the poorest countries in the world in terms of water resources. The rapid increase in population imposes the need for additional resources of water in Jordan. The Azraq basin region in Jordan, shown in Figure 3.1, is currently under considerable water demand. This is due to the rapid development of the industrial, the agricultural, and the residential sectors in that region. Jordan, in general, depends mainly on groundwater to meet its water demands. Thus, significant efforts are being carried out in Jordan aiming towards protecting groundwater from attrition and over-extraction. The Azraq basin currently suffers from over-pumping. The records of the recent years showed that there are deficit indications in the groundwater resources in the basin. To maintain the groundwater from over-pumping, artificial or natural recharge are required so that there is a balance between the amounts of extraction and the recharge process.

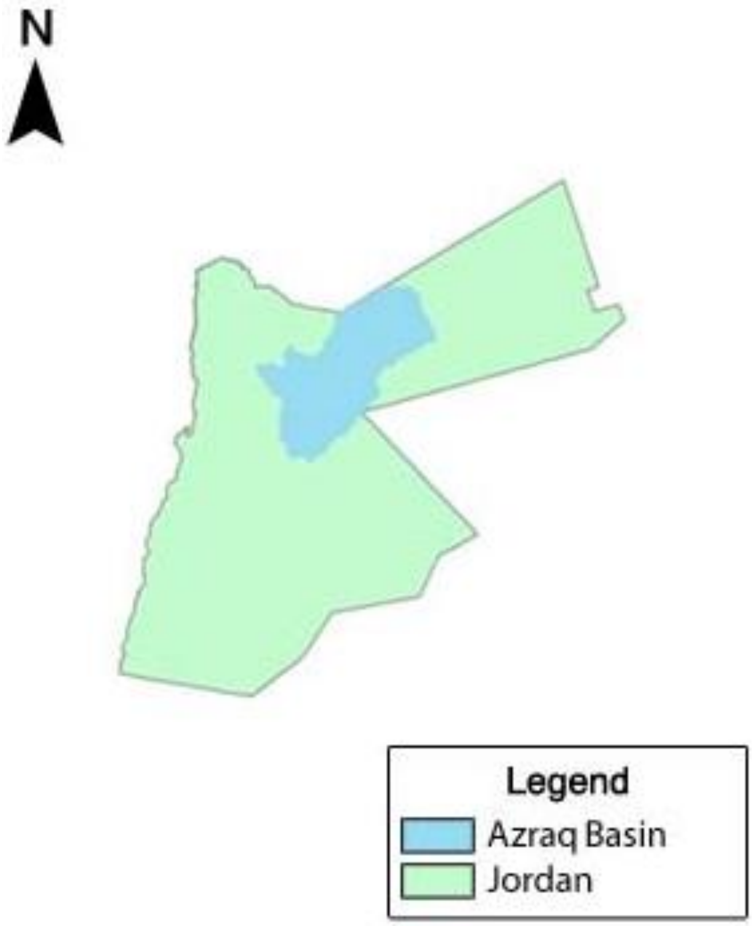
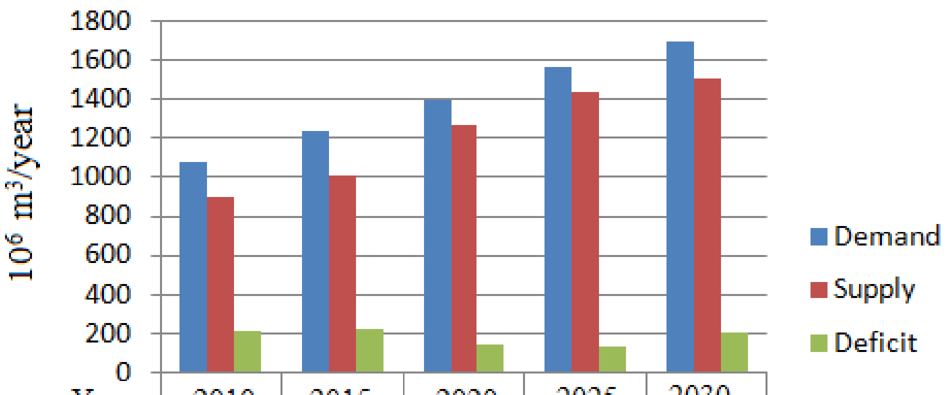


Figure 3.1. The Azraq Basin region of Jordan where this study takes place

At the end of 1992, the natural springs in the Azraq basin dried out as a direct result of over pumping from the basin for agricultural activities, and domestic supplies of water for the cities of Amman and Zarqa. This led to a drying out of the oases, which raised concerns with environmental groups. The safe yield of the Azraq basin is about m^3/year. Currently, the total annual abstraction is around 56×10^6 m^3/year (36.7×10^6 m^3/year for agriculture and 15.6×10^6 m^3/year to supply Amman and Zarqa cities), which resulted in a 32 $\times 10^6$ m^3/year deficit (Figure 3.2). Due to over pumping from the basin, the height of the water table has dropped significantly at a rate of 80-90 cm/year (Jordan Ministry of Water and Irrigation, 2011).



Years	2010	2015	2020	2025	2030
Demand	1079	1229	1397	1559	1695
Supply	892	1006	1260	1429	1500
Deficit	205	223	137	130	195

Figure 3.2. Water demand, supply and deficit in Jordan between 2010 and 2030. Adapted from the Jordan Ministry of Water and Irrigation (2011).

Local people in the Azraq basin of Jordan used to be livestock owners. They relied on the available rangeland in that area and in other areas within the Jordanian Badia, which comprises around 85% of the total area of the country (Millington *et al.*, 1999). However, in the early 1960's, new agricultural practices were introduced, which were based on digging wells and cultivating the land (Millington *et al.*, 1999). The study area is described as being a basalt aquifer of the Azraq Basin. Further justification for choosing this groundwater basin are the fact that there are potential groundwater recharge zones that are accessible for validation, rainfall rates are suitable to justify further investigation, there will be strong future demand for water resources and the availability of critical data sets and experts that will be explored in the following sections.

In summary, the Azraq Basin presents an ideal opportunity to test the development of novel interpretations of the AHP method for the determine importance of weights for selection criteria based on the multiple individual opinions of local experts, and the assessment of the consistency between these opinions through the pairwise comparisons method. The next section will describe a number of the underpinning data sets that are available in the study area.

3.3 Data Sets

3.3.1 Specific Definition of the Study Area

In order to maximise the availability of secondary data sets that characterise the Azraq basin and to ensure access to sites for the purpose of validation, it was necessary to analyse a subset of the Azraq basin. The study area selected for this research covers 46% of the Azraq basin area. The entire Azraq Basin covers an area of approximately 11,000 km^2, whilst the subset for the purpose of this study covers an area of 4,000 km^2 (Figure 3.3). The study area is inhabited by more than 60,000 people who live in 32 towns, villages and small settlements (DOS, 2011). The livestock business was a major source for household income in the study area, but due to the high cost of animal feed, most farmers sold their livestock and moved to work for the government and armed forces (Al-Oun, 2001). In the early 1990s, the irrigated agriculture started after a government decision to allow wells to be dug in order to start cultivating the land in areas close to the Syrian borders (Kirk, 1998).Currently, the agricultural activities are concentrated in the North Western part of the study area, while the remaining area is considered as free rangeland.

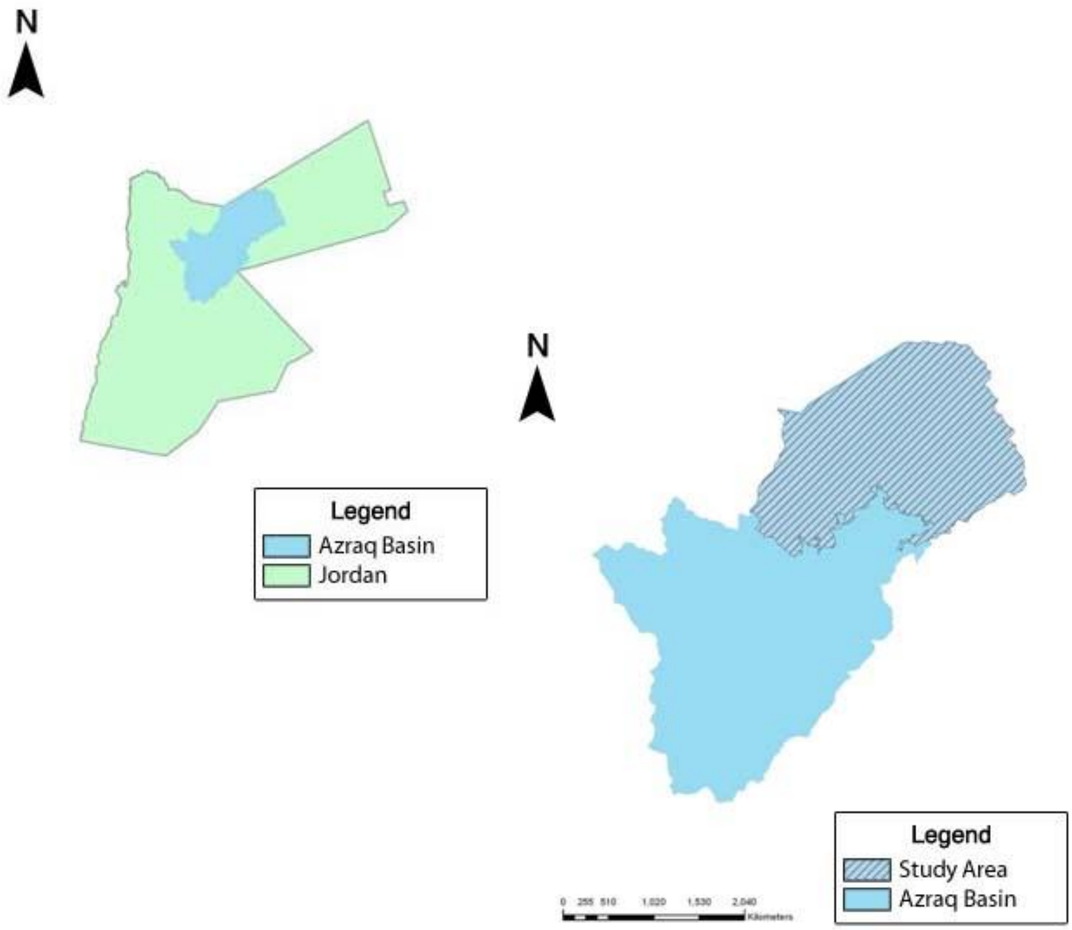


Figure 3.3. The revised study area within the Azraq Basin

3.3.2 Groundwater Data

Groundwater in the Azraq Basin exists in three aquifer complexes (Figure 3.4). The upper aquifer, the middle aquifer and the lower aquifer (Dottridge and Abu Jaber, 1999). Salameh and Bannayan (1993) classified these three aquifers as shallow, intermediate and deep sandstone. Each category is separated by low permeability aquitards (Allison *et al*., 2000).

The Upper Aquifer (shallow aquifer) consists of Neogene-Quaternary alluvial sediments, Miocene - Quaternary basalts (BS) and Lower Tertiary marly and chalky limestone with Cherts-Rijam (B4) aquifer. Water in this type of aquifers is renewable and located within 450m of the ground surface on the Druz foot slopes but drops to around 50m on the northern margin of the Azraq basin (Allison *et al*., 2000).

The Middle Aquifer consists of Upper Cretaceous limestone, sandy limestone - Amman Wadi Sir (B2/A7) aquifer Middle Cretaceous crystalline to chalky limestone-Hummar aquifer (Dottridge, 1994). Water in this aquifer is older than that in the shallow aquifer (hundreds to thousands of years). The depth from the ground surface is 400m in the north compared to 700m in the south (Allison *et al*., 2000).

The Lower Aquifer consists of Lower Cretaceous sandstones - Kurnub aquifer Palaeozoic - Disi aquifer (Dottridge, 1994). Water in the aquifer is estimated to be thousands of years old and depths from the ground surface ranges between 1.3 and 3.4 km (Allison *et al*., 2000).

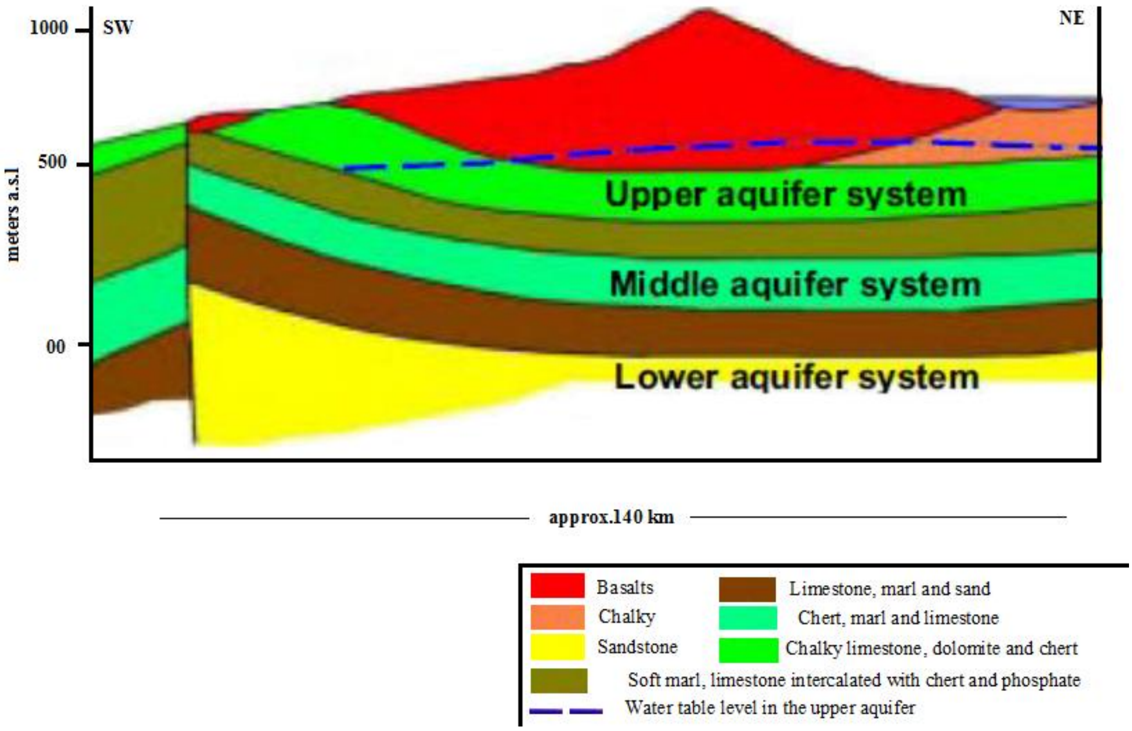


Figure 3.4. Simplified Hydrogeological cross-section running SW – NE. Adapted from Dotteridge (1998)

The study area is in the upper shallow of the Aquifer, which consists of four different members partly separated from each other by low permeability layers, partly directly connected. These are the Quaternary sediments, the Basalt, the Shallala (B5) and the Rijam (B4). The basalt extends from the centre of the basin to the north and ends up in the highlands of Syria (Bajjali and Hadidi, 2005). The basalt is hydraulically connected to the underlying calcareous rocks of the Rijam (B4) formation. The groundwater flow is from north towards the south and the groundwater moves from all directions towards the Azraq depression (NJWRIP, 1989). The depth to the ground water table ranges from few meters in the centre of the Oasis to 400m in the northern catchments area. The fresh water of the upper shallow of the aquifer is currently under threat of salinization due to overexploitation.

Water abstraction from the Azraq basin has exceeded the safe yield. The safe yield is the quantities of water perennially available from the groundwater basins, which is identified by the amount of the withdrawal and the recharge quantity. The history of the water withdrawal from the Azraq basin is shown in Figure 3.5. It shows that the amount of the pumped water has increased from 15×10^6 m^3/year in 1980 to 57×10^6 m^3/year in 2010, an increase of 368%. The safe yield of the basin is predicted to be $24.10^6 m^3$/year (Al-Adamat, 2002). Data shows that the water withdrawal from the Azraq basin exceeded the safe yield more than 25 years ago (Figure 3.5). In 2010, the water withdrawal exceeded more than 229% of the safe yield. This increase in the water withdrawal above the safe yield has caused a decline in the water table.

According to Jordan Ministry of Water and Irrigation (2011), the water levels in the Azraq Basin had dropped by 3-5m by the early 1990s. Al-Kharabsheh (1991) argued that severe pumping is the greatest problem in the basin and may cause salt-water interference especially if the water levels sink below 500m above sea level, which is the static water level of the Azraq area. Water level decline in the basin have resulted in an increase of dissolved solid concentrations in the basin over the years. The water level decline has caused an upward migration of more highly mineralised water into the aquifer (USGS, 2000).

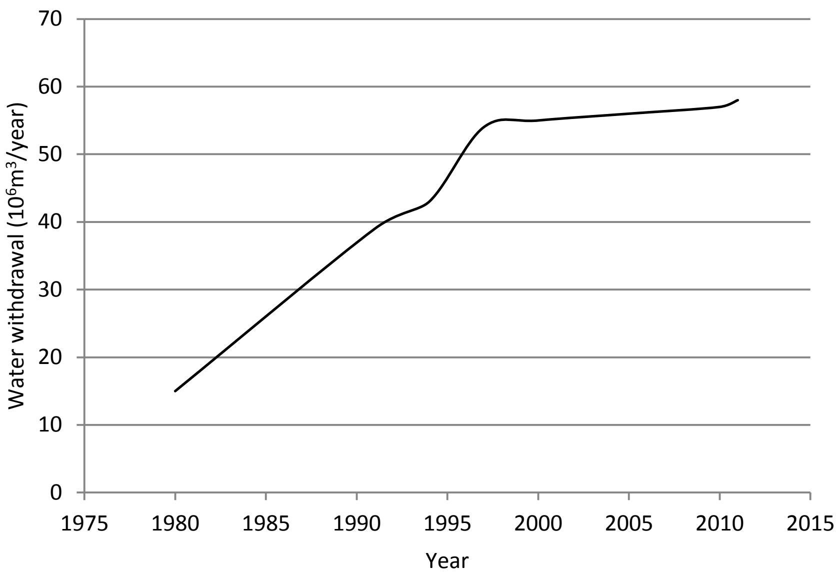


Figure 3.5. Water withdrawal from the Azraq basin between 1980 and 2011

High rainfall on the Jebel Druze Mountains in Syria is the major source of the groundwater recharge. The groundwater movement in the basalt aquifer is towards the east and the southeast with possible discharge along the borders of the basalt plateau (Salameh *et al*., 1997).

3.3.3 Land Use & Land Cover

Since the early 1990s, agriculture has expanded in the area of the basin where significant areas of grazing are used for agriculture. According to the Jordan Ministry of Environment (2006), the agricultural area has increased by 30 times between 1996 and 2006. This is mainly due to the use of agriculture as a means to register land and the tendency of investors from outside the basin to invest in agriculture. All the irrigation wells are drilled in the upper aquifer of the basalt area within the Azraq basin (Al-Hussein., 2000; Dottridge., 1998). These wells were drilled and owned by local people and people who live in the cities located in the western part of Jordan. The majority of farmers cultivated vegetables such as tomato and watermelon (Kirk, 1998), olive, and fruit trees (Al-Hussein., 2000, Waddingham., 1998).

The farming zones in the study area are concentrated in the area south and southeast of the town Um Al-Quttain and the area south and southeast of the villages (Abu Al-Farth and Qasim). In April, the irrigated agricultural season (vegetables only) begins and finishes in late November, whereas no irrigation in December, January, February and March (Al-Hussein., 2000, Millington *et al*., 1999, Waddingham, 1998). The only method used to distribute water to the crops in the study area is through drip irrigation (Waddingham, 1998). The size of the tree farms and the vegetable farms differ. The size of the vegetable farms ranges from 10 ha to around 50 ha (Al- Hussein, 2000), whereas the tree farms range from around 100 trees to more than 90,000 trees.

3.3.4 Climate

The climate of the study area is generally characterised by its extremities (hot dry summers and cold winters). This area is broadly classified as a semi-arid (Salameh *et al*., 1997). The study area falls in an area known to be a zone of transition between the Jordan Valley environment and the arid interior desert areas of Eastern Jordan. It is characterised by low precipitation and high potential evaporation (Allison *et al*., 1998).

The annual rainfall in Jordan varies between 600 mm over the heights in the north of Jordan to around 50 mm in the south east (Meteorological department, 2011). In the study area, rainfall usually falls in the form of a high intensity, short duration and irregular storms (Al-Ansari and Baban, 2001, Jordan Ministry of Water and Irrigation, 2009). The highest parts of the study area towards the Syrian border receive the greatest amount of rainfall (Dutton and Shahbaz, 1999). The spatial distribution of the annual precipitation in the study area is shown in Figure 3.6. The average of the rainfall varies between around 50 mm/year in the southeast to 100 mm/year in the north-west.

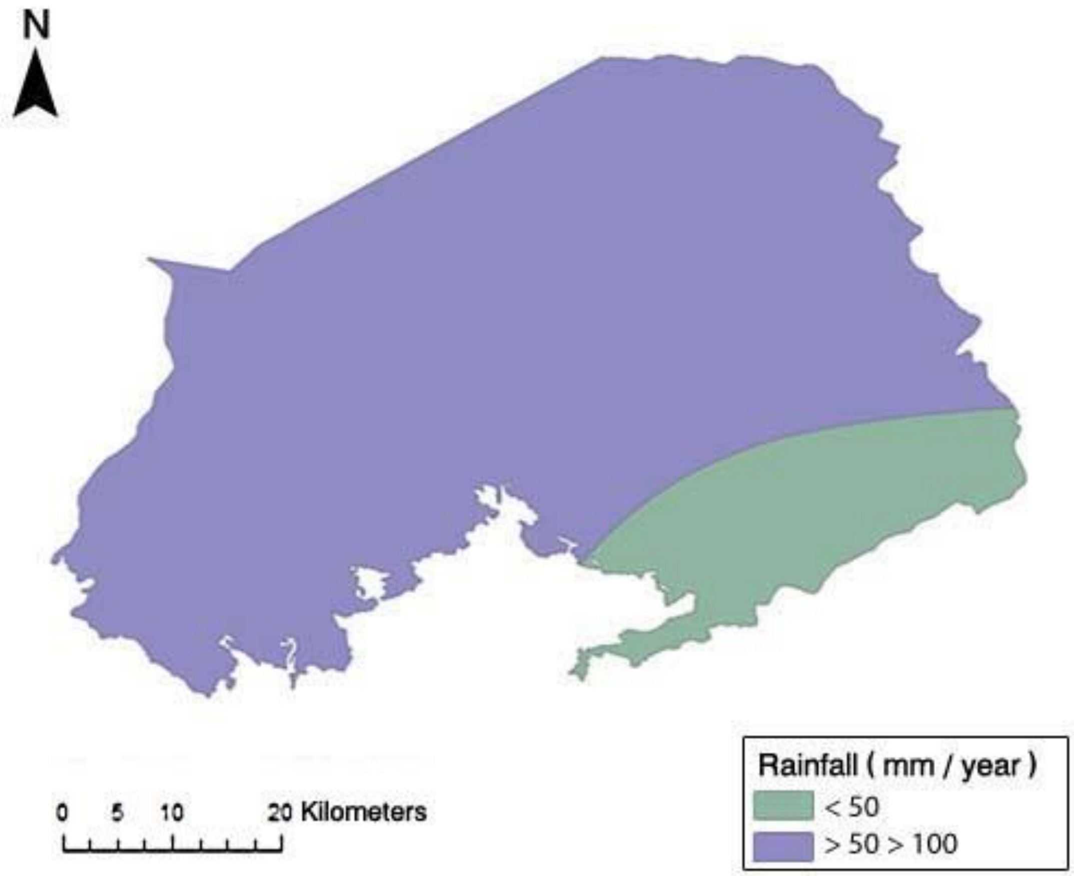


Figure 3.6. Precipitation in the study area (The Higher Council for Science and Technology, (2007)

Rainfall occurs mainly between November and May, with 80% of the annual precipitation between the months of December and March (Allison *et al*., 1998). The rainfall amount varies from one year to another and from decade to decade (Dutton and Shahbaz, 1999). There are two weather stations inside the study area located at Al-Safawi and Dayr Al-Kahf village. The monthly average rainfall recorded by the Al-Safawi and Dayr Al-Kahf stations for the period from 1980 to 2010 (Meteorological Department, 2011) is shown in Figure 3.7. It can be seen that no rainfall were recorded in June, July and August, whereas the highest monthly rainfall occurs between December and March.

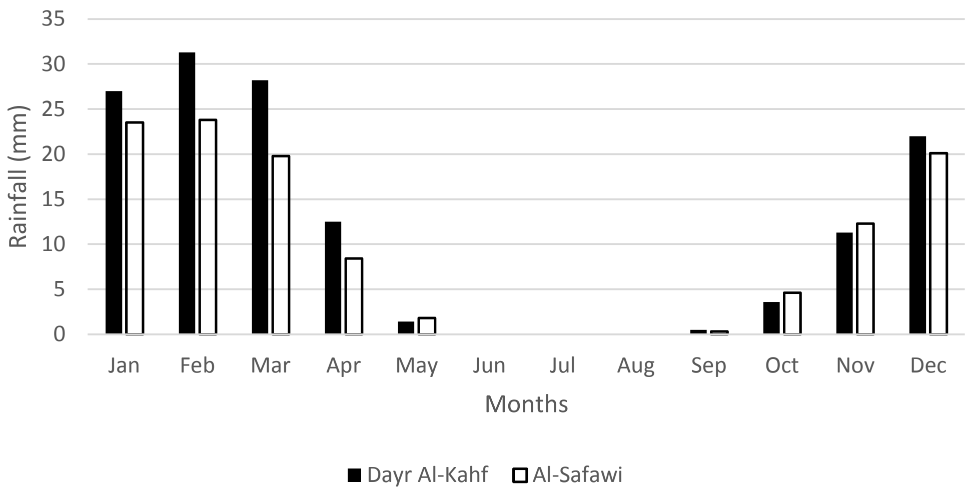


Figure 3.7. Average monthly rainfall (mm/month) in Dayr Al-Kahf and Al-Safawi stations (Meteorological Department, 2011)

Rainfall is erratic at a maximum of more than 100 mm/year to a minimum of less than 50 mm/year in the study area. The annual average rainfall at these two stations over the last four decades is shown in Figure 3.8. The average annual rainfall declined from 137.8 mm in the 1980’s to 105.6 mm in the 2010’s at the Dayr Al-Kahf. Likewise, the Al-Safawi station rainfall records show that the average annual rainfall has fallen from 115.04 mm in the 1980s to 98.5 mm in the 1990’s.

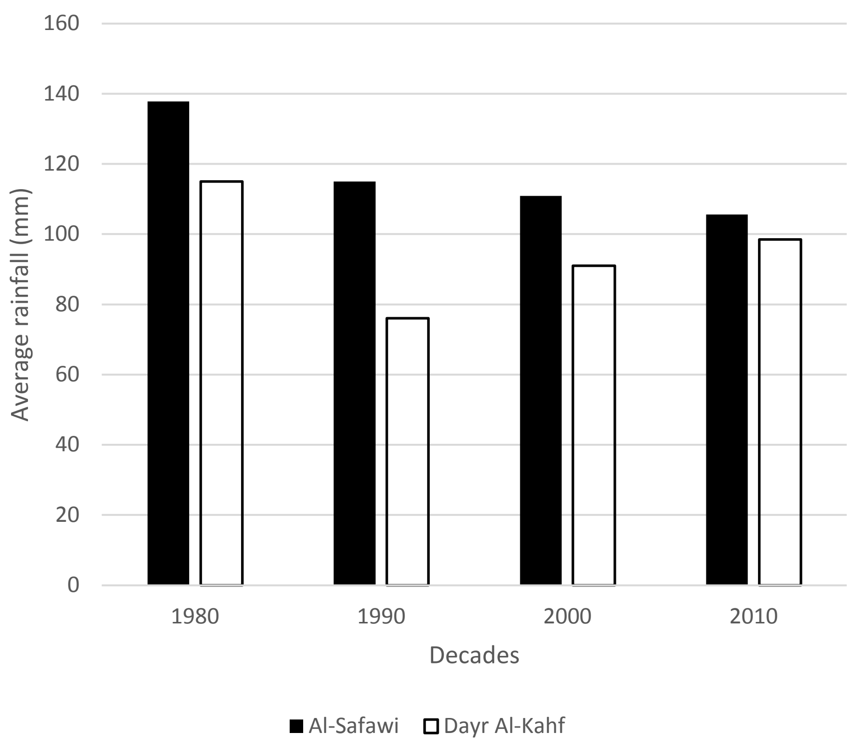


Figure 3.8. The annual average rainfall recorded by Dayr Al-Kahf and Al-Safawi stations over the last four decades (Meteorological Department, 2011)

There is a seasonal variation in the temperature in the study area. In summer, the mean annual maximum temperatures vary from 35°C to 38°C. However, the absolute maximum temperatures rarely exceed 40°C in August. In winter, the temperature hardly falls below freezing, with annual minimum temperatures as low as 2°C to 9°C (Allison *et al*., 1998; Meteorological Department, 2011; Millington *et al*., 1999). The average monthly minimum and maximum temperatures in the study area is shown in Figure 3.9.

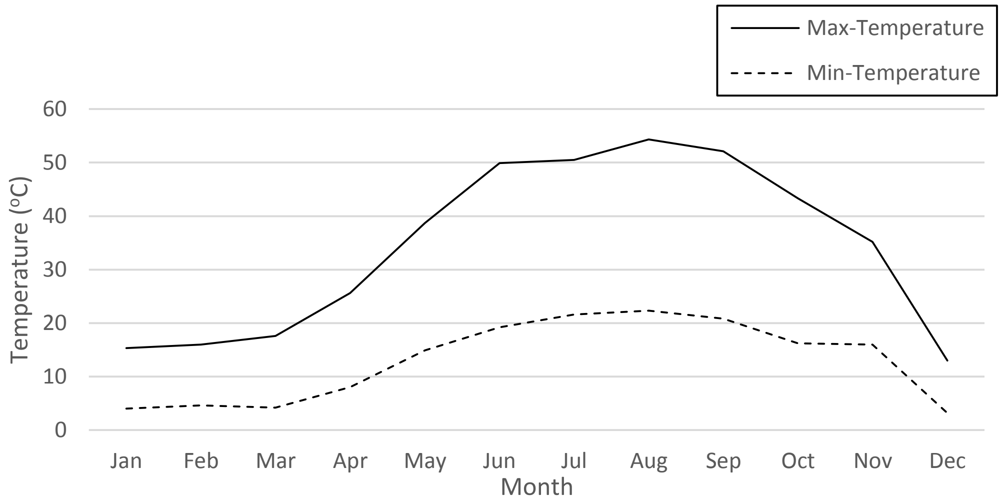


Figure 3.9. The average monthly minimum and maximum temperatures in the study area (Meteorological Department, 2011)

The climatic conditions in Jordan significantly affect the amount and the distribution of precipitation and the potential of evaporation. The estimated evapotranspiration can be fifty times greater than the mean annual rainfall (Al-Ansari and Baban, 2001) averaging 1500 mm to 2000 mm/year (Allison *et al*., 2000). According to Al-Ansari and Baban (2001), the average daily evaporation for the study area during the period from 1967 to 1995 was between 5.9 to 6.3 mm/day. Kirk (1998) estimated the daily average evaporation within the study area in the summer months to be above 7.5 mm/day and 5 mm/day in October. As mentioned previously, it is believed that around 85 to 92% of the annual precipitation in the area is lost due to evaporation.

3.3.5 Topography

The difference in topography within the study area is as a result of various basaltic flows. The age, physical and mineralogical characteristics are specific to each type of theses basaltic flows. The surface topography of the oldest flows is smooth, with well-established drainage patterns. The younger flows seem to have an irregular topography, filled depressions and a crudely connected drainage network. Areas of smoothly rising hills with dark basalt rocks of assorted sizes cover the desert plain and control the topography of the study area (Al-Ansari and Baban, 2001). Figure 3.10 shows that the highest land is located near the Syrian border, which rises up to 1100 m a.s.l., while the south-western part of the study area sits around 500 m a.s.l.

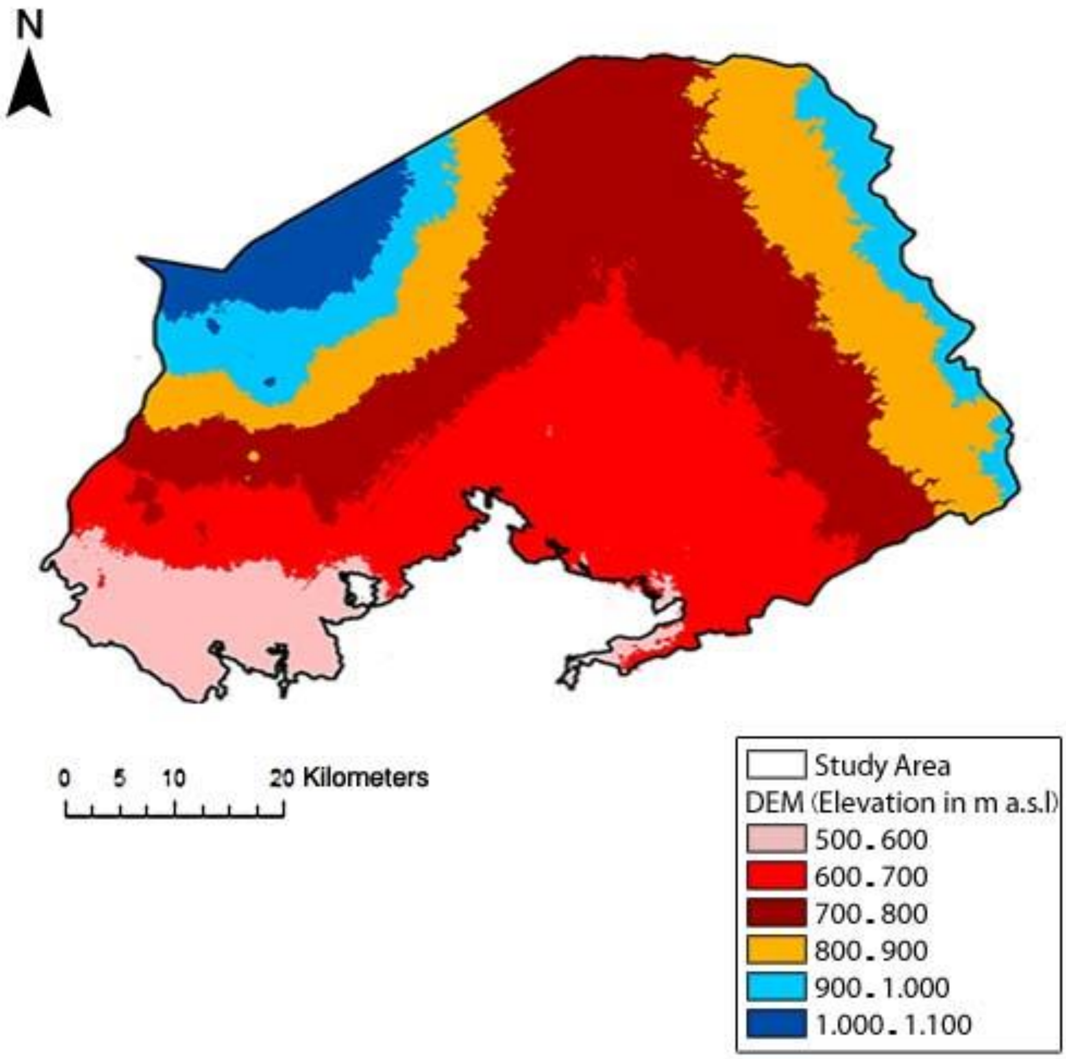


Figure 3.10. Elevations within the study area in metres above sea level (m a.s.l), based on USGS ASTER DEM

3.3.6 Soils

In Jordan, soil formation, types and properties are mainly measured by the parent material, the topography and climate (Allison *et al*., 1998). The study area consists of a basaltic lava plateau that spreads out from the main lava source in Jebel Druze, which is located in the Syrian Republic. The two most recent flows are the only ones that outcrop to form a soil parent rock. The latest flows have very little weathering and soil formation that is very small. Over much of the area, Aeolian silt is potentially contributed to the soil parent materials. The main soil subcategories are xeric and xerochreptic calciorthids on the central and higher slopes of the interfluves. The second most common subcategory is Xerochreptic paleorthids on the very gently sloping interfluves. Lithic subgroups in this area are common occurring on the crests and craters while camborthids occur in the basins, valley sand the lower foot slopes (Allison *et al*., 1998; IALC., 2006).

3.3.7 Surface Hydrology

Several ephemeral river channels (Wadis) flow within the study area (Figure 3.11). The direction of their course is towards the south following a gentle north–south slope (1%) of the physiography (Waddingham, 1994). Within the study area, there are no natural surface water bodies. Surface waters run through the remaining Wadis in wet years and drain into the Qa'aAzraq. These Wadis have poorly outlined the drainage patterns due to the low gradient slopes throughout the study area. However, voluminous Wadi runoff in the form of a flash flooding is created following the intense thunderstorms (Waddingham, 1994). It is estimated that the surface water within the study area is between 2 – 4% of the annual rainfall Infiltration in these Wadi channels is high and can reach a maximum of 200 mm/hour (Allison et al., 2000)..

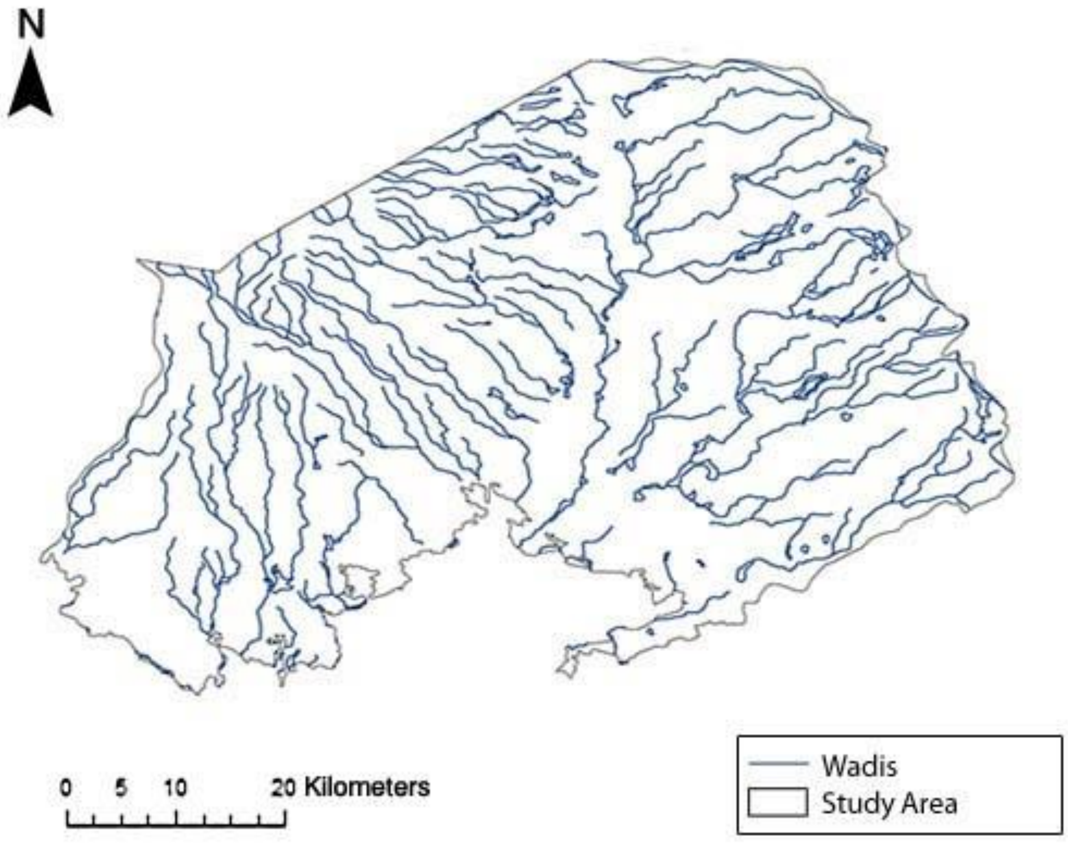


Figure 3.11. Drainage (Wadi) map of the study area (Royal Jordanian Geographic Centre, 1998)

3.3.8 Geology

The basalt outcrops of various ages emerge on the surface within the north and northeast, and extend towards the north covering a wide area referred to as the “Basalt Plateau”, which is linked to the North Arabian Volcanic province (Allison *et al*., 1998). Six different eruptive phases have been acknowledged by Bender (1964, 1974) (B1-B6), the latter four (B3, B4, B5 and B6) of which outcrop at ground level in Jordan. They total 150m in thickness with palaeo-soils up to 5m thick splitting the flows, and a 30m zone of coriaceous lava and soil on top of the third flow unit. The fourth flow is up to 60m thick covering the three older flows and is overland by Miocene sandstones and marls. A fifth flow, up to 25m thick, is the most extensive basalt unit and forms the major part of the total basalt coverage in the Eastern Badia of Jordan. The last eruptive phase, of Middle Pleistocene age, created flows more than 50km long, 10km wide and 30m thick. Lavas originating from the sixth and final eruptive phase show little sign of weathering (Al-Tarawneh., 1996; Ibrahim *et al*., 2001; Ibrahim., 1993; Sunna., 2000).

The Azraq basin is considered to be one of the most important structures in Jordan. The basin area is confined by

- The northern bounding Fuluq fault.
- The southern bounding Siwaqa Fault.
- The eastern curvature of the Fuluq fault as it joins towards the Siwaqa fault, and
- The western outcropping sedimentary column in the Amman area (Ibrahim *et al*., 200).

The study area lays within the basalt plateau and consists of six geological groups (Figure 3.12) including: (a) Bishriyya, (b) Rimah, (c) Asfar, (d) Safawi, (e) Wisad and (f) Belqa. Every group is divided into a number of formations as shown in Table 3.2

Table 3.2. The geological formations of the study area, adapted from Al-Tarawneh (1996), Ibrahim *et al*., (2001), and Ibrahim (1993)

Group	Formation	Age (Ma)	Depth (m)
Bishriyya (BY)	Fahda Vesicular Basalt (AF)	0.10 - 1.45	25 - 60
	Wadi Manasif Basalt (WMF)		
Rimah (RH)	Aritayn Volcanoclastic (AT)	2.01 - 2.94	15- 40
	Hassan Scoriceus (HN)		Up to 100
Asfar (A)	Mahadda Basalt (M)	1.96 – 3.41	10 - 25
	Madhala Olivine Phyric Basalt (MOB)		
	Hahimyya Aphanitic Basalt (HAB)		
	Ushayhib Olivine Pyroxene Phyric Basalt (UB)		
	Ufayhim Xenolithic Basalt (UM)		
Safawi (SW)	Salaman Flood Basalt (SN)	8.45 – 9.30	35
	Abed Olivine Phyric Basalt (AOB)		
	Ali Doloritic Trachytic Basalt (AI)		
Wisad (WS)	Wadi Es Sibhi Basalt (WSB)	9.37 – 10 .53	47
Belqa (BU)	Wadi Shallala Chalk (WSC)	>11	50 - 139
	Umm Rijam Chret-Limestone (URC)		

Bishriyya group: The Bishriyya group is the youngest basalt in the study area (Allison et al., 1998, Ibrahim *et al*., 2001). It is distinguished from the other groups by (1) the darker colour and the less weather-beaten basalt (2) well conserved linear pressure ridges, (3) darker tones on aerial photographs and Landsat images, (4) poorly developed drainage networks and (5) a thin soil cover (Allison *et al*., 1998; Ibrahim *et al*., 2001).

Rimah group: This group includes all the volcanic sedimentary and the coriaceous deposits regardless of their magmatic source and age (Ibrahim *et al*., 2001).

Asfar group: The Asfar group is defined simply as those flows which post-data of the regional extensive Safawi flood basalts and pre-data of the Bishriyya group. The unit exhibits a wide variety of morphologies and weathering characteristics. The major characteristics of this group are the existence of (1) point source feeders (associated with volcanic centres) and (2) xenoliths and/ or xenocrysts. This group is usually fine-grained (Ibrahim *et al*., 2001).

Safawi group: This group is defined by Ibrahim (1993) as a complex unit consisting of several different flood lavas. The Safawi group is subdivided into three formations, as shown in table 3.1. The common features of these formations are: (1) no point source feeders, (2) the units are intimately associated, (3) the vascularity is mostly confined to rounded clots, (4) the pipes and cylindrical, always holocry, stallin, medium- grained. Mostly olivine phyric, micro- vascularity is typical (Ibrahim *at el*., 2001; Ibrahim., 1993).

Wisad group: The Wisad group is an all-basaltic formation of various morphology, whichis older than the safawi group. By definition, the group includes several volcanic centres, flood flows and dyke systems (Ibrahim, 1993, Ibrahim *at el*., 2001).

Belqa group: According to Ibrahim (1993), the Belqua group is subdivided by two formations including Wadi Shallala Chalk (WSC) and Umm Rijam Chret-Limestone (URC). The lower part of the Belqua group from the Sehab- Muwaqqar area has alternating layers of thinly bedded limestone and brown or black chert with some light brown marl bands. The thickness of the Belqua group is 2547 km.

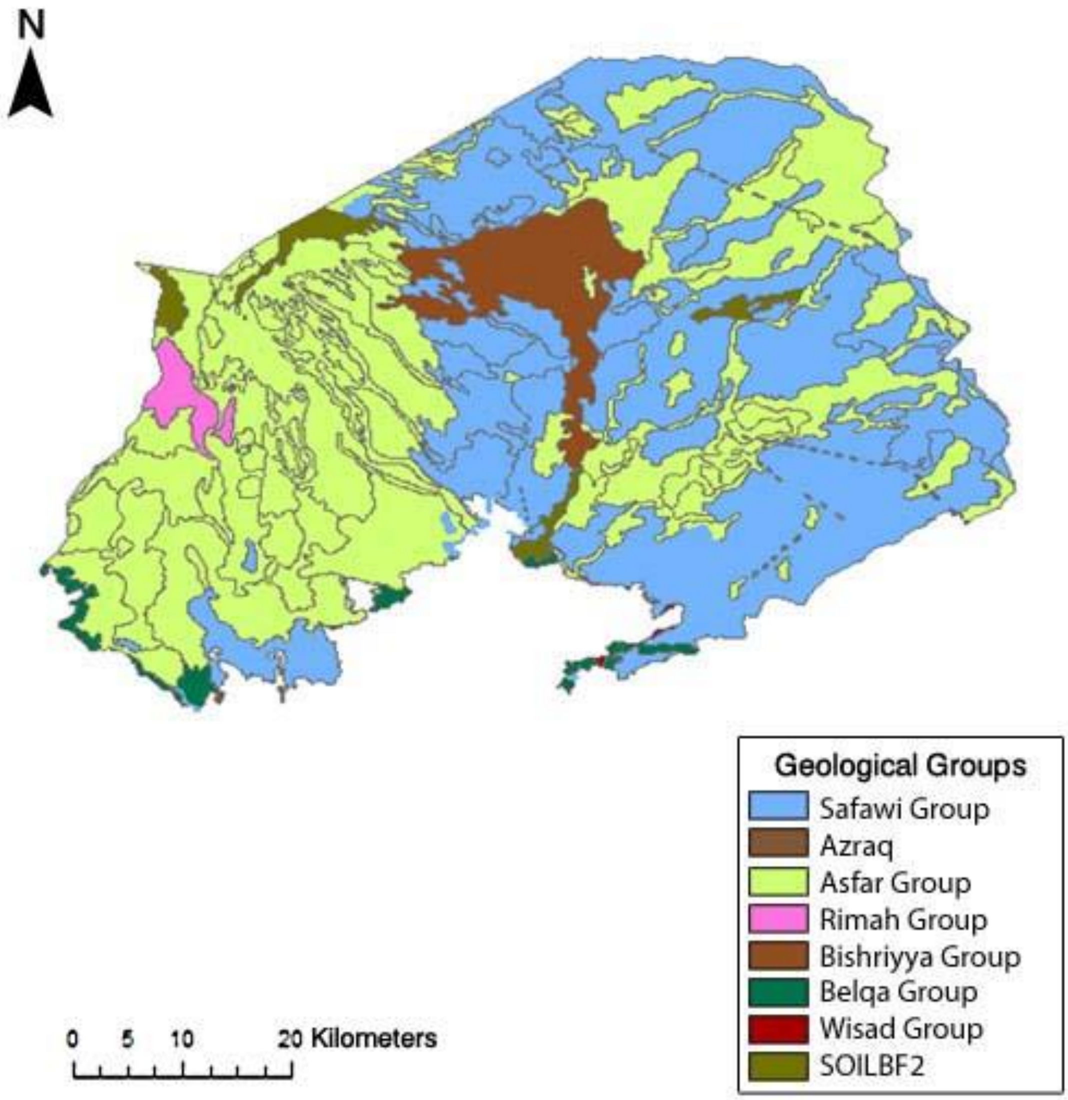


Figure 3.12. Geology map for study area (Royal Jordanian Geographic Centre, 1998)

3.3.9 Data Summary

The selection sites for the groundwater recharge require the availability of suitable data; these are both secondary and primary data. The primary data collection procedures will be defined later in this thesis. Spatial data including (a) rainfall, (b) geology, (c) soil, (d) climate and (f) hydrology. The secondary data are collected from various national organizations working in the Jordan. These data are digital maps and other data for different physical and socio-economic aspects of the study area. Table 3.3 lists the data collected and their sources.

Table 3.3. Secondary and primary data used in this research and their sources

Data type	Data	Scale/ Resolution	Source
Secondary Data	Rainfall	1:250,000	HCST, (2007)
	Vadose Zone (Lithology)	1:250,000	NRA., (1998)
	Slope based on ASTER DEM	30 m	USGS, (2011)
	Lineament	1:250,000	HCST, (1998)
	Soil	1:250,000	MOA (1993)
	Drainage (Wadi)	1:250,000	RJGC, (1995)
	Static Water Level	Well Data (Excel File)	WAJ, (2012)
	Aquifer Media	1:250,000	NRA., (1998)
	Road	1:250,000	RJGC, (1998)
	Urban (Town and Villages)	1:250,000	RJGC., (1998)
Primary Data	Site Selection Criteria Weighting	Questionnaire with Experts	
	Land use/ Land cover based on Landsat TM. Data	30 m	USGS, (2003)
	Soil Data Collection		Fieldwork
	Geophysical investigation		

Royal Jordanian Geographic Centre (RJGC), Natural Resources Authority (NRA), Jordan Ministry of Agriculture (MoA), Higher Council for Science and Technology (HCST), Water Authority of Jordan (WAJ), United States Geological Survey (USGS)

3.4 Data Pre-Processing

The methods used to address the research questions was divided into three stages. The main aim of stage 1, addressed in Chapter 4, is to determine the important criteria used for the selection of potential sites suitable for the groundwater recharge and to identify the optimal weights for these criteria. This stage depends on the literature review and the experts' opinions. The available studies on groundwater recharge sites selection were reviewed in order to identify the appropriate criteria that affect the groundwater recharge sites selection. The experts' opinions were then used to develop the suitable weights for each criterion. The Analytical Hierarchy Process (AHP) method was applied to check if the experts' opinions were consistent by implementing the pairwise comparison method (PCM).

In stage 2, addressed in Chapter 5, the optimum sites for groundwater recharge were identified based on the outcomes of stage 1. GIS analysis methods were used to identify the suitable sites for the groundwater recharge in the study area. The AHP method integrated to the Weighted Linear Combination (WLC) method, known as AHP-WLC method, was used to combine the sites selection criteria from stage (1) and multiplying the weights by rating (ranking) for each criterion. The sites that cannot be used for groundwater recharge were eliminated in this stage using the Boolean technique. This includes the site that are under existing human activities such as urban sites (villages and towns), agriculture sites (farms), wells and roads. The outcome of the Boolean technique was then integrated with the AHP-WLC outcomes to generate the final suitability map for the groundwater recharge of the study area.

Stage 3, described in Chapter 6, focuses on the validation of the methods and the verification of the results acquired by the GIS analysis. The geophysical investigation (Time Domain Electromagnetic (TDEM)) and soil physical characterisation (soil texture analysis) were conducted at several sites within the study area that represent all the potential categories for the groundwater recharge resulted from the GIS analysis.

Data pre-processing was a critical underpinning component of the research. It was necessary in this step to determine the necessary selection criteria, design the questionnaire that was to be used on experts to collect their valuable opinion, the resolution of weights for the selection criteria, the derivation of land use/land cover information and to design the fieldwork campaign to collect validation data. This is summarised in Figure 3.13.

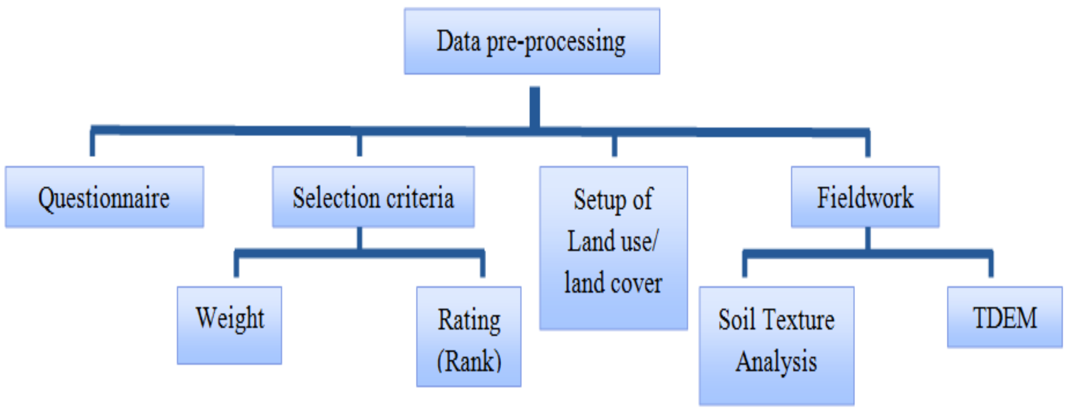


Figure 3.13. Summary of the data pre-processing component of the study

3.4.1 Selection Criteria

As stated in Chapter 2, there are many studies concerned with the groundwater recharge site selection using GIS. These studies were used in this research to define the groundwater recharge site selection criteria, together with the opinions of local experts. Nine physical criteria were used in this research, which include the rainfall, the slope, the material of the vadose zone, the aquifer media, the static water level, the drainage density, the lineament density, the land use/land cover and the soil texture. The importance of each criterion and the cited literature is described below.

- The rainfall is the major criterion in sites selection for groundwater recharge. More rainfall on any particular area means higher possibilities of recharge (Al-Adamat *et al*., 2010; Anbazhagan *et al*., 2005; Juaidi, 2008; Machiwal *et al*., 2011).
- The material of the vadose zone represents the unsaturated zone above the water table where recharge water has to pass through. It is a significant criterion to determine sites for groundwater recharge (Chenini and Mammou., 2010; Shaban *et al*., 2007; Shatnawi., 2006; Chowdhury *et al*., 2010)
- The slope is very important when identifying sites for groundwater recharge. Slopes play a major role in surface water runoff characteristics. Areas with a low slope have a greater opportunity for recharge than areas with a high slope (Chowdhury *et al*., 2009; Chowdhury *et al*., 2010; Saraf and Choudhury,1998; Valliammai *et al*., 2013).
- The lineament density affects the site selection for groundwater recharge because it reflects the rock structures through which water can recharge the groundwater. Lineament in basaltic area has a considerable importance as fractures and joints serve as channels for the movement of water to the aquifer (Balachandar *et al*., 2010; Shaban *et al*., 2007; Shankar and Mohan, 2005; Valliammai *et al*., 2013).
- Soil texture could play an important role when selecting a site for a groundwater recharge. The recharge capacity is among others dependents on the porosity of soil, which determines the water infiltration capacity and affects the resistance of water to flow into the aquifer. The highest infiltration capacities are observed in loose, sandy soils while heavy clay or loamy soils have considerably smaller

infiltration capacities (Al-Adamat., 2008; Ghayoumian *et al*., 2005; Sargaonkar *et al*., 2011; Shirahatti *et al*., 2010).

- Drainage density is considered one of the major criteria for groundwater recharge siting. It can indirectly indicate the sites suitable for the groundwater recharge. This is due to its relation with surface runoff and permeability (Balachandar *et al*., 2010; Chenini and Mammou, 2010; Chowdhury *et al*., 2010; Ghayoumian *et al*., 2007).
- The depth to the water table plays a major role in identifying suitable sites for groundwater recharge because it represents the depth from the ground surface to the water table. In addition, the depth to the water table is used to determine the potential distance travelled by the water before reaching the groundwater (Ghayoumian *et al*., 2005; Machiwal *et al*., 2011; Riad *et al*., 2011; Shatnawi, 2006).
- The aquifer media is used to identify the speed at which the water would travel to the aquifer and the amount of recharge that could be expected in the aquifer. The characteristics of the saturated zone material control the flow of the water within the aquifer. Determining the rate at which the groundwater flows controls the rate at which it enters the aquifer (Chenini and Mammou, 2010, Chowdhury *et al*., 2010, Sargaonkar *et al*., 2011, Al-Adamat *et al*., 2003).
- Runoff is greatly depending on land use/land cover. It is well known that recharge is high in the cultivable land and irrigated land compared to the bare rock and settlements. Hence, land use/land cover is considered one of the main criteria for selecting appropriate sites for groundwater recharge (Al-Balachandar *et al*., 2010; Chowdhury *et al*., 2010; Sargaonkar *et al*., 2011; Shirahatti *et al*., 2010).

In addition, five socio-economic factors are used along with the nine criteria in this research to select the optimum sites for groundwater recharge in the study area. These factors include, the distances to the urban areas, the agricultural lands, the roads, the wells and the international borders. These factors represent the major socio-economical activities in the study area. These five factors were given a zero value for the excluded areas (not suitable) and a value of one for the included ones (suitable). The importance of these factors are:

- According to Al-Adamat (2008), urban area must be excluded from being selected as groundwater recharge sites for safety reasons. A buffer zone of 500m around urban areas is used in this research (Al-Adamat, 2008, Al-Adamat *et al*., 2010, Baban and Wan-Yusof, 2003).
- The agricultural lands must be excluded because they are valuable resources and for environmental reasons (Al-Adamat, 2008). In the study area, Land use is classified into six major groups including the bare rock, the urban, the bare soil, the farms, the natural vegetation, and the *Marab* (Al-Ayyash *et al*., 2012). Urban and farmlands (under cultivation) were excluded from the selection factors, because they represent economical identities and such land cannot be used as sites for groundwater recharge. In addition, a buffer zone of 500 m around the agricultural areas was used in this research to account for any future possible expansion (Al-Adamat *et al*., 2010; Baban and Wan-Yusof, 2003).
- In the study area, roads have significant socio-economic value for the local community in terms of transportation. By these roads, they can move their trucks from one area to another when moving with their livestock searching for water and grass. A buffer zone of 250 m is applied to all roads including unpaved ones to protect these roads from being selected as a possible site for a groundwater recharge. The buffer zone around these roads will prevent any future conflict between the recharge projects and roads development (Al-Adamat *et al*., 2010; Baban and Wan-Yusof, 2003).
- The distance to the wells is of a significant socio-economic value for the central government and the local community. They are used in the study area for both agricultural and drinking purposes. Therefore, it was decided that a buffer zone of 500 m would be used to protect these wells from being selected (Al-Adamat, 2008; Al-Adamat *et al*., 2010; Shatnawi, 2006).
- Areas close to the international borders must be excluded from being selected for groundwater recharge sites for security reasons. A buffer zone of 1000 m is used in this research to prevent the selection of any sites for groundwater recharge that are not accessible when implemented in such zones (Al-Adamat *et al*., 2010; Al-Adamat, 2008).

In order to identify the potential sites for groundwater recharge, site selection depends on the ranks and weights of each thematic layers. The weight of each criterion is determined based on the experts' opinions. The methodology adopted for calculating weights for the selection criteria is explained in Chapter 4. Based on an extensive literature review, summarised in Table 3.4, the rating (rank) was assigned in terms of 4, 3, 2 and 1 for each individual criterion of the thematic layers to obtain the suitability map for the groundwater recharge sites. These numbers represent very high, high, moderate and low suitability for groundwater recharge.

Table 3.4. The rating (Rank) of the nine criteria selected based on literature review

Criteria	Rating	Criteria	Rating
Rainfall (Al-Adamat *et al*., 2010; Anbazhagan *et al*., 2005; Machiwal *et al*., 2011)		Static Water Level (m) (Ghayoumian *et al*., 2005; Machiwal *et al*., 2011; Riad *et al*., 2011)	
<50	1	>135	1
50-100	2	100-135	2
100-300	3	50-100	3
>300	4	0-50	4
Material of the Vadose Zone (Chenini and Mammou., 2010; Shatnawi., 2006; Chowdhury *et al*., 2010)		Slope (Chowdhury *et al*., 2009; Chowdhury *et al*., 2010; Valliammai *et al*., 2013)	
Mud flat	1	>8%	1
Volcano	2	4-8%	2
Basalt	3	2-4%	3
Alluvium	4	0-2%	4
Lineament Density (Km/sq.Km) (Balachandar *et al*., 2010, Shaban *et al*., 2007, Valliammai et al., 2013)		Drainage Density (Km/sq.Km) (Chenini and Mammou., 2010, , Chowdhury *et al*., 2010, Ghayoumian *et al*., 2007)	
0-1.5	1	>2.55	1
1.5-2.5	2	1.5-2.25	2
2.5-3.5	3	0.75-1.5	3
>3.5	4	0-0.75	4
Soil Texture (Al-Adamat., 2008; Sargaonkar *et al*., 2011; Shirahatti *et al*., 2010)		Land use/land cover (Al-Balachandar *et al*., 2010; Chowdhury *et al*., 2010; Sargaonkar *et al*., 2011; Shirahatti *et al*., 2010)	
The Loam	1	Bare Rock and Urban	1
The Silt Clay Loam	2	Bare soil	2
The Silt Loam	3	Marab	3
The Sandy Loam	4	Agricultural and natural vegetation	4
Aquifer Media (Chenini and Mammou., 2010; Chowdhury *et al*., 2010; Sargaonkar *et al*., 2011; Al-Adamat *et al*., 2003)			
(Massive shale, Metamorphic/igneous, Weathered metamorphic/ igneous)			1
(Bedded sandstone, limestone, Massive sandstone , Massive limestone)			2
The Sand and gravel			3
The Basalt and Karsts limestone			4

3.4.2 Questionnaire

In March 2012, a questionnaire survey was carried out with Jordanian experts from the Ministry of Water and Irrigation and Jordanian universities (Table 3.5). The aim this questionnaire is to determine the weights of the selected criteria for the groundwater recharge siting in the study area.

The questionnaire survey was used to explore opinions of experts to determine the relative importance of the selection criteria for groundwater recharge using a scale of 1-9. The questions used in this research were based on closed ended questions. Interviews were conducted with seventeen experts individually. This is because it was difficult to gather all the experts in one place. An interview was conducted with each expert to discuss his/her opinion about the selection criteria, At the beginning of each interview, the researcher explained to the expert the research aim and objectives and the importance of the expert opinion regarding the appropriate weight for each criterion. Then the expert was asked to identify the importance of each criterion by using a scale from 1 to 9, where 1 represents a low importance and 9 represents a high importance. The experts were selected through contacting the relevant Departments of Hydrogeology. Then Al al-Bayt University (Mafraq, Jordan) issued an official letter to each university and to the Ministry of Water and Irrigation in order to encourage full cooperation with the researcher. Through phone calls with the relevant departments, experts were identified and a meeting with each expert was organized. Some of the questions asked and discussed with each expert include:

- What are the most important criteria that affect the sites selection for the groundwater recharge?
- What is the most important criterion in the sites selection for the groundwater recharge and why?
- What is the relationship between all the criteria?
- What are the weights for each selected criteria?

The outcomes of the questionnaire survey and the methodology adopted to analyse the weighting for the selection criteria will be discussed in Chapter 4.

Table 3.5. The experts from the Jordanian universities and the Government organisations

Organisation	Number of Experts	Department
Al Al-Bayt University	6	Geology - Civil Engineering - Surveying Engineering
Yarmouk University	6	Geology
Jordan University	1	Geology
Hashemite University	2	Earth Sciences
Ministry of Water and Irrigation	2	Groundwater Directorate
Total	17 experts	

3.4.3 Land Use/Cover Mapping

Research, previously discussed has shown that land use and land cover is one of the criteria that affects groundwater recharge. The land use/land cover map was extracted from the satellite imagery (Landsat TM imagery) and classified using a supervised classification to identify the land use/land cover classes for the study area (Figure 3.14). The satellite imagery, with 30m spatial resolution was acquired by the USGS Landsat sensor in July 2003. This imagery was available free of charge.

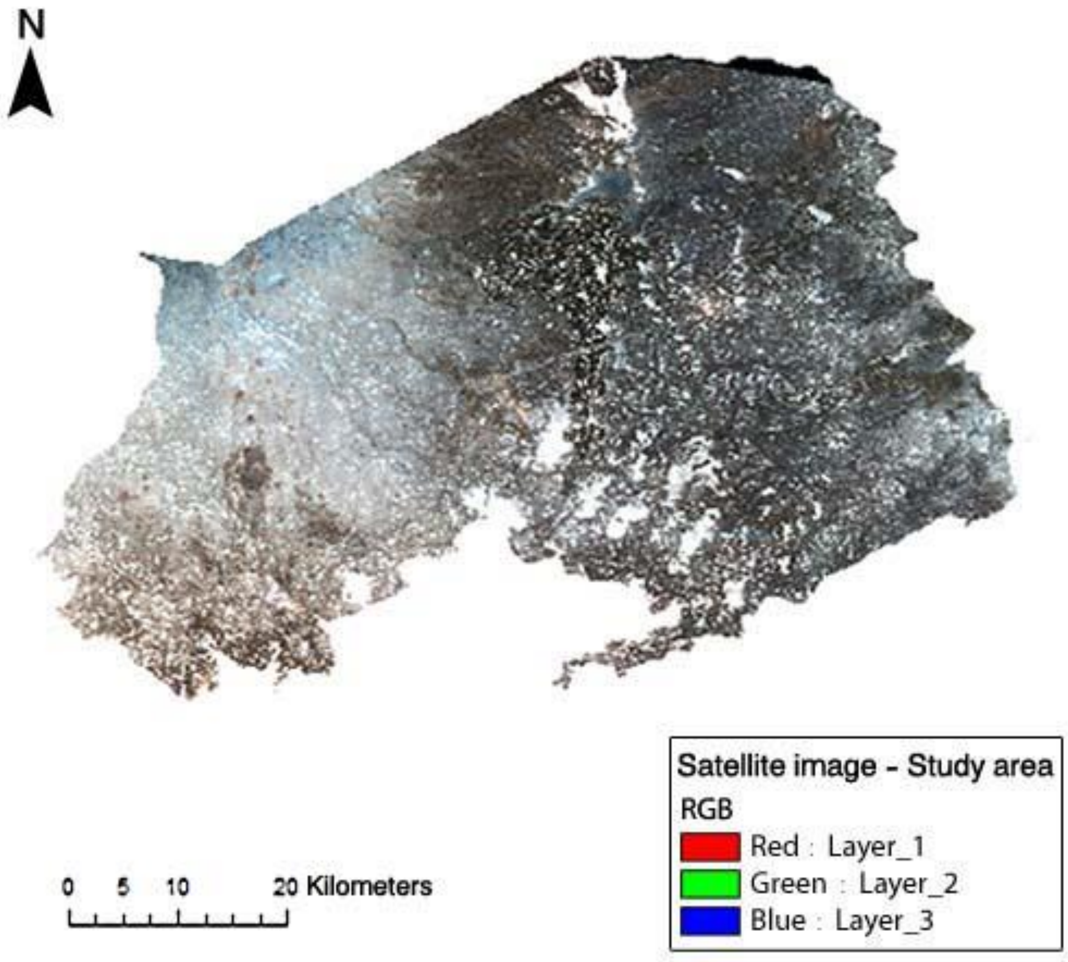


Figure 3.14. The Landsat TM image (shown here as a True Colour Composite) used to derive land use/cover in the study area (USGS, 2003)

The process of classifying the Landsat imagery included the following major steps:

1. Downloading the Landsat imagery for the study area (free of charge) from (http://earthexplorer.usgs.gov/
2. Importing the imagery to the ERDAS imagine Software,
3. Training of the software for six classes,
4. Conducting the supervised classification.
5. Importing the supervised classification outcome into ArcGIS and convert it into Vector format
6. Using the final land use/ land cover map in the selection criteria.

Figure 3.15 shows the classified image. Five different land use/cover types in the study area are identified: bare rock, urban, bare soil, natural vegetation, agricultural areas e.g. farms, and the Marab. The Marab is formed from blockages that are not substantial enough to create pools but which impedes runoff which has led to soil accumulation. Flood water that does not infiltrate into the soil finds its way out of the Marab (Al Ayash *et al.*, 2012). Land use/land cover classes comprising natural vegetation and agriculture were given the higher rating, whereas the Marab was given a moderate rating, the bare rock and the urban were given low ratings.

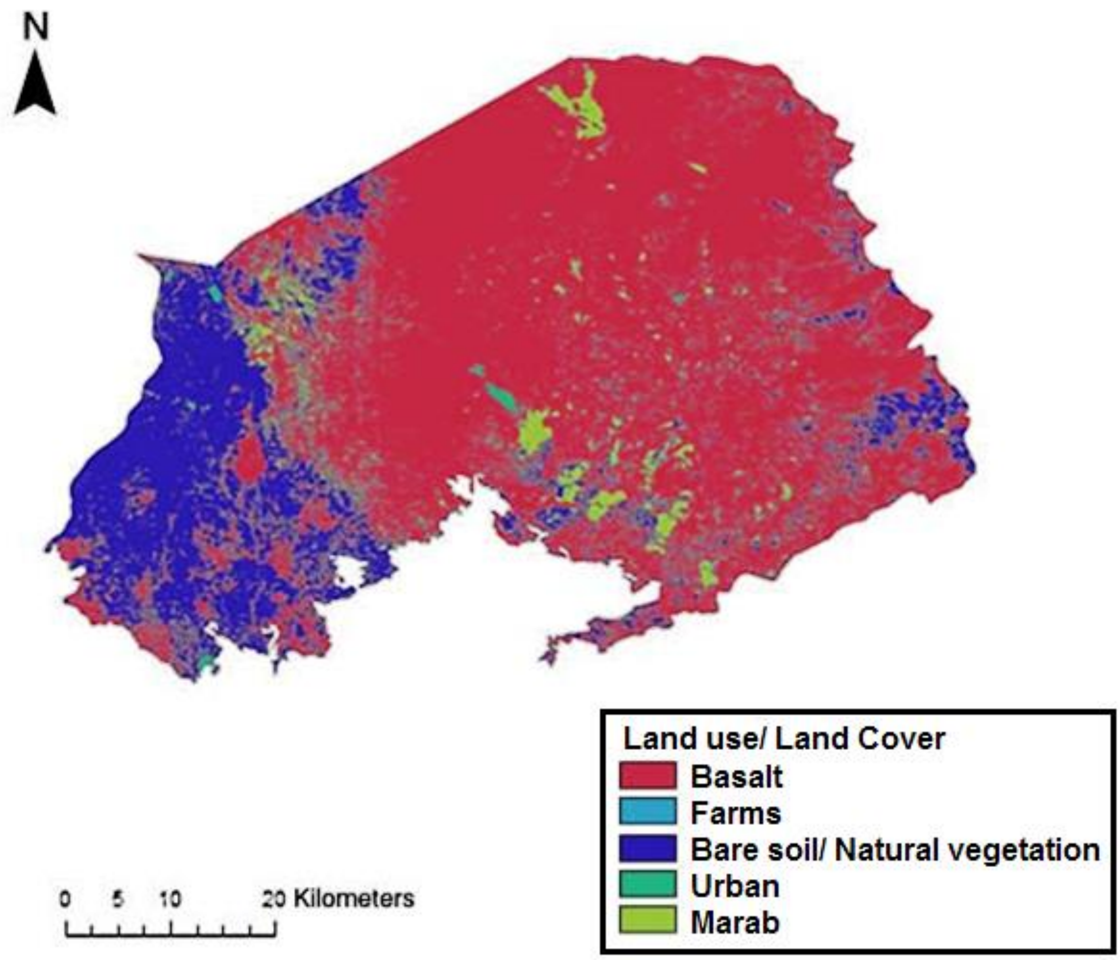


Figure 3.15. Classified land use/land cover map of the study area, derived from Landsat TM imagery (USGS, 2003)

3.5 Spatial Data Analysis Methods

The Weighted Linear Combination (WLC) and the Boolean methods are used to select the potential sites for the groundwater recharge within the study area. Figure 3.16

summarises the methods used to select potential sites for the groundwater recharge. Nine physical and five socio-economic factors are used in this study to identify optimum sites for groundwater recharge.

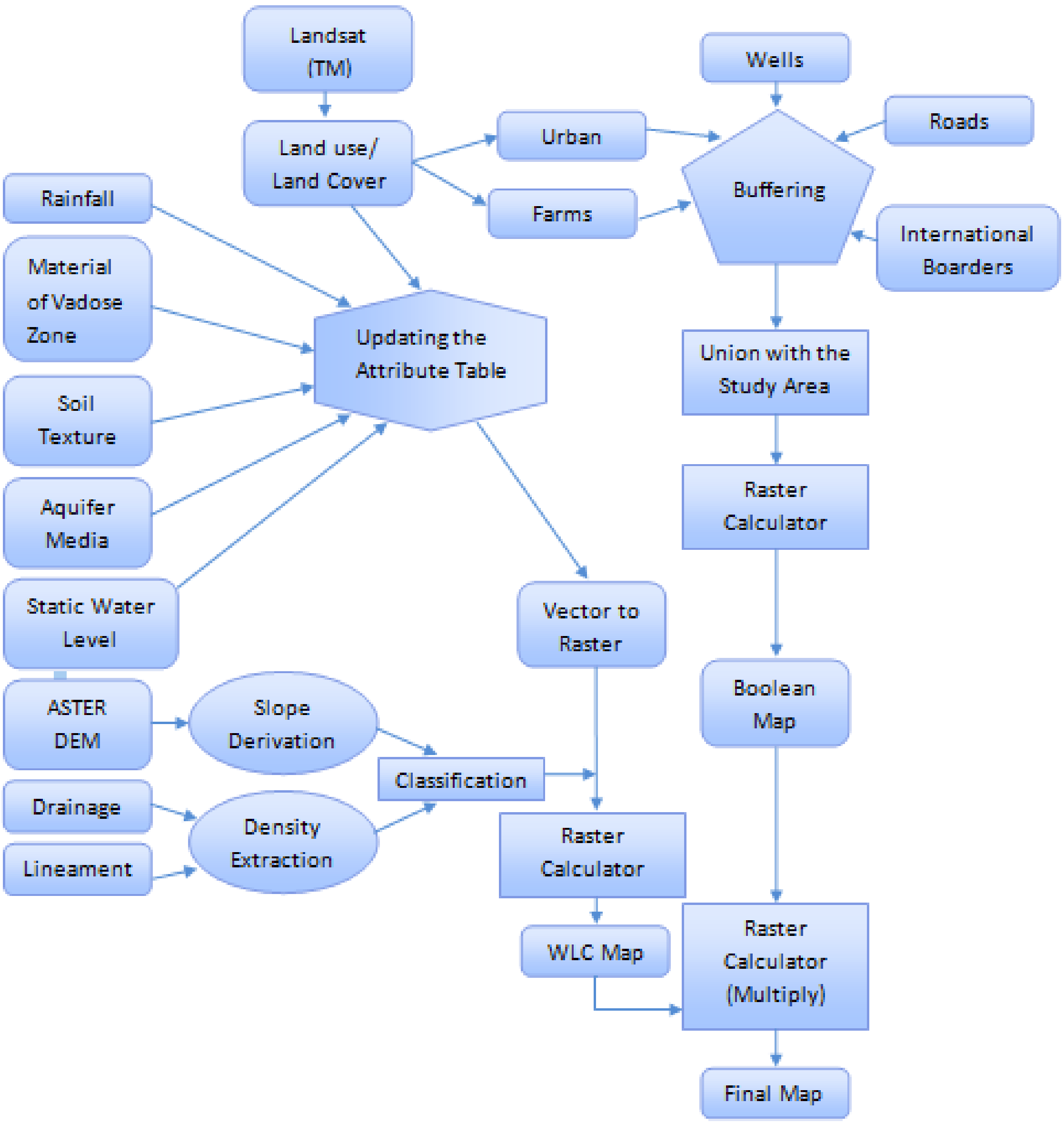


Figure 3.16. Flowchart of the spatial analysis method used in this study

Furthermore, the following spatial data techniques were used:

- Buffering
- Union
- Updating attribute tables

- Slope derivation
- Density extraction
- Raster reclassification
- Raster calculation (addition and multiplication).

The buffer zones applied for each socio-economic criterion is based on the appropriate buffer distance listed in Table 3.6.

Table 3.6. Groundwater recharge selection factors based on the Boolean technique

Factors	Suitable (1)	Not Suitable (0)
Roads	>250 m	<250 m
Proximity of international border	>1000 m	<1000 m
Urban	>500 m	<500 m
Agricultural	>500 m	<500 m
Wells	>500 m	<500 m

Union in ArcGIS was used to spatially merge the buffer zones of each socio-economic criterion with the study area to incorporate the areas beyond the selected zone distances. The 3D Analyst in ArcGIS is used to derive the slope from the 3D ASTER DEM. In addition, ArcGIS is used to extract the density of the Wadis and the Lineament based on a mythology adopted by Al-Adamat, (2012).

Raster reclassification is used to reclassify the slope, the densities, the Wadis and the lineaments. Finally, all maps were subjected to a raster calculation to select the potential sites for the groundwater recharge after multiplying each layer with its appropriate weight.

3.6 Fieldwork

Fieldwork was carried out to investigate the physical characteristics of the soil and to conduct a geophysical investigation for some selected sites within the study area. These investigations were carried out to validate the result of the site selection process. The geophysical methods (TDEM) and the characteristic of the soil (Soil texture analysis) were implemented in some selected sites that represent all the classes that resulted from the GIS analysis. The geophysical investigation uses the TDEM method to search for a high resistivity zone (recharge layer). The soil physical characterisation uses the soil texture analysis to determine the sand, the silt and the clay percentages.

Global Positioning System (GPS) data and Google Earth images were used to conduct the fieldwork of this research. Site selection took into account:

- Accessibility: the selected sites are close to roads, which would facilitate reaching the sites and carrying the necessary equipment.
- Time: the available time to carry out the fieldwork was very limited, which prevented visiting more sites for extra investigation,
- Financial resources: Equipment and technicians were provided free of charge by Al al-Bayt university (Mafraq Jordan) for a limited period. Transportation to the field was privately funded by the researcher.

The methodology used to select sites for the soil properties and geophysical investigation is shown in Figure 3.17. The selected sites were randomly selected, to represent all classes of the GIS results. In the GIS environment, the X, Y coordinates for the centre of each polygon was added. A point shape file was generated based on the X and Y coordinates for each polygon. A KML file was then generated and opened by Google Earth. In addition, the X and Y coordinates were uploaded to Germen GPS and the tracking capabilities of GPS were used to locate the sites. A laptop with internet access via USP internet stick was also used in the field to access Google Earth imageries to compare the imagery with the actual land cover for extra verification.

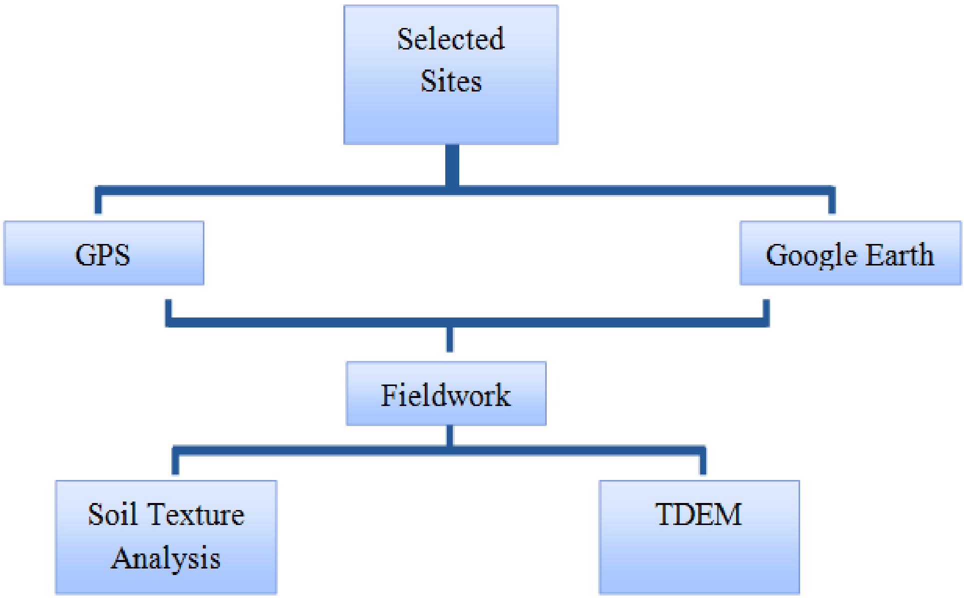


Figure 3.17. Methodology adopted for selecting sites for fieldwork

TDEM was used in this research to identify the layer with a high resistivity and link this layer with the groundwater recharge suitability map. If the zone has a high resistivity, located near the surface, and the suitability is high, this means that the area is suitable for groundwater recharge. The TDEM survey involves the transmission of a current through a rectangular loop, normally laid on the ground. According to Faraday's Law, the current is transported in the subsurface, decaying with time and producing secondary magnetic fields that create a measurable voltage in the receiver. The measured voltages can be converted into apparent resistivity values to represent the properties of the subsurface. In addition to TDEM, the hydrometer method of particle size analysis of Al-Amoush *et al.* (2012) was used in this research for the soil texture analysis of the investigated sites. The percentage of sand, silt and clay in the inorganic fraction of soil is measured in this procedure. The method is based on Stake's law governing the rate of sedimentation of particles suspended in water.

In this research, sixteen sites were investigated using the TDEM geophysical survey in which coincident single turn of 20 m x 20 m loop was used to gain sufficient penetration depth (~60m). The system was set to transmit currents of up to 2 ampere using 12 voltage source batteries with 48 active time gates (15360 µs –t center). The stacking time was set to about 3 minutes with 50 Hz noise filter in order to avoid aliasing effects of possible galvanic interference. Sixteen surface soil samples were collected from eight sites located in the study area. The distance between the two samples was 50 m. The soil samples were collected from the top 30 cm. The results of this method are explained in Chapter 6.

3.7 Methodological Limitations and Uncertainties

The following limitations and possible sources of errors might lead to some uncertainties in the research outcomes.

ASTER DEM of USGS: Holmes *et al*. (2000) investigated the errors resulting from the use of USGS DEM on terrain analysis. The authors suggested that although the global (average) error is small, local error values could be large. This might lead to generate a slope map for the study area with some errors that should be accounted for when implementing the groundwater recharge sites within the selected areas.

Spatial resolution of image data from Landsat TM: Satellite imagery data used in this research were outdated (since 2003), which limited the land use/land cover map. In addition, the spatial resolution of the satellite imagery data used in this research is 30m. This resolution could be improved by using higher resolution imageries to quantify more accurately the land use/land cover in the study area.

Map Scale errors: Maps data were available at a scale of 1:250,000, which limits the sites identification. Errors in map scale is equal to 0.1 mm which means that all maps used in this research is expected to have an error of 25 m each. This might generate some errors in the final map. Therefore, the final map needs to be verified through the fieldwork as described in the previous section.

Limited fieldwork for site verifications: Although it is recommended to visit all sites (suitable and not suitable) for further investigation, this could not be achieved due to the site accessibility difficulties, time constrains, and funding limitations.

Selection criteria: Due to the paucity of publications that used GIS for the groundwater recharge site selection worldwide, it was the author responsibility to generate a new selection criteria based on the available literature. In order to overcome this limitation, the researcher collected the selection criteria from different sources including the local experts.

Expert opinion: It was not possible for the researcher to organise a meeting for all experts in one place as suggested in the literature (Malczewski, 1999; Saaty, 1980). This is due to the time constraint and funding limitations. In addition, uncertainty in experts' opinions is expected since not all the experts have the same information on the criteria. Thus, the AHP approach was implemented to evaluate the consistency between the experts opinion.

3.8 Summary

A study area has been defined in a groundwater basin in Jordan that meets the criteria necessary to address the research questions that have been defined in this study and meet the overall aim. A section of the Azraq basin, approximately 4,000 km2 was identified for the purpose of this study. Data sets related to physical characteristics of the data have been compiled from various sources including the classification of Landsat TM satellite data. A questionnaire has been designed and experts identified. The setting for fieldwork activity has been defined to validate the findings of the study outcomes. Finally, in this chapter, limitation that may lead to uncertainties in the findings are discussed.

4 ACQUIRING AND ANALYSING THE OPINIONS OF EXPERTS

This Chapter describes how individual experts' opinions are combined in the decision making process for siting the appropriate sites for groundwater recharge. Experts' views are reconciled. The methodology to calculate the Analytical Hierarchy Process (AHP) is implemented. Criteria identification is useful for indicating the degree to which these criteria are suitable for the groundwater recharge (Malczewski, 1999). Determining the criteria is an important method for the site selection of groundwater recharge, where site selection is based on the appropriate literature reviews and experts' opinions. The opinions of the experts and the literature review were combined to determine the most important criteria for the groundwater recharge sites selection within the study area. As defined in an earlier Chapter, nine criteria were defined:

a) Rainfall
b) Material of Vadose Zone
c) Slope
d) Lineament Density
e) Soil Texture
f) Drainage Density
g) Static Water Level
h) Aquifer Media
i) Land cover/use

4.1 Defining weights of criteria from individual opinions of local experts

There are different assessments to the criteria required to determine the suitability of a site for the groundwater recharge. Therefore, it is necessary to determine the importance of each of these criteria in respect to the suitability of recharge. Analytical Hierarchy Process (AHP) is a powerful tool that was developed to help decision makers and experts to assess the criteria and make effective decisions based on the importance of each criterion to locate suitable sites for the groundwater recharge.

4.2 Selection of the Local Experts

After defining the criteria for selecting sites for the groundwater recharge, the structured interviews were undertaken with local experts. The interviews were carried out in March 2012. The questionnaire, shown in Table 4.1 was used to identify the relative importance of all the selected criteria. This questionnaire was based on the scale of 1-9 for the experts to assess the relative importance of each individual criterion. The interview was conducted with 17 experts from Jordanian Universities and some institutions that are relevant to the issues of the groundwater recharge (e.g. The Ministry of Water and Irrigation). The background of experts covered the fields of geology, hydrogeology, civil engineering (water resources), groundwater and Geographic Information System (GIS). The experts were selected based on their knowledge of the study area and the water issue in Jordan in general and the study area in particular. Breaking down their seniority, 7 were professors and 10 associate professors with 8 - 17 years of experience in their respective fields. Many of the experts had previously published their research (Rida Al-Adamat, 2012; Saad Al-Ayyash *et al*., 2012; Al-Adamat *et al*., 2010; Al-Adamat *et al*., 2007; El-Naqa, 2010; Al-Amoush, 2010). Interviews were conducted face to face.

Table 4.1. A sample from the questionnaire used to determine the relative importance of criteria. The explanantion box was a free hand text box where the expert could off more details about the Criteria if necessary

Criteria	Weight	Explanations
Rainfall		
Lineament Density		
Static Water Level		
Aquifer Media		
Material of Vadose Zone		
Slope		
Land cover/use		
Drainage Density		
Soil Texture		

Based on the literature review, the criteria were selected and subjected to a review by the local experts to determine the relative importance of each criterion. Generally, there are two types of questionnaire surveys: (a) descriptive and (b) analytical. The aim of a descriptive survey is to find facts and describe a certain phenomenon, whereas the analytical surveys aim to explain the phenomenon they describe (Oppenheim, 1992). In this research, an analytic questionnaire survey was carried out to explore the opinions of the experts in the relative importance of the criteria selected for groundwater recharge using a scale of 1 to 9. The analytic questionnaire was used to check the consistency ratio (CR) and identify the weights for the selected criteria. This involved interviewing the groundwater experts and collecting specific data about the criteria.

Questions in an interview are normally open or closed (Jolliffe, 1986). A closed question is where the respondents are given a choice of alternative answers and an open question does not give any kind of choice as the answer has to be recorded in full (Oppenheim, 1992). The questions used in this survey were based on closed questions. Oppenheim (1992) argued that the main advantage of using open questions is that respondents are able to answer with freedom. However, open questions can take a long time to be answered, the replies vary and the analysis may be difficult.

The results of the conducted questionnaire are summarised in Table 4.2. The experts' opinions were selected according to the scale 1-9, and then the Pairwise Comparison Method (PCM) was applied within the Analytical Hierarchical Process (AHP) to check the CR and to identify the final weights for each criterion.

Table 4.2. Summary of the importance of criteria determined by each expert

Criteria	Experts																
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Rainfall	9	9	9	9	9	9	9	8	9	8	9	6	8	9	9	9	9
Vadose Zone	5	8	8	6	8	4	5	8	8	6	6	8	8	8	8	7	8
Slope	4	6	6	8	8	8	7	5	5	6	8	9	9	9	7	4	5
Lineament Den.	8	7	7	5	6	4	5	6	6	5	4	4	8	5	5	4	7
Soil Texture	8	5	5	4	7	5	4	5	4	6	4	8	6	8	7	4	3
Drainage Density	7	5	5	3	6	6	7	7	6	4	5	5	5	8	4	5	4
Static Water Level	8	4	4	5	4	4	4	4	6	3	7	3	7	8	7	5	5
Aquifer Media	7	4	4	3	4	7	3	7	3	4	4	5	4	9	6	7	6
Land use/cover	4	3	3	4	4	6	3	3	3	5	3	7	3	9	3	3	4

It can be noticed from Table 4.2 that there are a strong agreement about the relative importance of some of the criteria such as the rainfall. However, major discrepancies can be observed in the experts' opinion on the relative importance of some of the selected criteria such as the slope and the liniment density. This does not mean that there is no consistency between the experts' opinions.

4.3 Assessment of the Consistency

CR is calculated using Pairwise Comparison (PWC) technique to assess the consistency between the acquired experts' opinions. PWC was applied to check that the weights for the selection criteria given by the experts are consistent. The traditional implementation of AHP is modified in this study (Al-Harbi, 2001; Malczewski, 1999; Mendoza *et al.*, 1999; Ozturk and Batuk, 2011). Using the traditional AHP method, the group of experts are asked to provide weights for the selection criteria in a general meeting, where discussion between experts is encouraged to reach appropriate weight for each criterion (Malczewski., 1999; Saaty., 1980). In this study, the adopted AHP method was based on providing a questionnaire to each expert individually to provide a weight for each criterion. Given that it was difficult to bring all experts together, discussion on agreement was not possible. Furthermore, the discrepancies of the raw opinions of the experts was considered to be useful information.

The aggregation uses a feedback from all the experts' opinions, and each expert opinion assessment was weighted using the relevance matrix. This idea comes from Bailey *et al.*, (2003). They applied the new fuzzy algorithm for finding and exploring the criteria group site selection, by involving a group of individuals and evaluating a set of alternative sites based on multiple criteria to use in the site selection for a recycling facility on the Brisbane Airport site.

CR was calculated for all the acquired experts opinions to check if it is less than or equal to 0.1, thereby to check the suitability of each pairwise comparison matrix for the AHP analysis. The process of constructing the pairwise comparison matrixfor all the experts in this study was based on the study of Al-Harbi (2001); Malczewski (1999); and Ozturk and Batuk (2011). The pairwise comparison matrix analysis was produced (Tables 4.3 and 4.4). The pairwise comparison matrix of the criteria evaluations given by expert number 1, and the computed criteria weights respectively. The letters (a, b, c, d, e, f, g, h, i) represent the 9 criteria selected as shown in Table 4.1. The pairwise comparison matrix produced for the remaining 16 experts are shown in Appendix A. The computed Principal Eigenvalue (λ_{max}), the Consistency index (CI), random consistency ratio (RI), and the Consistency Ratio (CR) of the evaluations of all the experts are shown in Table 4.5. It can be seen that the computed CR is less than or equal to 0.1 for all experts. This indicates that all experts' weightings are consistent and suitable of the implementation of the AHP approach.

Table 4.3. The pairwise comparison matrix of expert number 1 opinions

Criteria	a	b	c	d	e	f	g	h	i
a	1.000	1.800	2.250	1.125	1.125	1.286	1.125	1.286	2.250
b	0.556	1.000	1.250	0.625	0.625	0.714	0.625	0.714	1.250
c	0.444	0.800	1.000	0.500	0.500	0.571	0.500	0.571	1.000
d	0.889	1.600	2.000	1.000	1.000	1.143	1.000	1.143	2.000
e	0.889	1.600	2.000	1.000	1.000	1.143	1.000	1.143	2.000
f	0.778	1.400	1.750	0.875	0.875	1.000	0.875	1.000	1.750
g	0.889	1.600	2.000	1.000	1.000	1.143	1.000	1.143	2.000
h	0.778	1.400	1.750	0.875	0.875	1.000	0.875	1.000	1.750
i	0.444	0.800	1.000	0.500	0.500	0.571	0.500	0.571	1.000
Sum	6.667	12.000	15.000	7.500	7.500	8.571	7.500	8.571	15.000

Table 4.4. The criteria weights (priority vector)

Criteria	Weight (priority vector)
Rainfall	0.150
Lineament Density	0.083
Static Water Level	0.067
Aquifer Media	0.133
Material of Vadose Zone	0.133
Slope	0.117
Land cover/use	0.133
Drainage Density	0.117
Soil Texture	0.067

Table 4.5. The computed values of λ_{max}, CI, RI, and CR for all the local experts

Experts	λ_{max}	CI	RI	CR
1	9.81	0.10	1.45	0.07
2	10.08	0.14	1.45	0.09
3	10.08	0.14	1.45	0.09
4	10.3	0.20	1.45	0.10
5	9.88	0.11	1.45	0.08
6	9.79	0.10	1.45	0.07
7	10.3	0.20	1.45	0.10
8	9.93	0.12	1.45	0.08
9	10.30	0.20	1.45	0.10
10	9.70	0.90	1.45	0.06
11	10.20	0.10	1.45	0.10
12	10.10	0.10	1.45	0.10
13	10.20	0.10	1.45	0.10
14	9.28	0.04	1.45	0.02
15	10.05	0.13	1.45	0.09
16	10.03	0.13	1.45	0.09
17	10.08	0.14	1.45	0.09

Due to the difficulty of gathering all the experts in one place, there was a need to create or find methods to represent all the experts' opinions and use the relationship amongst all the opinions. Thus, the Mean, the Median, and the Mode of the criteria weights were calculated to represent and compare the experts’ opinions. The mean of a data set is the average of all the data values, while the median of a data set is the value in the middle when the data items are arranged in ascending order. The mode of a data set is the value that occurs with the greatest frequency. Ezell (2001) utilised the mean, the median, and the mode to measure the central tendency in stakeholders for site selection. Due to the response of the individual experts, determining a single good measure of weights for the criteria was difficult. Although the mean is usually preferred to assess the different experts' opinions in criteria weights, the experts were interviewed individually and thus such approach is susceptible to outliers. An answer to the outlier susceptibility was the median. The final measure of the different experts' opinions, the mode, represented what would have occurred if the local experts voted on the relationship between the weights of the criteria. Since the mean, the median, and the mode each had advantages in measuring weights criteria relationships, they were calculated for all the expert evaluations and later used to generate three different suitability maps. The pairwise comparison matrix of the computed mean, median and mode are shown in Tables 4.6 to 4.8 respectively. The CR was less the 0.1 for the pairwise comparison metrics of the mean, the median, and the mode of the experts' evaluation of the site selection criteria represents the consistency ratio of the combined opinions of all the experts, the averaged, the median, and the mode of the weights. Since the calculated CR is less than or equal to 0.1 for all the experts weightings, both individually and collective, this indicates that the acquired experts opinions are consistent, and are suitable for the implementation of the AHP analysis.

Table 4.6. The pairwise comparison matrix of the average of the experts' evaluations of the site selection criteria

Criteria	a	b	c	d	e	f	g	h	i
a	1.000	1.236	1.289	1.531	1.581	1.599	1.670	1.689	2.100
b	0.809	1.000	1.043	1.239	1.280	1.294	1.351	1.367	1.699
c	0.776	0.959	1.000	1.188	1.227	1.240	1.295	1.311	1.629
d	0.653	0.807	0.842	1.000	1.033	1.044	1.091	1.104	1.371
e	0.632	0.781	0.815	0.968	1.000	1.011	1.056	1.068	1.328
f	0.625	0.773	0.806	0.958	0.989	1.000	1.044	1.057	1.313
g	0.599	0.740	0.772	0.917	0.947	0.957	1.000	1.012	1.257
h	0.592	0.731	0.763	0.906	0.936	0.946	0.988	1.000	1.243
i	0.476	0.589	0.614	0.729	0.753	0.762	0.795	0.805	1.000

λ_{max} = 9.38, CI= 0.05, RI= 1.45, CR= 0.03

Table 4.7. The pairwise comparison matrix of the median of the experts' evaluations of the site selection criteria

Criteria	a	b	c	d	e	f	g	h	i
a	1.000	1.125	1.286	1.800	1.800	1.800	1.800	2.250	3.000
b	0.889	1.000	1.143	1.600	1.600	1.600	1.600	2.000	2.667
c	0.778	0.875	1.000	1.400	1.400	1.400	1.400	1.750	2.333
d	0.556	0.625	0.714	1.000	1.000	1.000	1.000	1.250	1.667
e	0.556	0.625	0.714	1.000	1.000	1.000	1.000	1.250	1.667
f	0.556	0.625	0.714	1.000	1.000	1.000	1.000	1.250	1.667
g	0.556	0.625	0.714	1.000	1.000	1.000	1.000	1.250	1.667
h	0.444	0.500	0.571	0.800	0.800	0.800	0.800	1.000	1.333
i	0.333	0.375	0.429	0.600	0.600	0.600	0.600	0.750	1.000

λ_{max} = 9.99, CI= 0.12, RI= 1.45, CR= 0.085

Table 4.8. The pairwise comparison matrix of the mode of the experts' evaluations of the site selection criteria

Criteria	A	b	c	d	e	f	g	h	i
A	1.000	1.125	1.125	1.800	2.250	1.800	2.250	2.250	3.000
B	0.889	1.000	1.000	1.600	2.000	1.600	2.000	2.000	2.667
C	0.889	1.000	1.000	1.600	2.000	1.600	2.000	2.000	2.667
D	0.556	0.625	0.625	1.000	1.250	1.000	1.250	1.250	1.667
E	0.444	0.500	0.500	0.800	1.000	0.800	1.000	1.000	1.333
F	0.556	0.625	0.625	1.000	1.250	1.000	1.250	1.250	1.667
g	0.444	0.500	0.500	0.800	1.000	0.800	1.000	1.000	1.333
h	0.444	0.500	0.500	0.800	1.000	0.800	1.000	1.000	1.333
i	0.333	0.375	0.375	0.600	0.750	0.600	0.750	0.750	1.000

λ_{max} = 10.24, CI= 0.15, RI= 1.45, CR= 0.1

The calculated CRs for the individual and merged weights show that there is a good consistency in the experts' opinions. This result explains that there are no disagreements amongst the individuals of local experts and there is a competency in all the experts for the given weights of criteria. The result indicated that the rainfall criterion has the highest weight than any other criteria. Therefore, the rainfall criterion was considered to be the most significant criterion in the study area (Table 4.9).

Table 4.9. CR values of the combined opinions of all experts for all criteria

Experts	CR weights opinions individual	Final CR Averaged weights	Final CR Median weights	Final CR Mode weights
1	0.07			
2	0.09			
3	0.09			
4	0.1			
5	0.08			
6	0.07			
7	0.1.			
8	0.08			
9	0.1	0.03	0.085	0.1
10	0.06			
11	0.1			
12	0.1			
13	0.1			
14	0.02			
15	0.09			
16	0.09			
17	0.09			

Table 4.10 summarises the selected criteria for the groundwater recharge and their weights based on the experts' opinions and the literature reviews. These weights are used to extract the suitability map of the study area for the groundwater recharge.

Table 4.10. Weights of the criteria for groundwater recharge sites

Criteria	Weight of mean	Weight of Median	Weight of Mode
Rainfall (a)	0.162	0.176	0.180
Material of Vadose Zone (b)	0.131	0.157	0.160
Slope (c)	0.126	0.137	0.160
Lineament Density (d)	0.106	0.098	0.10
Soil Texture (e)	0.103	0.098	0.080
Drainage Density (f)	0.101	0.098	0.10
Static Water Level (g)	0.097	0.098	0.080
Aquifer Media (h)	0.096	0.078	0.080
Land use/ Land cover (i)	0.077	0.059	0.060

4.4 Summary

The weights for the selection criteria from the individual opinions of multiple experts and the assessment of the consistency between these opinions through the pairwise comparisons method has been determined. The suitability of this opinion for the implementation of the AHP approach has been determined. Seventeen local experts were asked to determine the relative importance of the different criteria. The individual opinions of the local experts were used to determine the weights of criteria selected through PCM and then merged to identify the final weights for each criterion. After calculating the CR for the opinions of each individual expert, the mean, the median and the mode weights were calculated out of all the experts' evaluations in order to further assess the discrepancy between experts' opinions.

Reflecting on the research questions and objectives of this study, the following have been addressed. Further discussion on the implications of these findings are presented in the final chapter.

- Can we utilise the views and opinions of multiple experts in the field of groundwater recharge with a spatial analysis framework to identify the suitable site for groundwater recharge in the study area?

This research question has been partially addressed through the conduct of interviews to gather the opinion of experts in groundwater hydrology and recharge potential. Criteria have been derived from the literature and there is some consistency in the opinions of experts.

- What is the consistency in these opinions and can they be represented spatially?

This question and the others as stated in Chapter 2 will be further explored in the next Chapter. We have achieved the following objectives that underpin the investigation of the research questions:

- We have identified a range of local experts from which to gather their opinion and determined the importance of each criterion from the experts in the context of groundwater recharge.

Further objectives will be addressed in subsequent chapters of this thesis.

5 SITING GROUNDWATER RECHARGE AREAS USING GIS METHODS

This chapter describes the data analysis used to select the suitable sites for the groundwater recharge within the study area. The first section explains the rating and weights of the site selection criteria for effective groundwater recharge. The second section discusses the data analysis, the Boolean and the Weighted Linear Combination (WLC) technique used in selecting the optimum sites for the groundwater recharge within the study area. The final section provides a summary of the chapter.

5.1 Weights and Rating of the Selection Criteria

To identify the potential sites for the groundwater recharge, site selection depends on the ranks and the weights of each thematic layer. As described in Chapter 4, opinions of interviewed experts were used to determine the weights of each site selection criterion for the groundwater recharge and the Analytical Hierarchy Process (AHP) approach used to assess the consistency of the expert opinions by using the consistency ratio(CR), which should be less than or equal to 0.1.

As stated in Chapter 3, the rating (rank) of nine physical criteria was selected based on a review of the literature. Using the WLC technique, the rate (rank) was assigned to each criterion in the scale of 1 to 4. This is the scale adopted by most of the related literature to date. Table 5.1 represents the weights and the rating (rank) of the nine criteria. The weights for these criteria were identified based on the opinions of the interviewed experts acquired from the pairwise comparison process of Chapter 4. The rating of these criteria was based on a review of the literature.

As discussed in Chapter 3, five implementations representative of socio-economic criteria (factors) were taken into account (roads, farms, wells, urban areas and the international border). These layers were multiplied together after being converted into raster format in ArcGIS. The buffers were then applied on the factors as listed previously. Then, 0 and 1 values were added to the new map containing all the buffered zones. This map was then converted to raster format.

Table 5.1. Rating and weights of the selection criteria

Criteria	Rating	Weight	Criteria	Rating(Ri)	Weight
Rainfall (mm)			Static Water Level		
<50	1		(m)		
50-100	2	0.162	>135	1	
100-300	3		100-135	2	0.097
>300	4		50-100	3	
			0-50	4	
Vadose Zone			Aquifer Media		
Mud flat	1		(Massive shale,		
Volcano	2		Metamorphic/	1	
Basalt	3	0.131	Igneous, Weathered		
Alluvium	4		metamorphic/ Igneous		
Slope (deg.)			and Glacial till)		0.096
>8%	1		(Bedded sandstone,	2	
4-8%	2	0.126	limestone, Massive		
2-4%	3		sandstone , Massive		
0-2%	4		limestone)		
Lineament Density			Sand and gravel	3	
(km/km^2)			Basalt and Karsts	4	
0-1.5	1		limestone		
1.5-2.5	2	0.106	Land use/land cover		
2.5-3.5	3				
>3.5	4		Bare Rock and Urban	1	
			Bare soil		0.077
Soil Texture			Marab and	2	
Loam	1		Agricultural and	3	
Silt Clay Loam	2	0.103	natural vegetation	4	
Silt Loam	3				
Sandy Loam	4				
Drainage Density					
(km/km^2)					
>2.55	1	0.101			
1.5-2.25	2				
0.75-1.5	3				
0-0.75	4				

5.2 Groundwater Recharge Suitability Mapping

Nine physical criteria and five socio-economic criteria (factors) were used to determine the suitable site for the groundwater recharge in the study area. The methodology used to determine the potential sites for the groundwater recharge was based on using the GIS analysis techniques including: the Buffering, the Union, the Updating Attribute Tables, the Slope derivation, the Density, the Extraction, the Raster, the reclassification, and the Raster Calculation (Addition and Multiplication).

5.2.1 Physical Criteria Analysis

Nine physical criteria were used in the research for selecting the suitable sites for the groundwater recharge are: rainfall, slope, material of the vadose zone, land use/land cover, soil texture, drainage density, aquifer media, lineament density and static water level. Weights and ratings were given to each individual criterion as shown in Table 5.1. The WLC technique was used to integrate these physical criteria. The process of implementing the WLC technique includes standardising the suitability maps, assigning weights of relative importance to the suitability maps, then combining the weights and the standardised suitability maps and obtaining a suitability score.

All the generated thematic layers were integrated in ArcGIS® in order to derive a map depicting the suitable areas for the groundwater recharge of the study area. The total weight of each map of the final integrated layer was computed using Equation 5.1:

$$\mathrm{Si} = (\mathrm{Rw.Rr}) + (\mathrm{MVw.MVr}) + (\mathrm{SLw.SLr}) + (\mathrm{LDw.LDr}) + (\mathrm{STw.STr}) + (\mathrm{DDw\,.\,DDr}) + (\mathrm{SWtw\,.\,SWtr}) + (\mathrm{AMw.AMr}) + (\mathrm{LULCw\,.\,LULCr}) \qquad (5.1)$$

Where, ‘w’ represents the weight of each criterion, and ‘r’ represents the rating of each criterion namely: Rainfall (R), Material of the Vadose Zone (MV), Slope (SL), Lineament Density (LD), Soil Texture (ST), Drainage Density (DD), Static Water Level (SWT), Aquifer Media (AM) and Land use/cover (LULC). ‘Si’ is the artificial groundwater recharge index, which is a dimensionless number that identifies the suitable sites for the groundwater recharge in the area.

As shown in Table 5.1, the nine GIS layers representing the physical criteria were subjected to a GIS analysis in order to select the optimum sites for the groundwater recharge in the study area based on these criteria. The attribute tables for each map were generated according to Table 5.1. All maps were converted to a raster format. All nine raster layers were then integrated to produce the optimum sites for the groundwater recharge within the study area.

Rainfall

The Rainfall plays a major role in identifying the suitable sites for the groundwater recharge because it determines the amount of water that falls on a certain area, and hence, the amount of the potential groundwater recharge. Areas that receive more rainfall are more likely to have more groundwater recharge than those with low rainfall. The rainfall map shown in Figure 5.1 was classified according to the data shown in Table 5.1. The variations in the rainfall (0 to 100 mm/year) allowed for classifying the entire area into two rainfall classes: 0-50 and 50-100 mm/year. The areas that have a rainfall of 0-50 mm/year were assigned with low weights, whereas, the areas that have a rainfall between 50-100 mm/year, were considered as moderate from a groundwater recharge prospective.

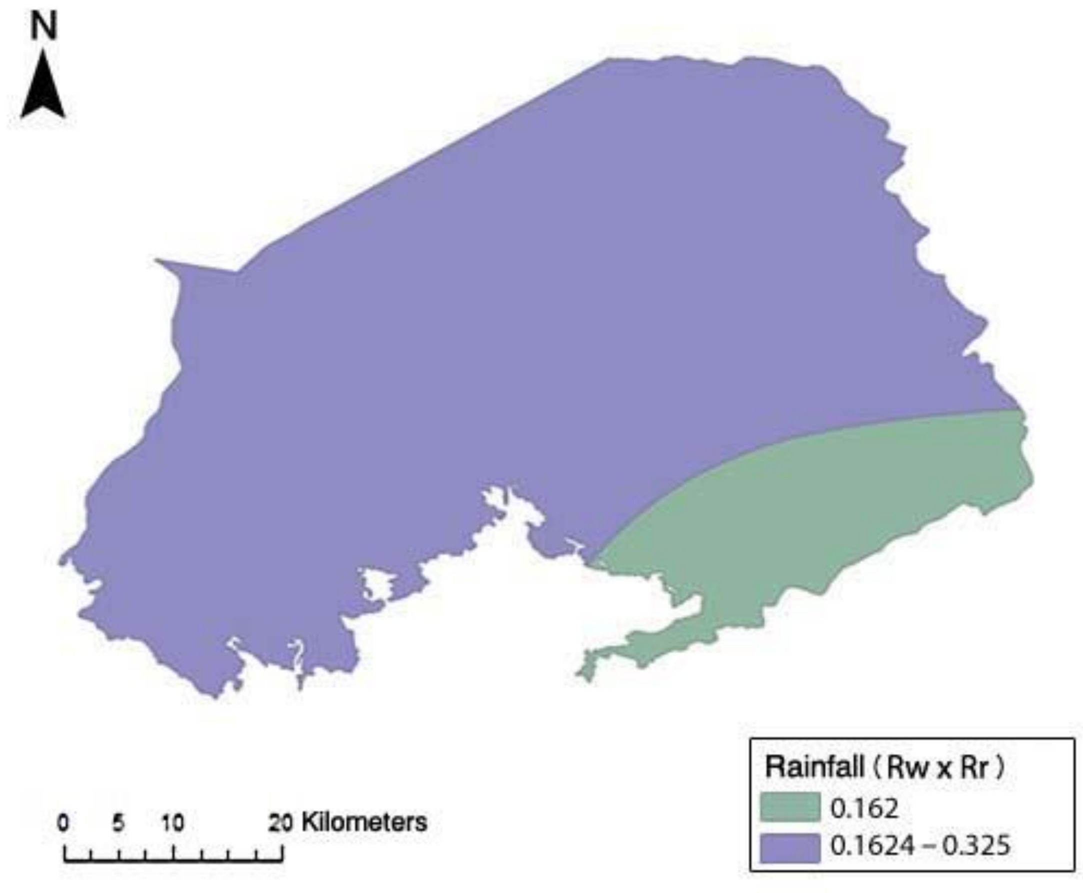


Figure 5.1. Rainfall suitability map of the study area

Material of the Vadose Zone

The vadose zone is the unsaturated zone above the water table where the recharge water passes through. The material of the vadose zone data of the study area was obtained from the Natural Resources Authority in a digital format. The major part of the material that makes up the vadose zone of the study area is the basalt, the alluvium, the volcano, and the mudflat. These four types of the vadose zone materials are classified based on their infiltration characteristics to: high (the alluvium), medium (the basalt), low (the volcano) and very low (the mudflat), and the weights were assigned according to Table 5.1. This is illustrated in Figure 5.2.

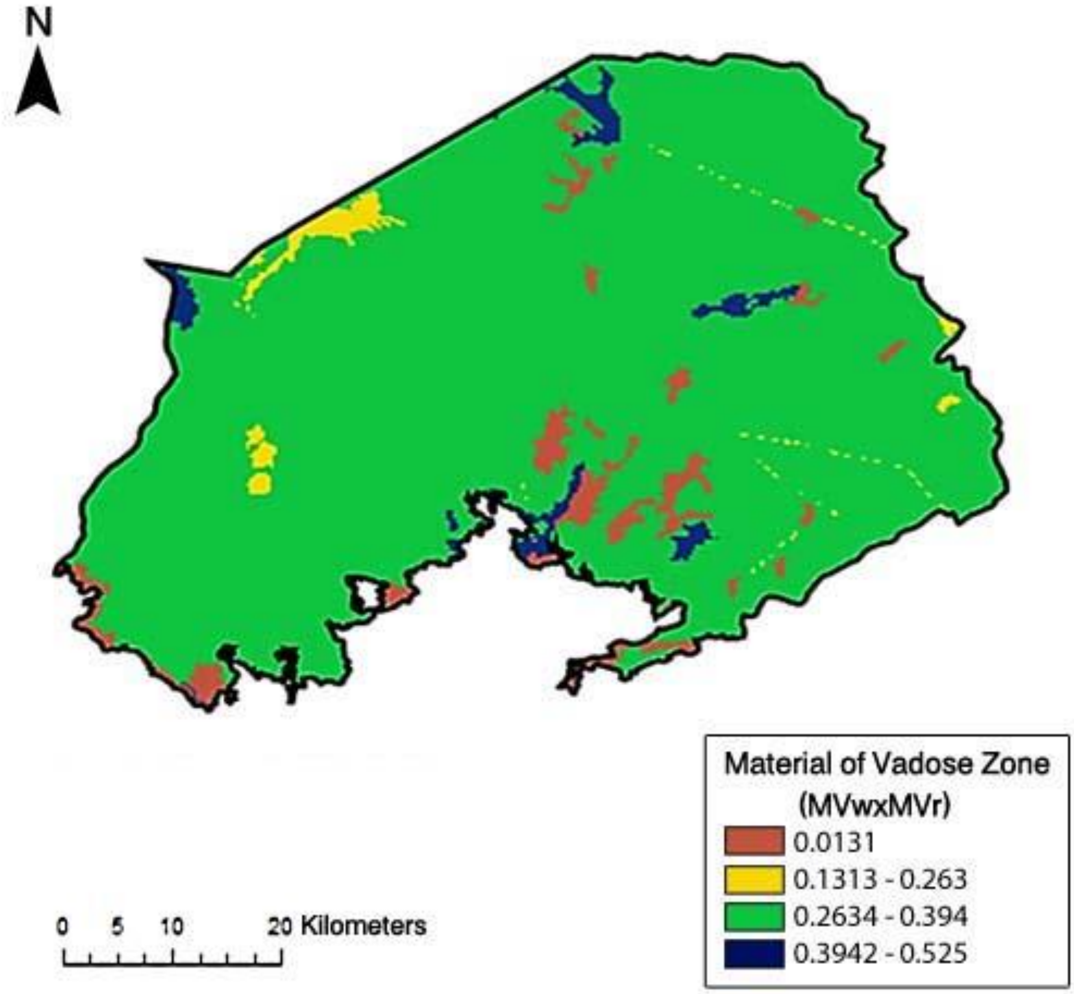


Figure 5.2. Material of the vadose zone suitability map of the study area

Slope

The slope is one of the main factors that affect the selection of the groundwater recharge sites. Water velocity is directly related to the slope angle of the ground. It predicts whether the runoff will stay on the surface enabling infiltration to the saturated zone. Areas with a low slope have a greater opportunity for recharge than areas with a high slope. The majority of the study area has a gentle slope. However, the slight variations in the slope of the study area (0 to 12.5 %) resulted in classifying the entire area into four slope classes i.e., 0-2, 2-4, 4-8 and > 8 %. The areas with a slope of 0-2 % were assigned with the highest rating values, whereas the areas that have a slope ranging between 2-4% were considered as moderate from the ground water recharge perspective. The areas that have a slope between 4-8 % and those with a slope that ismore than 8% were considered as low and very low respectively for the suitability for a groundwater recharge. Figure 5.3 illustrates the generated slope suitability map of the study area.

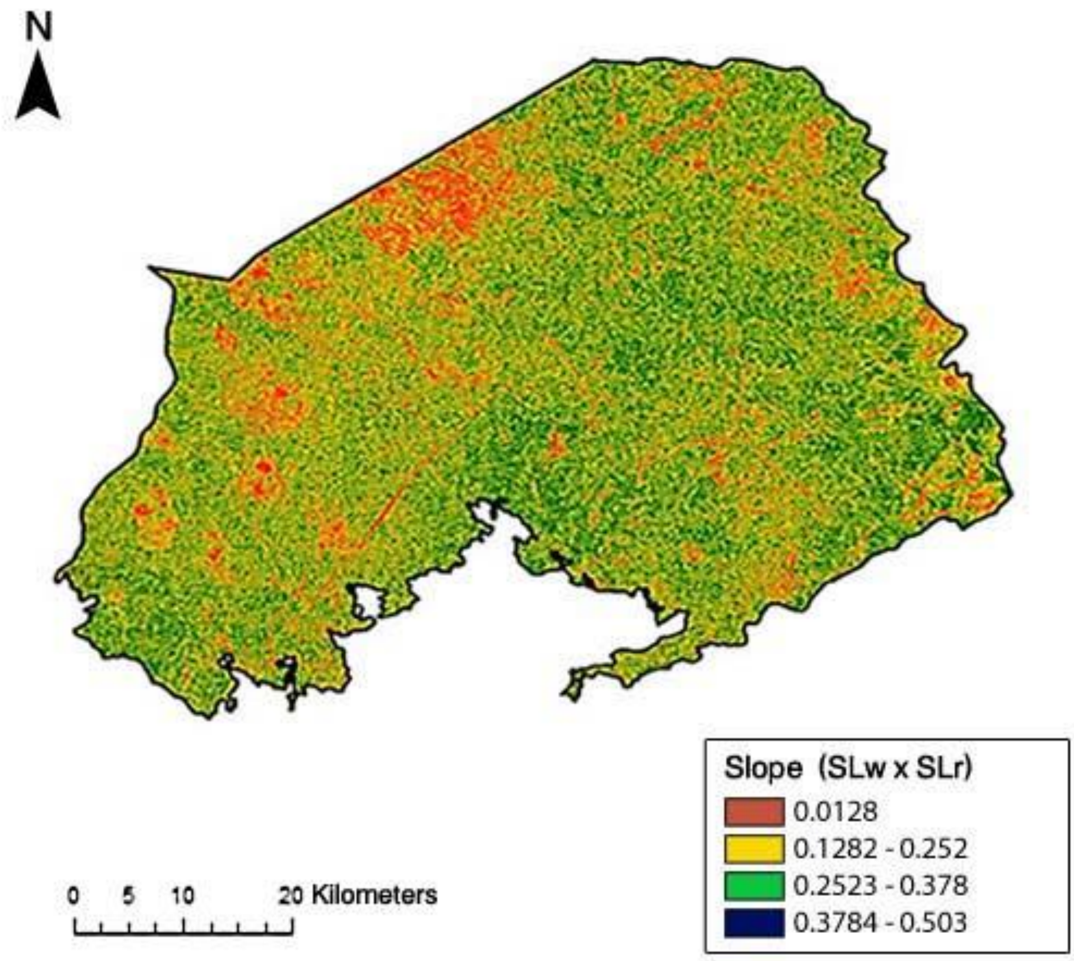


Figure 5.3. Slope suitability map of the study area based on ASTER DEM of USGS

Lineament Density

The lineament density plays an important role in identifying suitable sites for groundwater recharge because they reflect rock structures through which water can infiltrate. The lineaments map shown in Figure 5.4 was subjected to density calculation, and then classified according to the weights shown in Table 5.1. The lineament density map was prepared using the line density analysis tool in ArcGIS. The lineament density of the study area was in the range of 0 to 4.9 km/km^2. This range was classified into four classes namely, >3.5 (high), 2.5 to 3.5 (moderate), 2.5 to 1.5 (low) and < 1.5 (very low) km/km^2. From a groundwater recharge perspective, more weight was given where the lineament density was higher than 3.5 km/km^2, and, low weight was given where the lineament density was less than 1.5 km/km^2 as shown in Figure 5.4. If the lineament density zone is highly permeable then this will lead to a high infiltration.

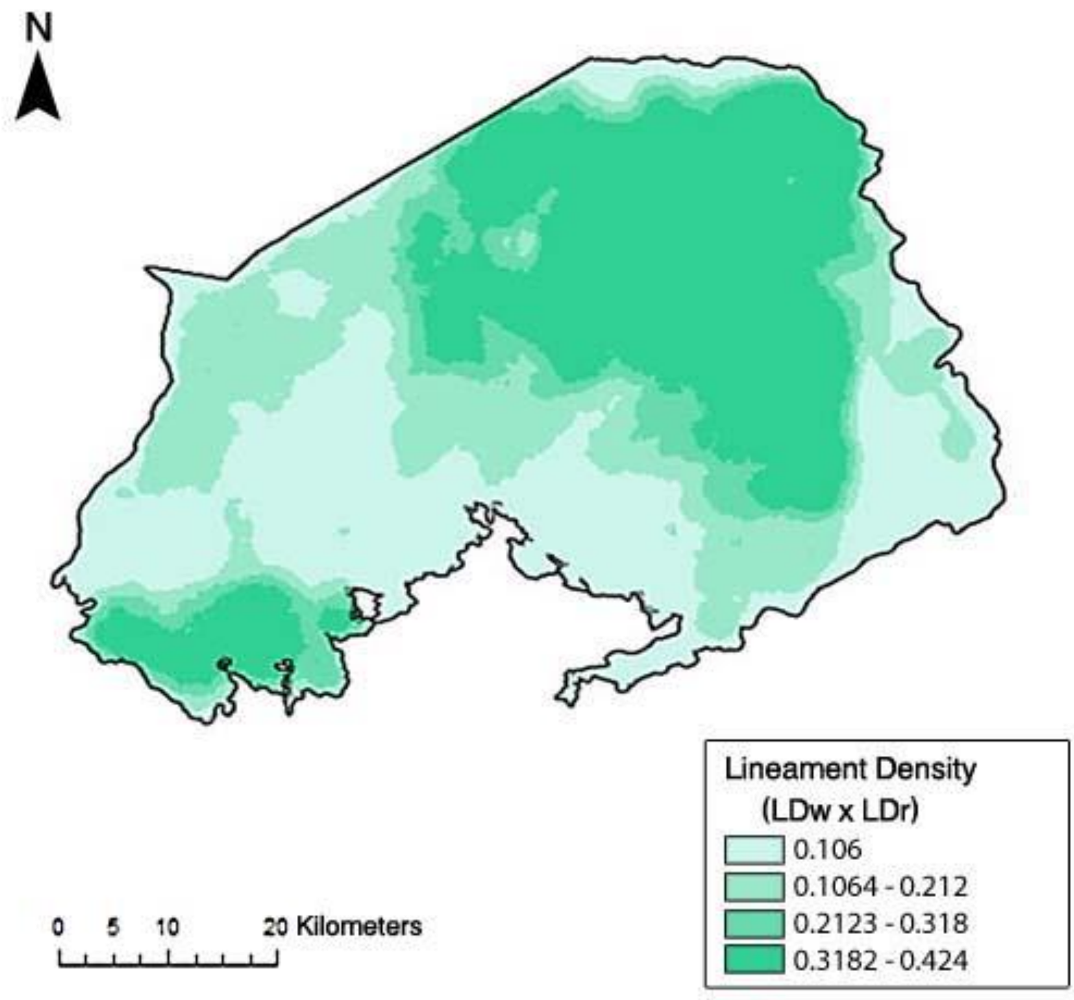


Figure 5.4. Lineament density suitability map of the study area

Soil Texture

The soil represents the uppermost portion of the vadose zone and controls the amount of recharge that can infiltrate downward to the saturated zone. This infiltration is affected by the texture, the structure, the thickness, the organic matter, the clay content, and the permeability of the soil. The soil texture map was classified according to the weights shown in Table 5.1. The soil texture plays a key role in the site selection process for the groundwater recharge, When the soil texture is sandy this indicates that the potential for a groundwater recharge is high, and if the soil has a clay texture, this indicates that there is limited opportunity for a groundwater recharge. Thus, the soil texture is one of the major criteria that affect the groundwater recharge process. The soils texture of the study area was classified into four categories: high (sandy loam), medium (silty loam), low (silty clay loam) and very low (loam). These values are shown in Table 5.1 and illustrated in Figure 5.5. It was assumed that the soils that have a sandy loam texture are suitable for groundwater recharge, while soils that have a clay or loam texture are not suitable for groundwater recharge.

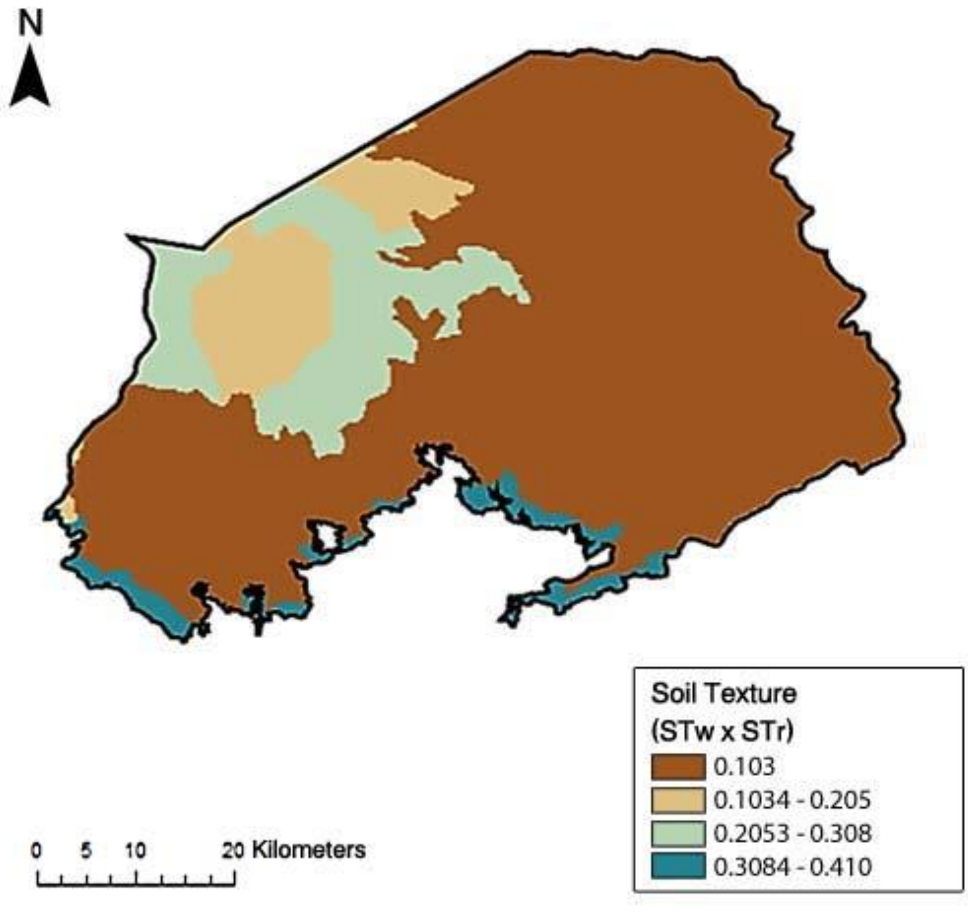


Figure 5.5. Soil texture suitability map of the study area

Drainage Density

The Drainage density is considered as one of the indicators for the groundwater recharge. It is inversely related to the permeability. The drainage density indirectly indicates the suitability for the groundwater recharge of an area because of its relation to the surface runoff and the permeability.

The drainage density map of the study area is shown in Figure 5.6. The drainage density map was prepared using the line density analysis tool in ArcGIS®. The dominant drainage pattern observed was parallel and dendritic. The density values of the study area ranged from 0 to 5.6 km/km^2. For the purpose of analysis, this range was classified in to four categories, i.e., high (> 2.25), medium (2.25-1.5), low (1.5-0.75) and very low (0-0.75) km/km^2. From a groundwater recharge perspective, high weight was assigned to the low drainage density regions, whereas low weight was assigned to the high drainage density regions. The zones with high drainage density values indicate high surface runoff, and hence, a low groundwater recharge.

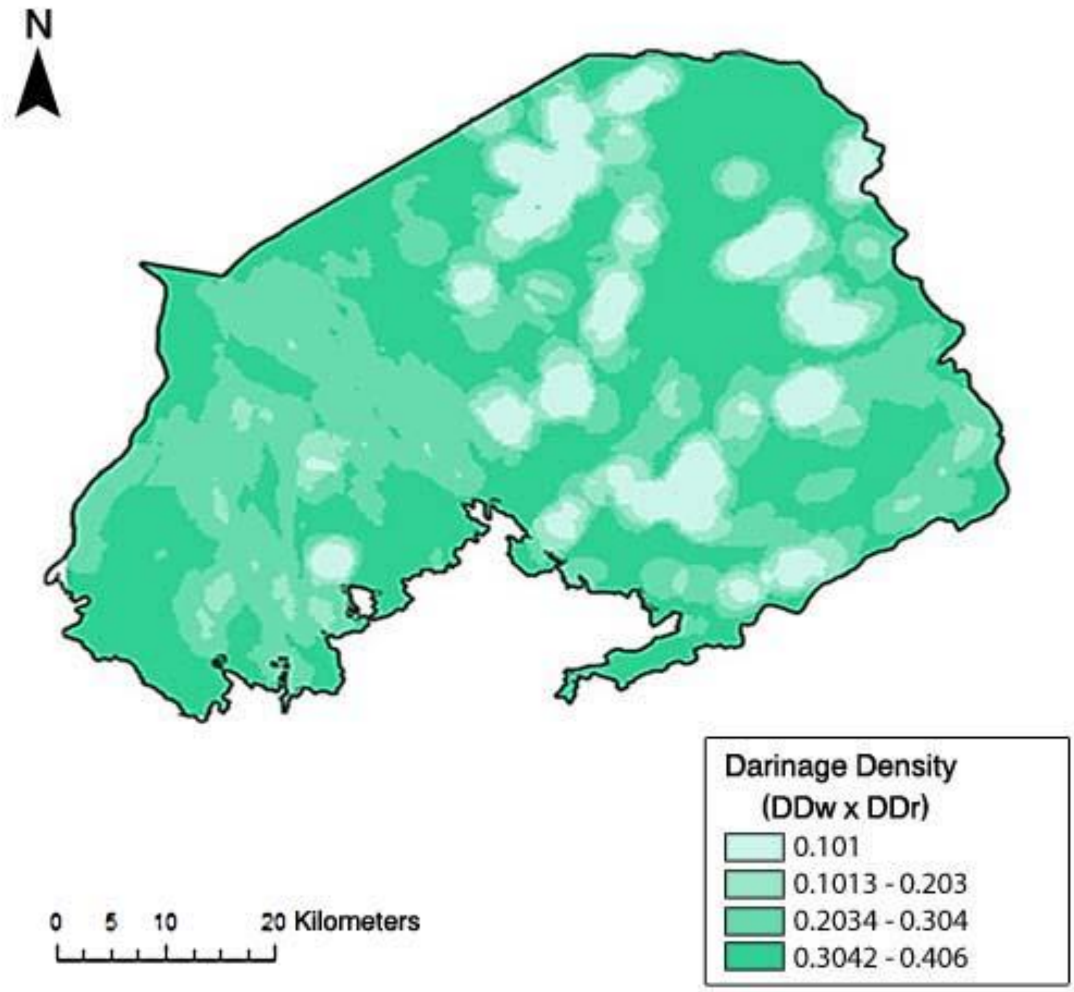


Figure 5.6. Drainage density suitability map of the study area

Static Water Level

The depth to the groundwater represents the depth from the ground surface to the static water level. This measure is used to determine the potential distance for water to travel to the aquifer. The depth to the groundwater map of the study area shown in Figure 5.7 was prepared using the IDW interpolation method of the spatial analysis tool in ArcGIS. There were significant variations in the depth of groundwater in the study area (0-480m). This variation has been classified into four classes including 0-50, 50-100, 100-135 and > 135m. The regions with the depth of 0-50m were given a high weight for a groundwater recharge, whereas the areas, which have a depth range of 50-100m, were considered as moderate from a groundwater recharge prospective. The areas that have a depth range of 100-135m and a depth of more than 135m were considered as low and very low respectively for a groundwater recharge.

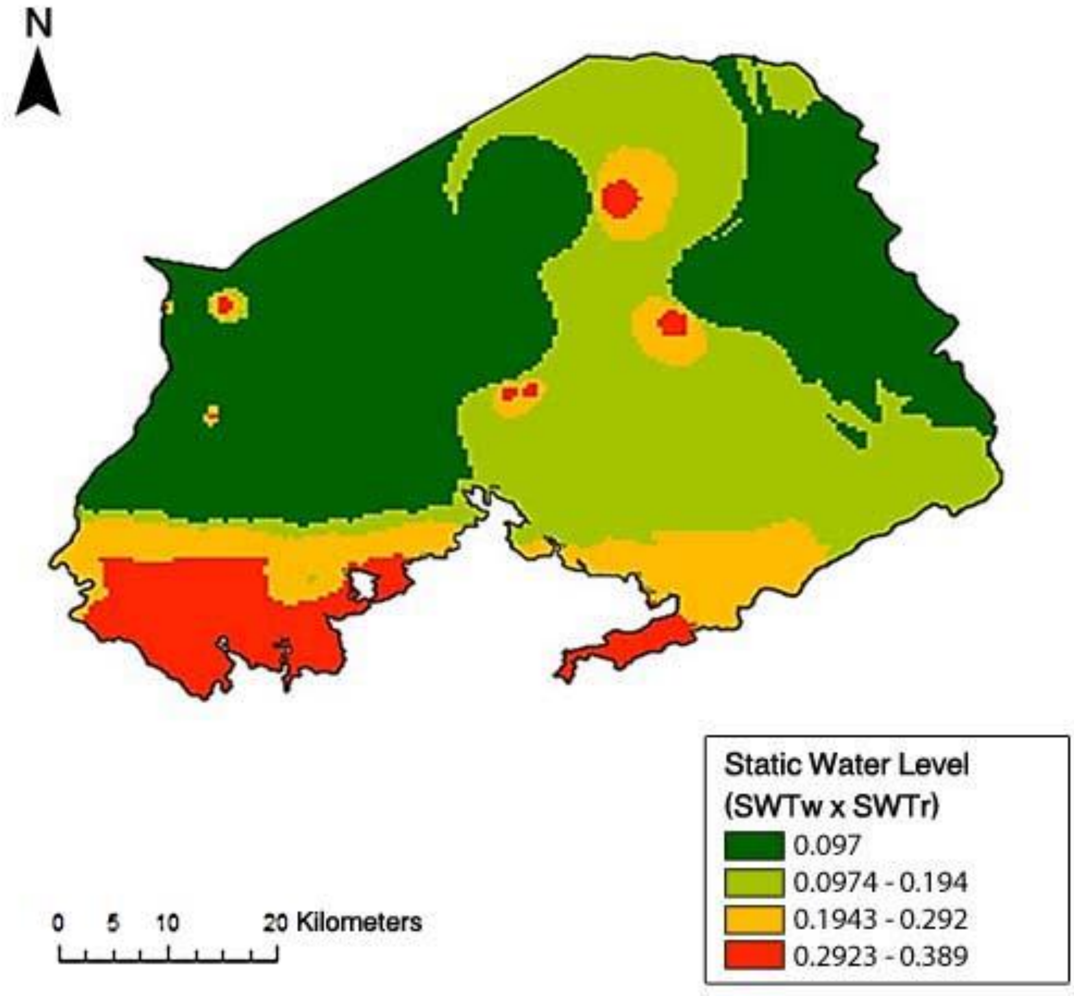


Figure 5.7. Depth of the groundwater suitability map of the study area

Aquifer Medium

The Aquifer medium is used to determine the speed at which water would travel to the aquifer and the amount of infiltration that could be expected in the aquifer. The properties of the saturated zone material control the pass of the waters. Thus, determining the rate at which the groundwater flow controls the rate at which it enters the aquifer. Rating was classified based on the DRASTIC index since there is a relationship between the groundwater variability and the groundwater recharge as explained in Chapter 2. Based on the geological data of the study area, it was assumed that the aquifer media within the study area is Basalt, which is equivalent to approximately 4 x 0.096. This gives a fixed number of 0.384, which is represented by multiplying weight (Wi) by rating (Ri).

Land Use/Cover

Land use/cover is an important factor that affects the recharge process. Land use refers to the human activities and various uses, which are carried on the land. Land cover refers to the natural vegetation, the water bodies, the rocks, the soil, the artificial cover and the other phenomena resulted due to land transferring. The recharge process has been affected by human settlements, man-made constructions, such as concrete embankments, buildings, hangars, roads, etc. (Boukheir *et al*., 2003).On the other hand, the groundwater recharge rate is enhanced by the vegetation cover due to the following processes:

- The biochemical disruption of the terrain surfaces by the roots and organisms.
- The vegetation cove helps in preventing water from direct evaporation by restricting the water under the vegetal zone.
- The capacity of plants helps to hold the soil in place rather than to erode away as the water runs off.

The land use/land cover map of the study area shown in Figure 5.8 was obtained from Landsat TM satellite imagery (TM) and classified acoording to the classes shown in Table 5.1. There are five different land use/cover types in the study area shown: Bare rock, urban, bare soil, natural vegetation including agricultural areas and the *Marab*. From a groundwater recharge prospective, the natural vegetation and agriculture were given higher weights whereas, the Marab and bare soil were given a moderate weight, the bare rock and the urban were given low weights and very low weights respectively.

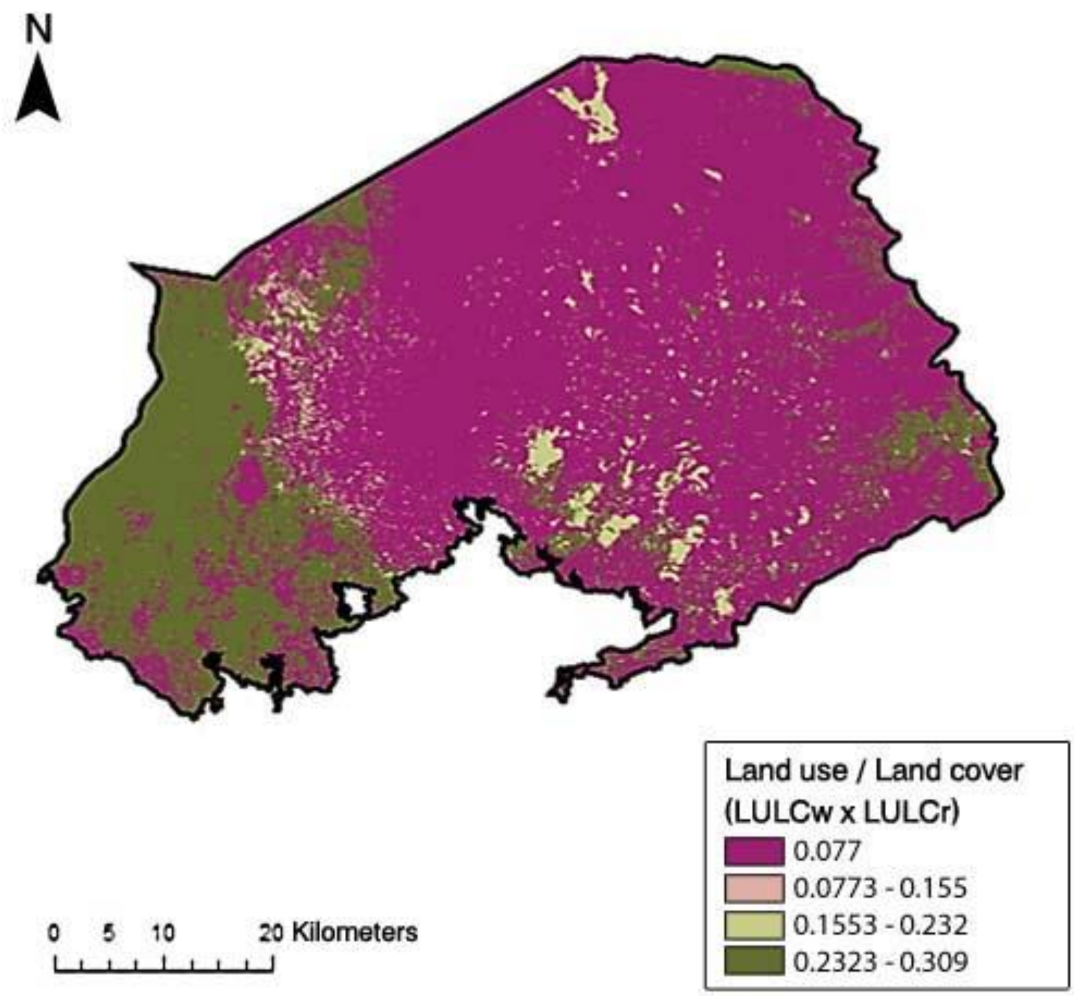


Figure 5.8. Land use/cover suitability map of the study area

5.3 Recharge Site Location based on WLC Analysis

According to Equation (5.1), nine thematic layers were added by the WLC method and were classified into five classes of potential groundwater recharge in the study are a including very low suitability, low suitability, moderate suitability, high suitability, and very high suitability for groundwater recharge. These thematic layers were integrated to generate a groundwater suitability map of the study area as shown in Figure 5.9.

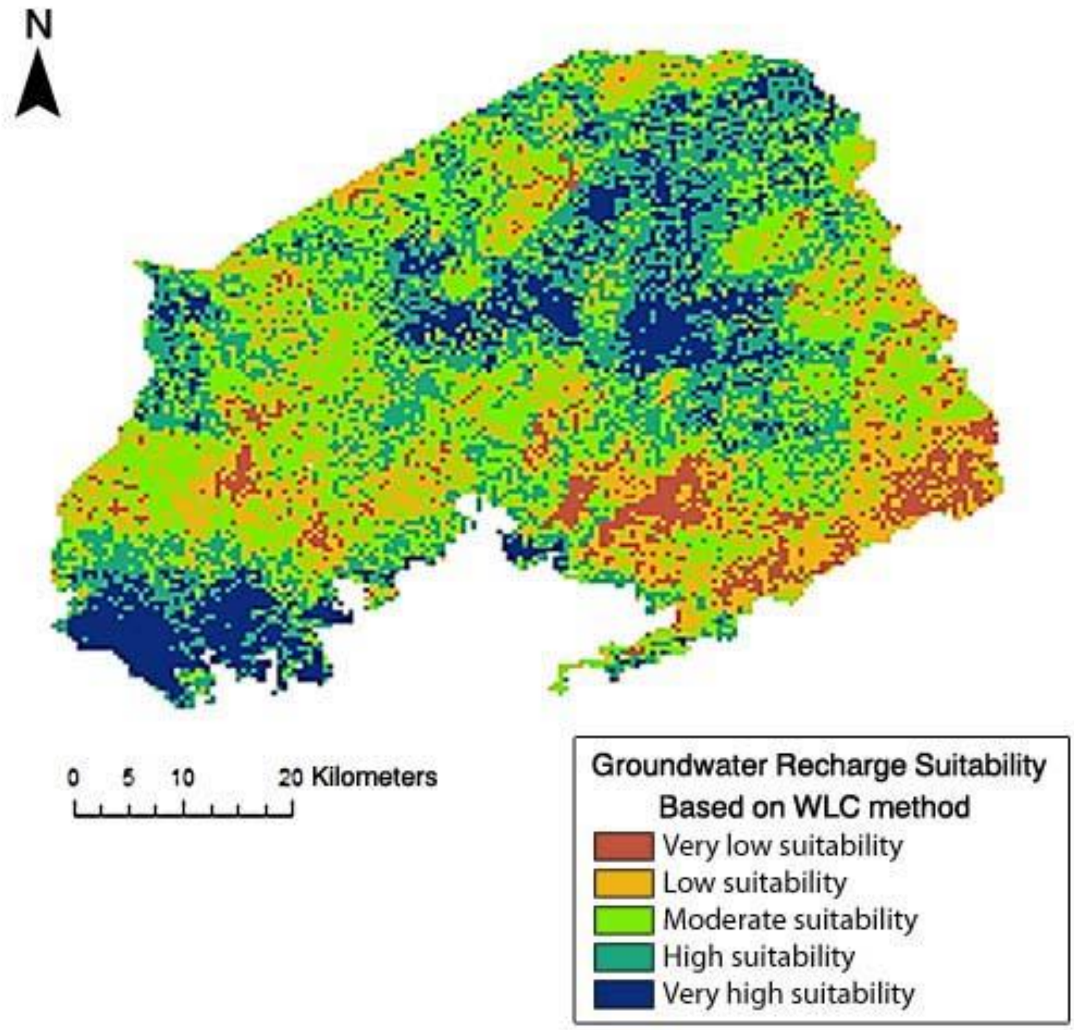


Figure 5.9. Suitability map for the groundwater recharge of the study area based on the WLC analysis

Five socio-economic criteria were also integrated into the result shown above.

Roads

Roads have a significant socio-economic value for the local community in the study area. Through these roads, they can move their trucks and tankers from one place to another when moving with their cattle, while searching for grassland and water. Buffering on the road map was done in order to have a safe zone around them (250m) to prevent any conflict between future artificial groundwater recharge projects and the expansion of the existing roads in the area. The road buffered map is shown in in Figure 5.10.

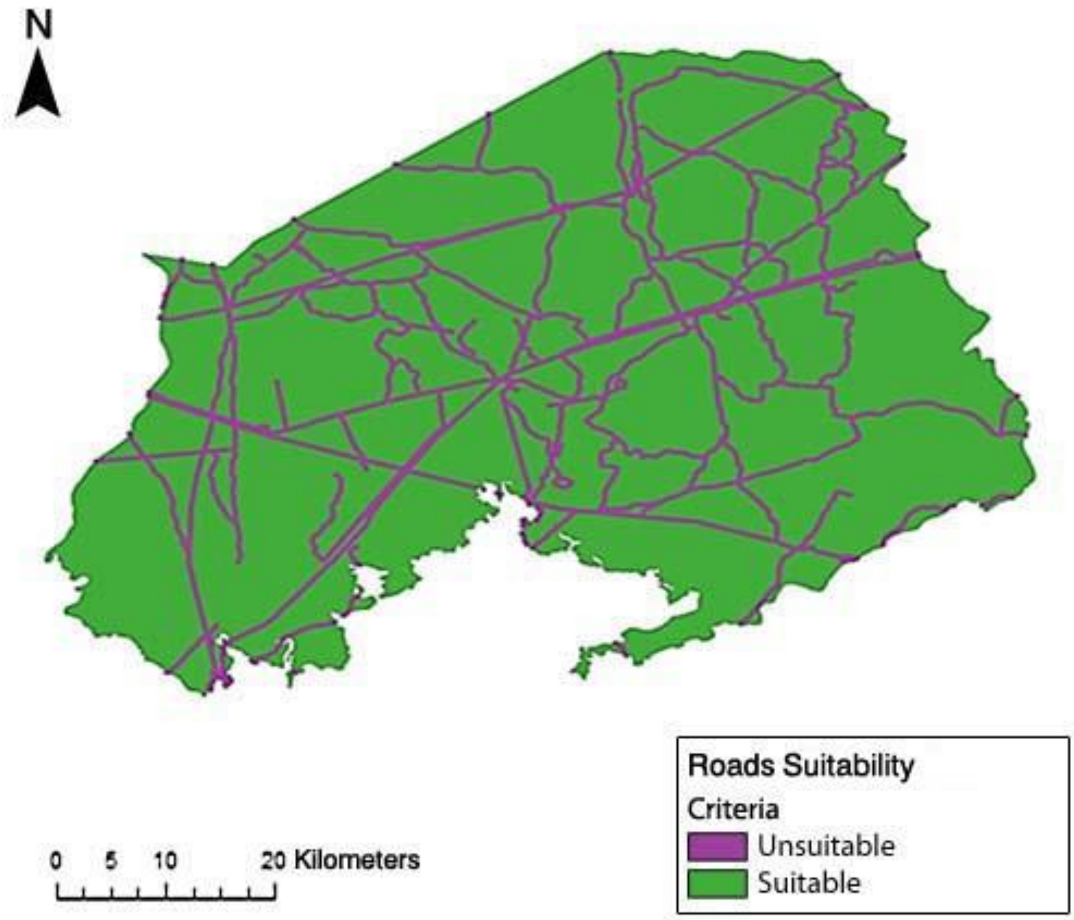


Figure 5.10. Roads buffered map of the study area

International Borders

The international borders must be excluded from being chosen as groundwater recharge sites for security reasons. Buffering on the international border was 1km as shown in Figure 5.11.

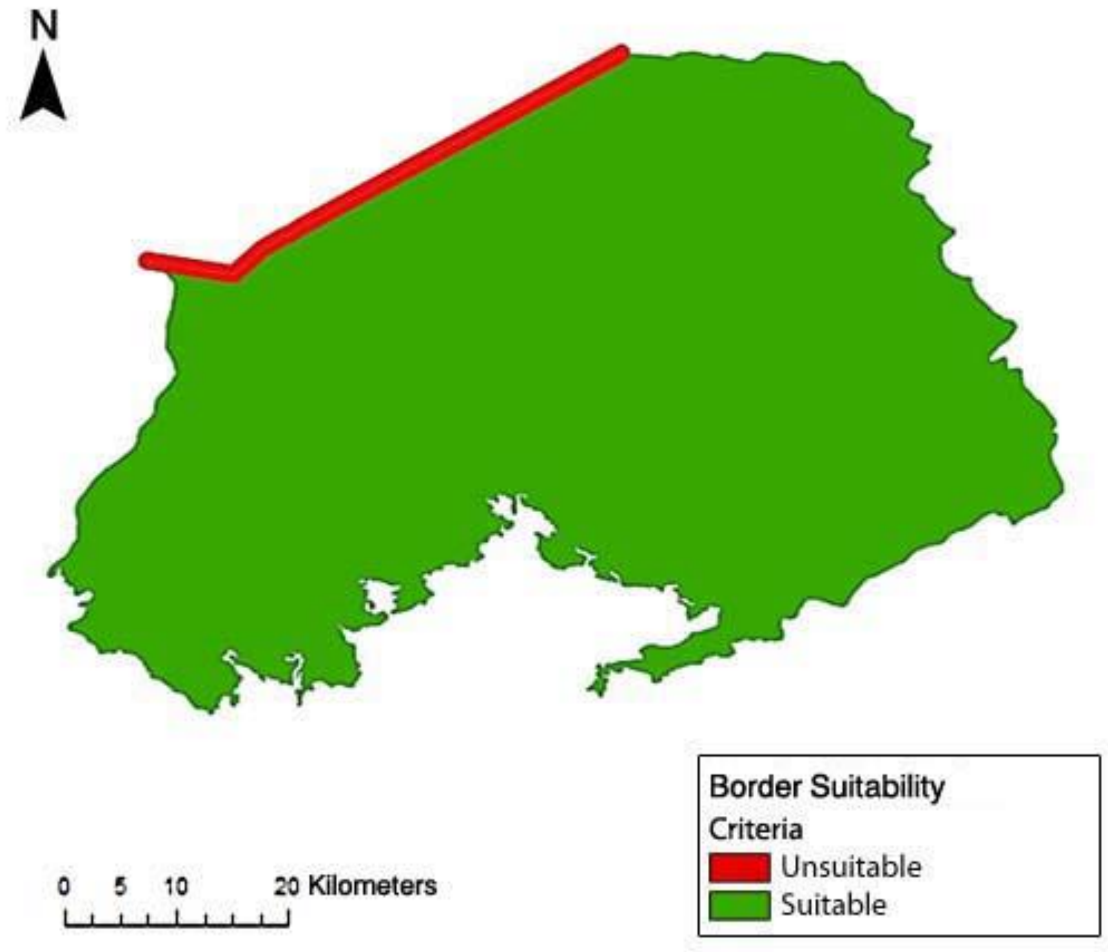


Figure 5.11. International border buffered map of the study area

Towns and Villages

Urban areas must be excluded from being chosen as groundwater recharge sites for safety reasons. A buffer zone of 500m was established around urban areas as shown in Figure 5.12 to prevent any conflict between future artificial groundwater recharge projects and the expansion of the existing urban area.

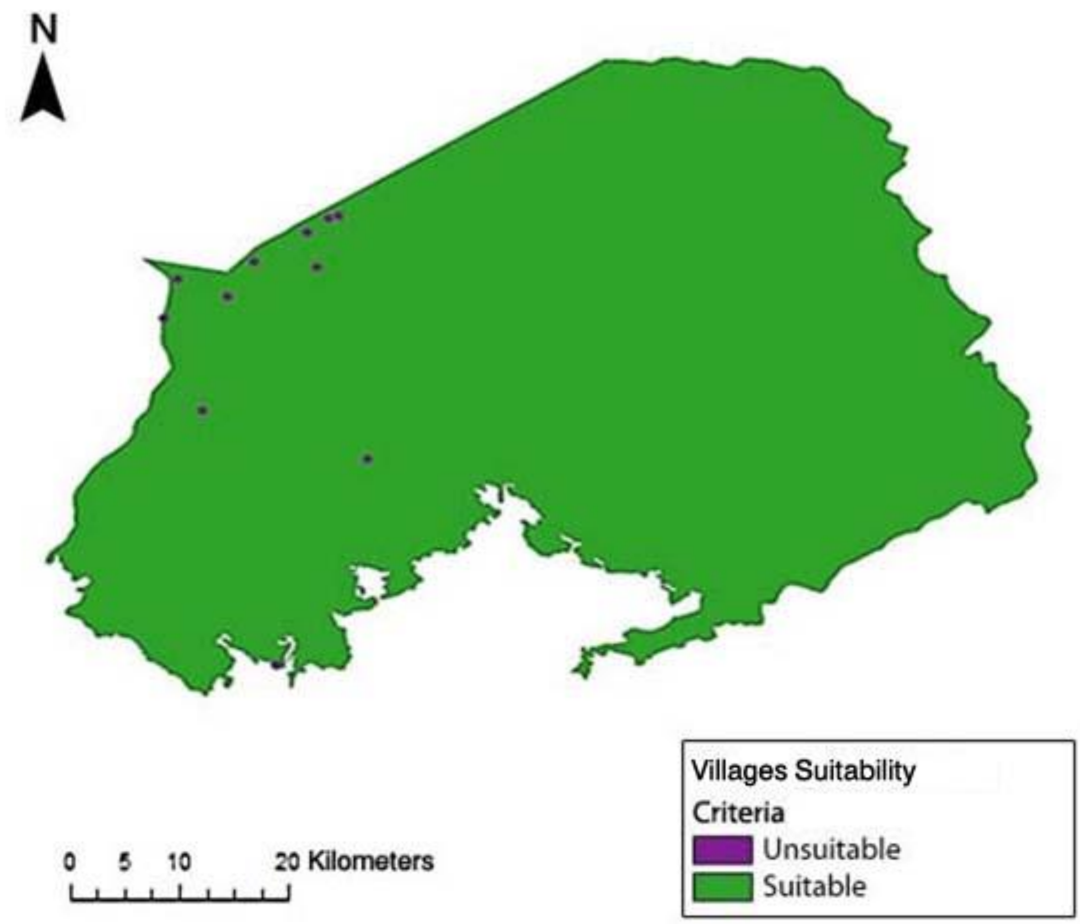


Figure 5.12. Towns and village buffered map of the study area

Farms

Agricultural lands must be excluded from being chosen as groundwater recharge sites because of their economical values and for environmental reasons. Buffering of 500m around the agricultural areas was established as shown in Figure 5.13 in order to have a safe zone around them and to prevent any conflict between future artificial groundwater recharge projects and the expansion of the existing agricultural areas in the study area.

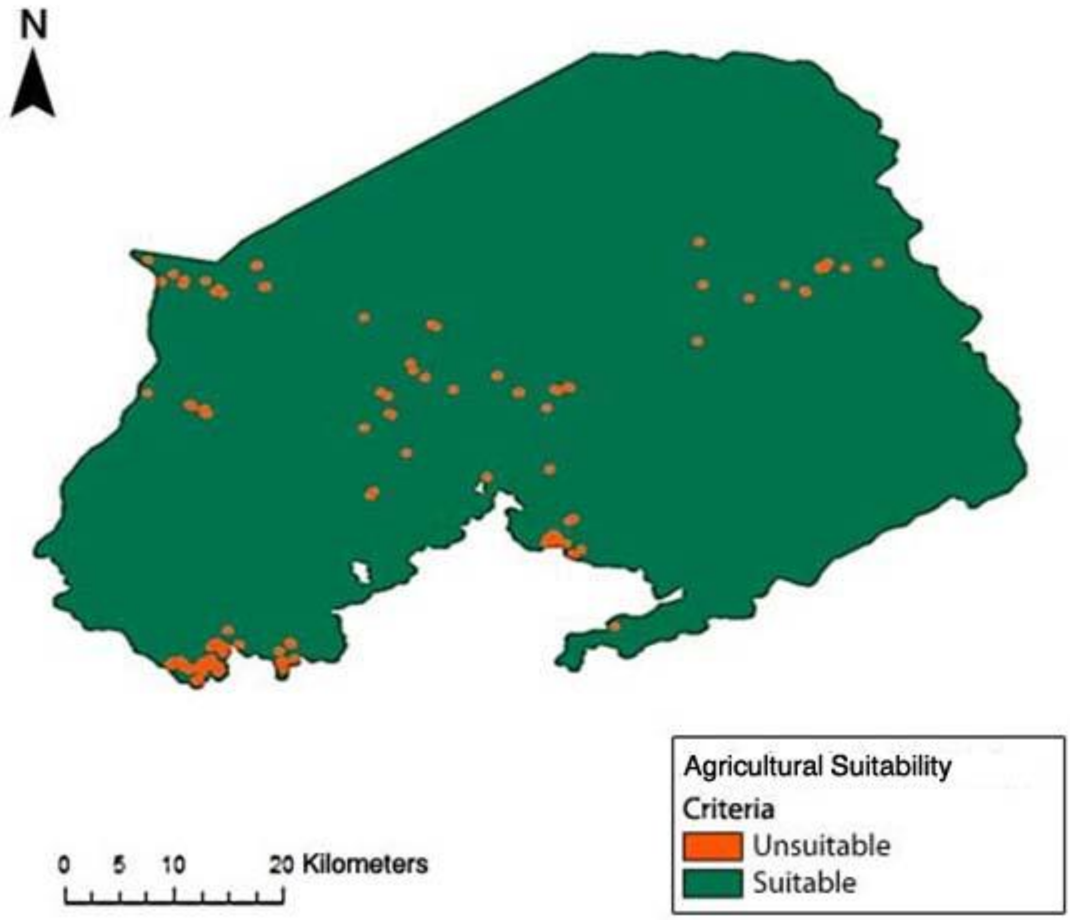


Figure 5.13. Farms buffered map of the study area

Existing Wells

Wells are of significant socio-economic value for the local community. The well sites must be protected from being chosen for groundwater recharge projects. Buffering of 500m was applied on the well map shown in Figure 5.14 in order to have a safe zone around them, and to prevent any conflict between future artificial groundwater recharge projects and the expansion of the existing wells in the area.

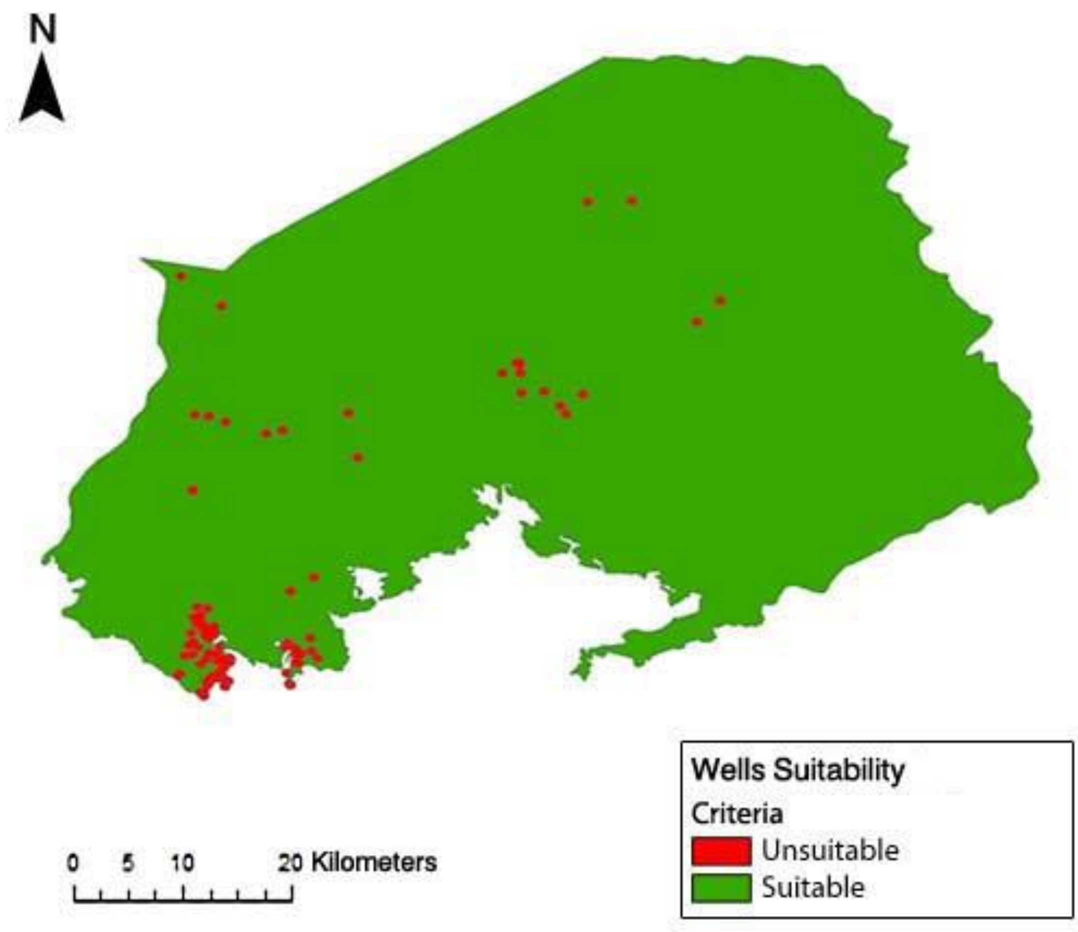


Figure 5.14. Wells buffered map of the study area

Boolean techniques were applied to the socio-economic factors that cannot be used as sites for groundwater recharge. The overlay of these factors is illustrated in Figure 5.15. In this figure all areas that are not suitable for recharge are shown.

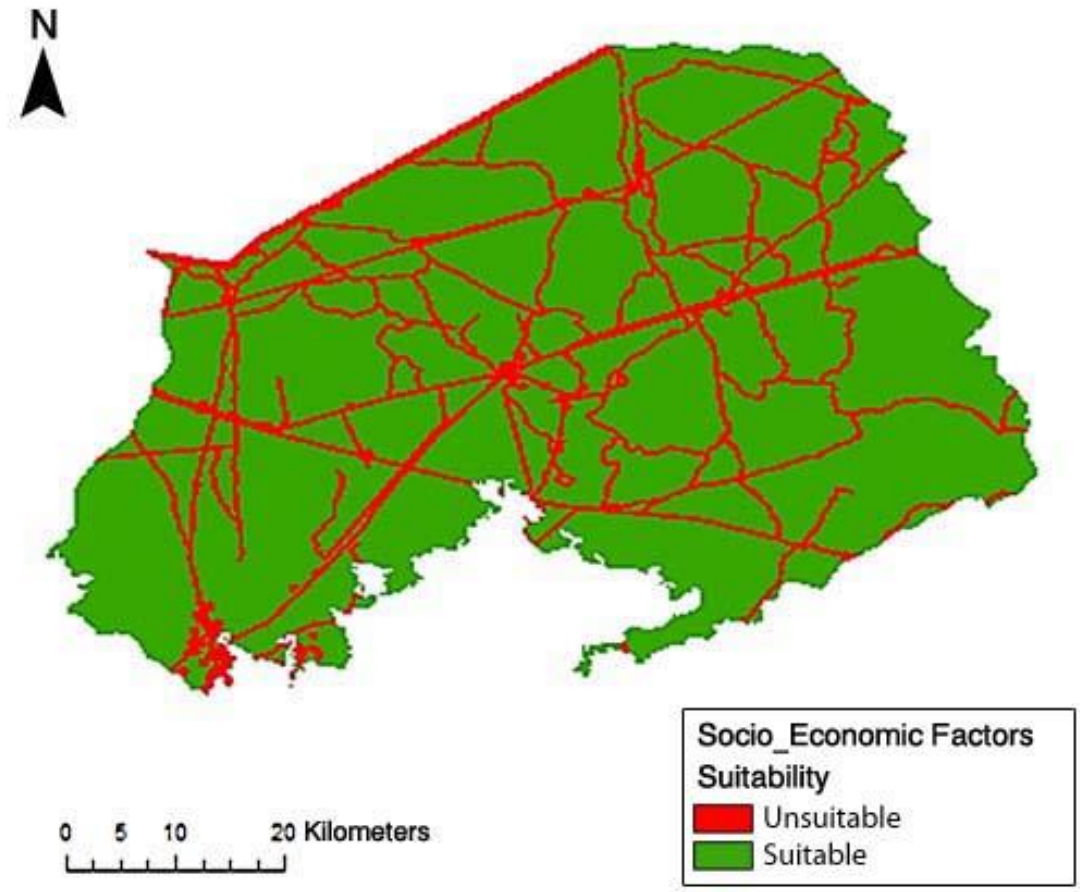


Figure 5.15. Unsuitability map for groundwater recharge based on Boolean techniques of the five socio-economic factors

5.4 Groundwater Recharge Suitability Mapping

The resultant maps (Figure 5.16) from the physical criteria, shown in Figure 5.9 integrated with the socio-economic criteria, shown in Figure 5.15. The classification determined the following outcomes for all parts of the study area:

- No suitability areas, which represent 10% of the study area.
- Very low suitability, which represent 4% of the study area
- Low suitability, which represent 8% of the study area.
- Moderate suitability, which represent 25% of the study area.
- High suitability areas, which represents 26% of the study area.
- Very high suitability areas, which represents 27% of the study area

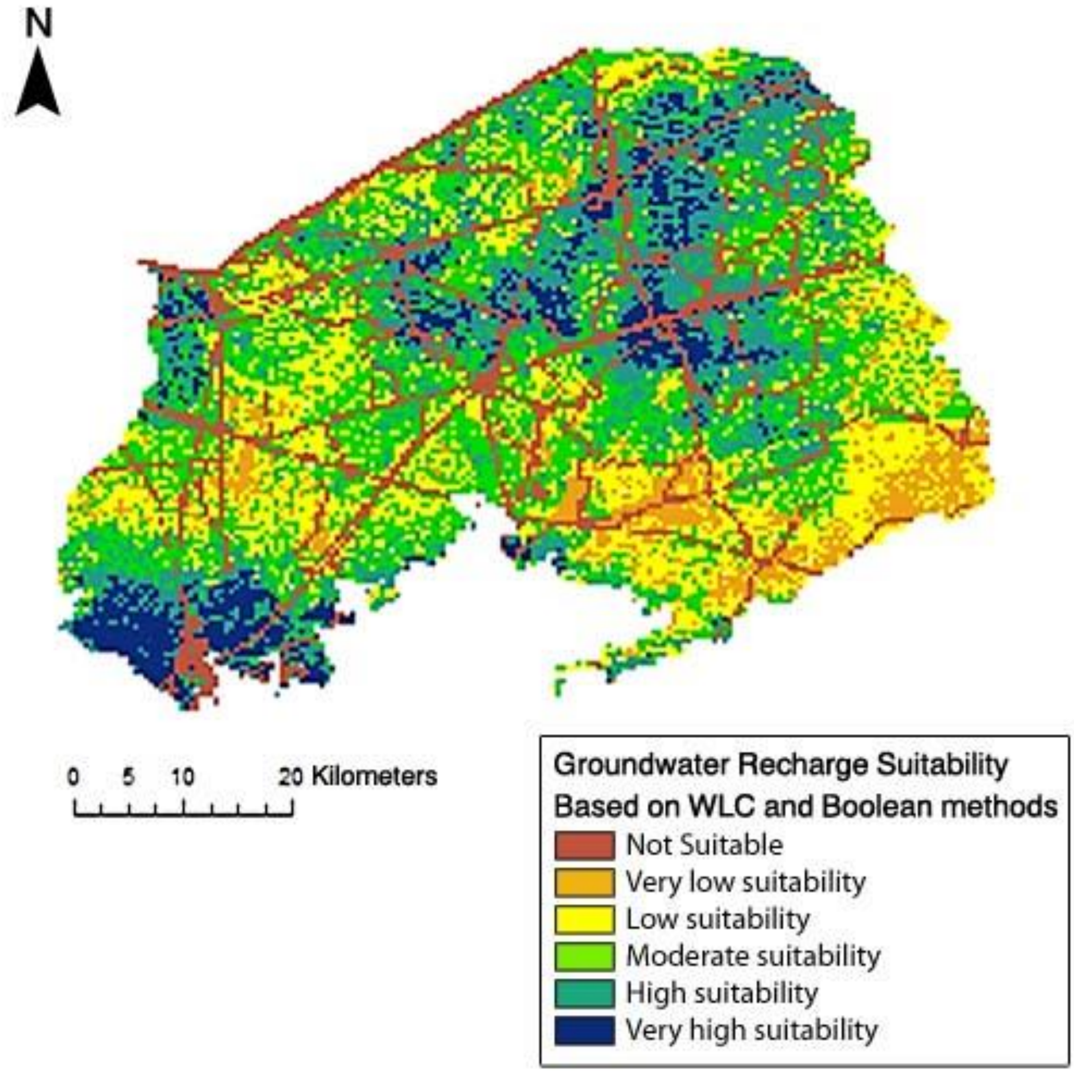


Figure 5.16. Combined, final suitability map for groundwater recharge of the study area

Three models (mean, median and mode weights) were compared and then evaluated for their ability to explore the difference associated with opinions of experts in the process of weights determination for each criteria. The suitability map of the study area based on the mean, the mode, and the median is shown in Figures 5.17 to 5.19 respectively. The differences in the acquired groundwater recharge suitability maps determined by the mean, the median and the mode approaches were trivial. This supports to finding that the evaluation of the experts are consistent as suggested in Chapter 4.

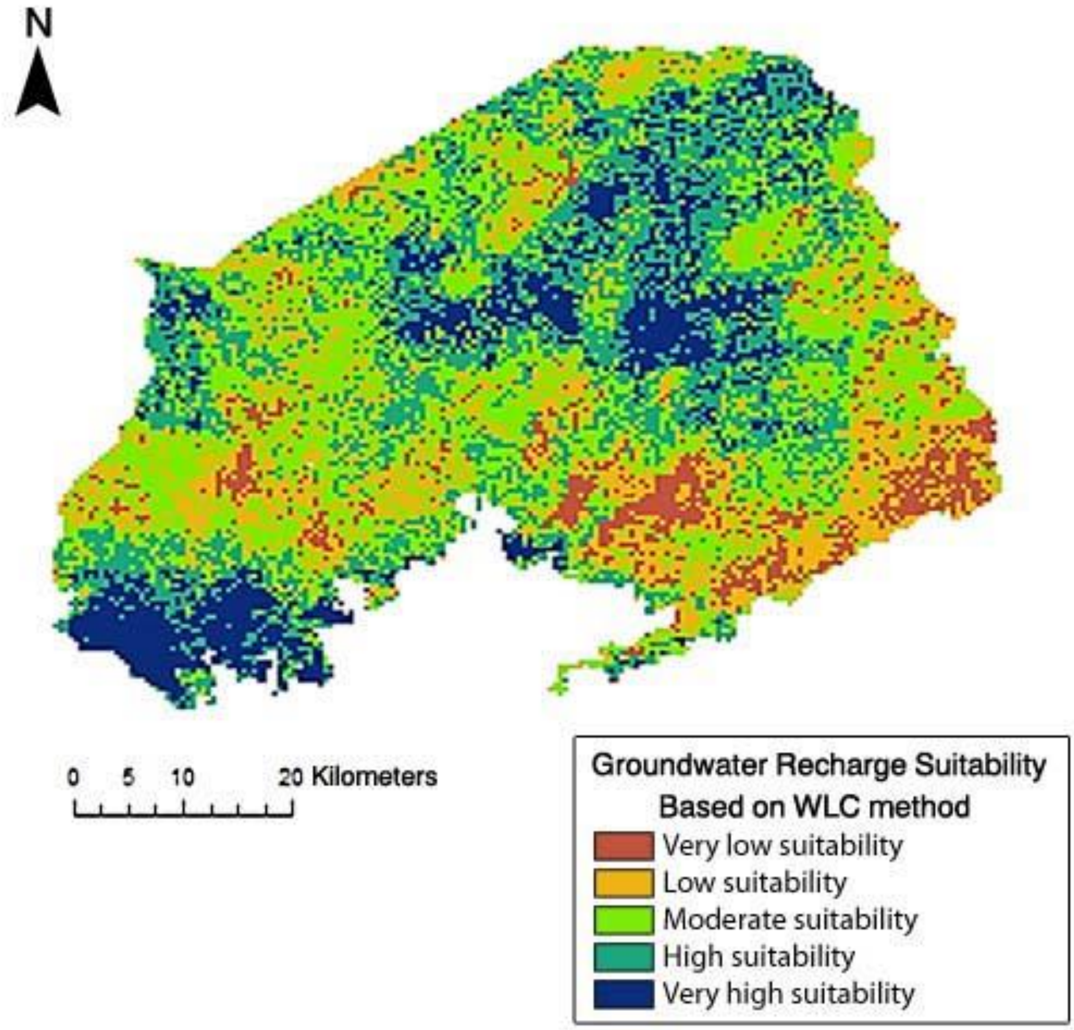


Figure 5.17. Mean suitability map for groundwater recharge of the study area

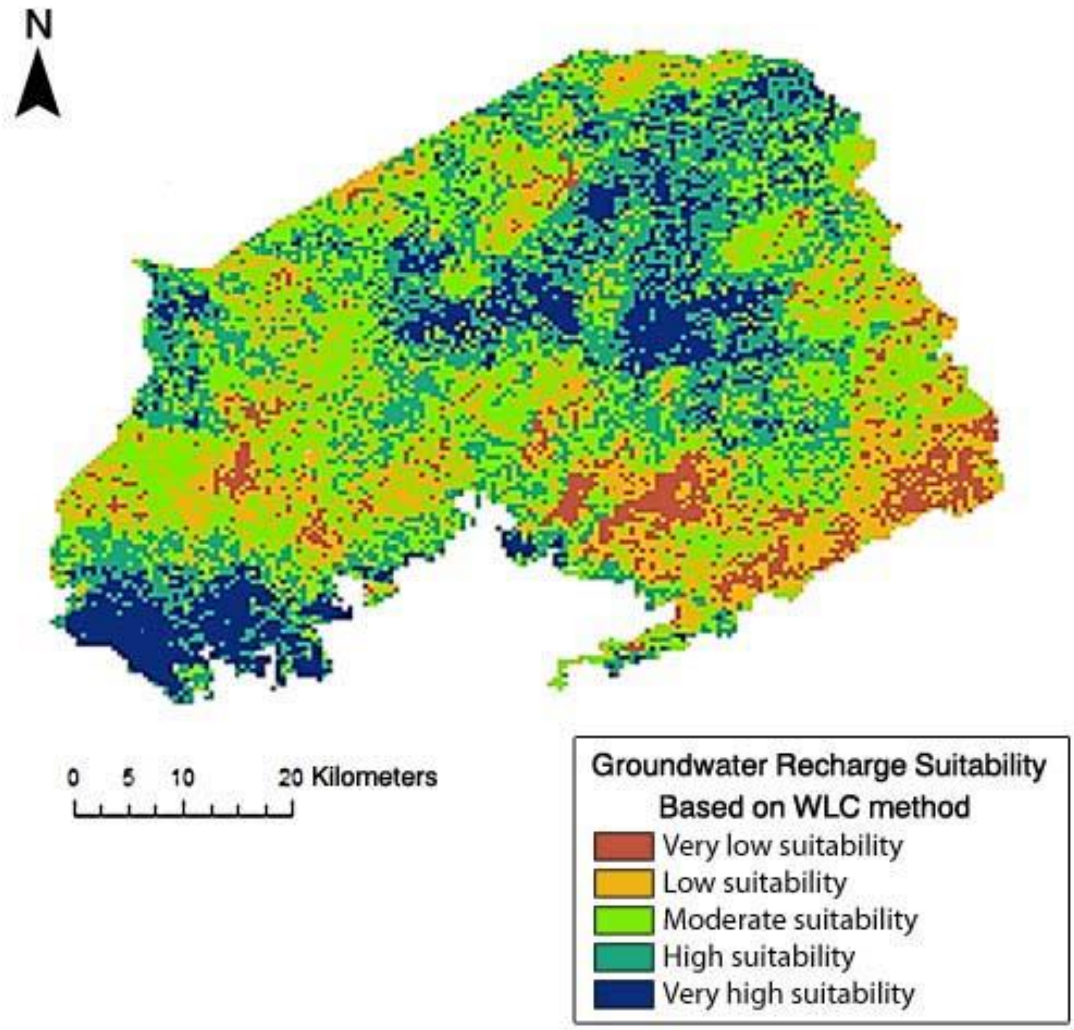


Figure 5.18. Modal suitability map for groundwater recharge of the study area

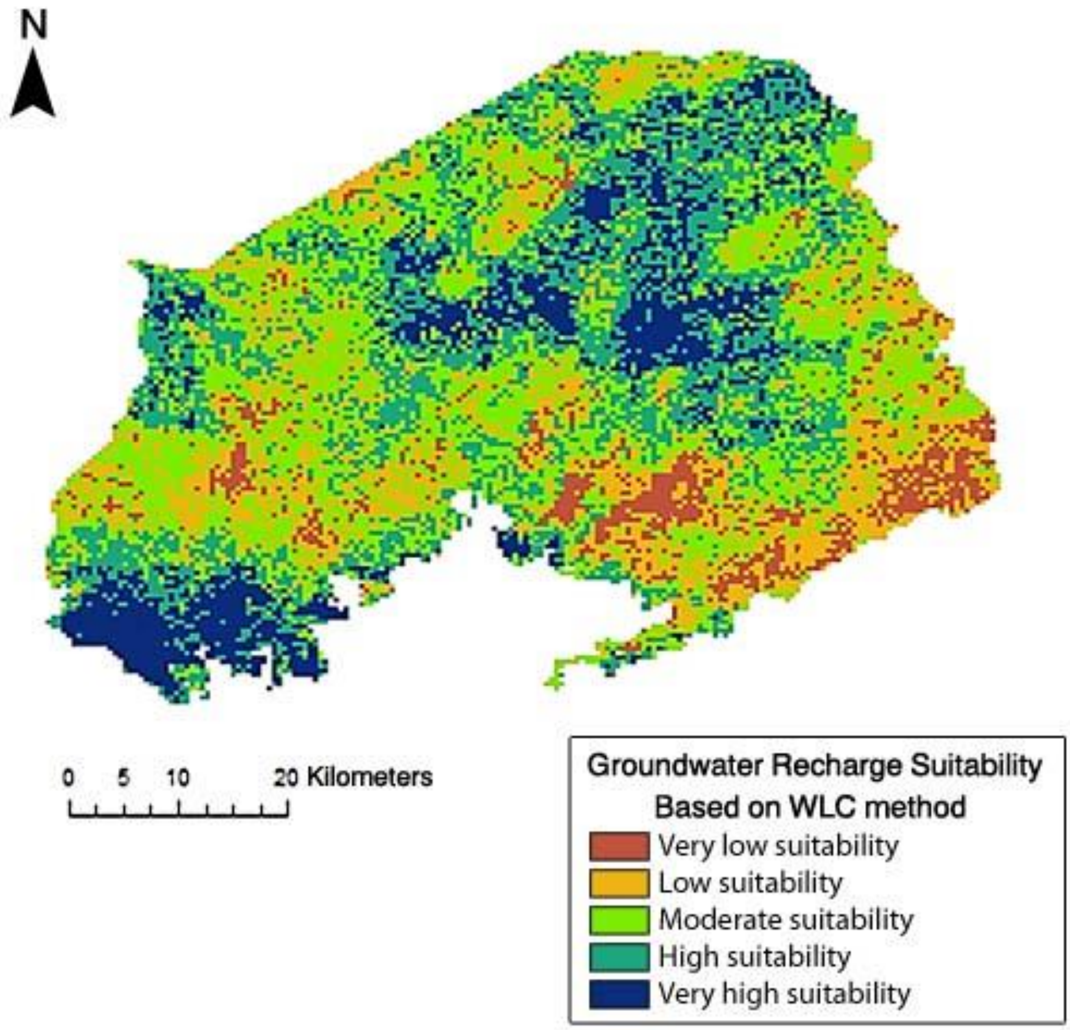


Figure 5.19. Median suitability map for groundwater recharge of the study area

5.5 Summary

This chapter presents finding to assist in the spatial mapping of sites of suitability for groundwater recharge. First, a suitability map representing each of the site selection physical criteria was generated for the study area. These maps were ranked in 1-4 classes based on a literature review. The WLC method was then used to integrate the generated suitability maps of the individual physical criterion in to a one suitability map for groundwater recharge in the study area. In addition, the Boolean method was used to eliminate the sites that are not suitable for a groundwater recharge, and generate an unsuitability map. This map was then overlain with the suitability map to derive a final suitability map. The resultant map showed that almost 26% of the study appears to be highly suitable for groundwater recharge, whereas

10% of the study are is not suitable for groundwater recharge. The remaining 64% varied between low suitability and high suitability.

In this Chapter, we have further addressed the research questions and objectives that were posed in Chapter 2. The spatial distribution of the importance of the factors and criteria have been shown. It has been demonstrated that the spatial variation of the weights and influencing criteria is reasonably constant or consistent. An objective has been achieved that critically underpins the aim of the study, that being to combine the selected criteria and social factors that affect the suitability of sites for groundwater recharge in the study area in a GIS environment to allow for the selection the optimal sites for groundwater recharge in the study area. The following chapter addressed issues of validation to test the outcomes of the spatial modelling experiments.

6 VALIDATION OF THE RESULTS

This chapter explains the verification stage of this study. Verification of the results are necessary to gain confidence and determine physical meaning to the spatial methodologies that have been developed in this study. Verification experiments can be set to look at soil surface properties that give insights and indications about the underlying suitability of the site. Geophysical investigation, using Time Domain Electromagnetic (TDEM) methods, enables the identification of zones of high resistivity that are suitable for recharge. Characterisation of the physical characteristics of the soil using texture analysis to determine the sand, the silt and the clay further helps us to understand the relative suitability of the site.

6.1 Field Site Selection

The sites selected for conducting fieldwork investigations were randomly selected to represent all the four classes of the GIS analysis. Sixteen locations in eight sites (two locations in each site) were investigated using TDEM geophysical survey and soil texture analysis. Google Earth images and Global Positioning System (GPS) were used to accurately locate each site. Google earth was used after converting the suitability map of the groundwater recharge to a KML format as shown in Figure 6.1. All the classes of the GIS results were identified and the coordinates of the sites from the centre of the polygon of each visited site recorded. The centre of the polygon was chosen to overcome any errors generated through the site selection process that might have resulted from errors in the map scale.

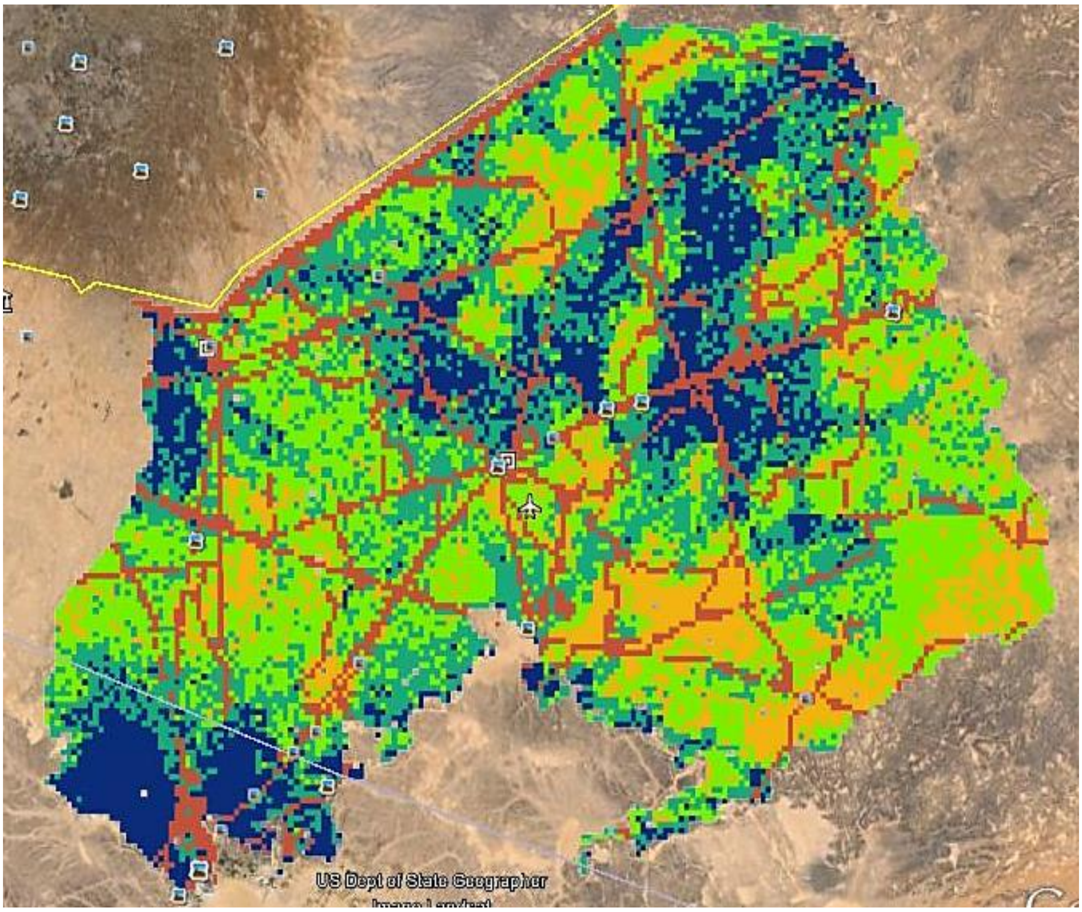


Figure 6.1. Suitability map for the groundwater recharge integrated into Google Earth

A GPS device was used in the field to locate the sites that were randomly selected across the study area. The centre of each visited site was entered to the GPS to lead the researcher to the position of each site. In addition, a laptop with an internet access via a USP internet stick was used in the field to access Google Earth imageries to compare the imageries with the actual land cover for further verification.

The location of the sites are shown in Figure 6.2. Table 6.1 also shows the location of the 16 verification sites. A detailed investigation is conducted for eight sites; these were chosen to represent each of the suitable areas classes of the GIS, i.e. Low suitability for the groundwater recharge, moderate suitability for the groundwater recharge, high suitability for the groundwater recharge and very high suitability for the groundwater recharge.

Table 6.1. Geographical coordinates of the investigated groundwater recharge sites

Location	Sample	N-latitude	E-longitude	Potential (GIS analysis using Selection criteria)
1	A, B	32.193748°	36.823530°	Very high suitability 1
2	C, D	32.194429°	36.831262°	High suitability 1
3	E, F	32.192496°	36.841928°	Moderate suitability 1
4	G, H	32.123470°	36.875827°	Low suitable 1
5	I, J	32.049247°	37.001976°	Moderate suitability 2
6	K, L	32.035040°	36.955821°	Low suitable 2
7	M,N	31.975741°	36.926239°	High suitability 2
8	O, P	31.970146°	36.897336°	Very high suitability 2

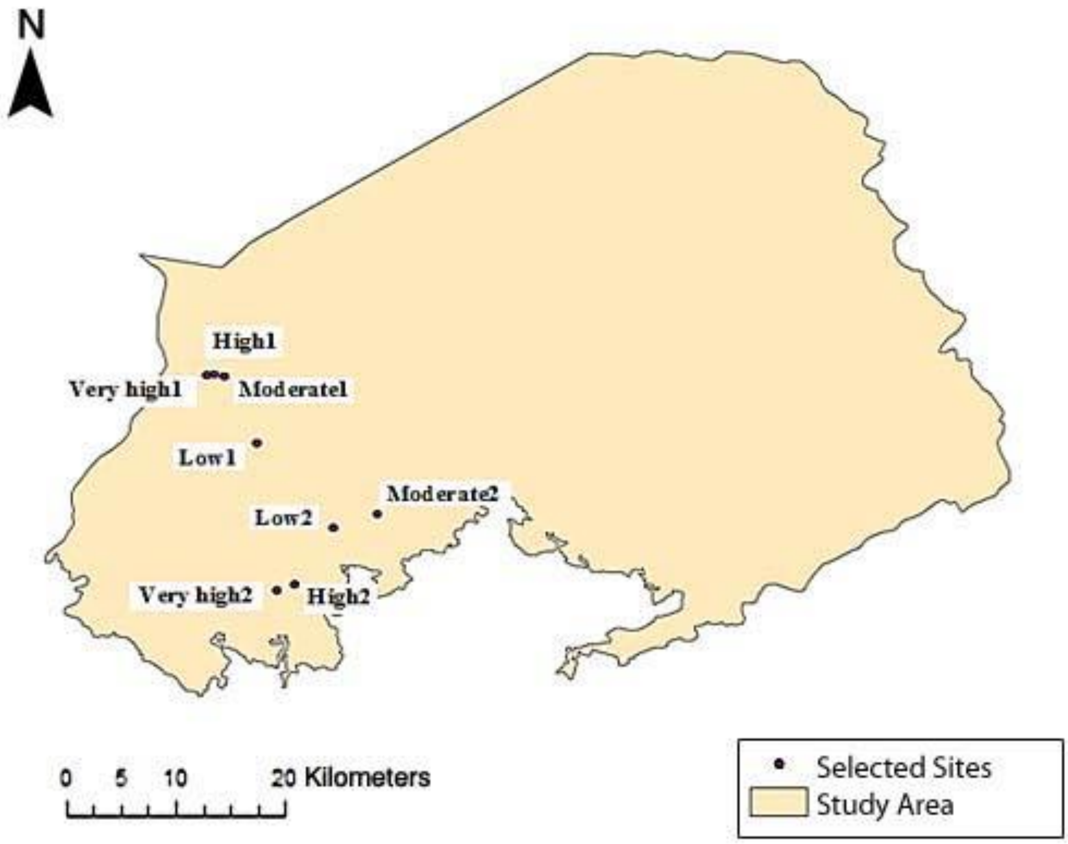


Figure 6.2. Location of sites used for verification of the results

6.2 Soil Texture Analysis

The soil within the study area consists of weathered rock material. The amount of different sizes and types of rock particles determines the texture of the soil. Soils without much presence of an organic layer comprise minerals with varying sizes, ranging from clay (smallest) to stone (largest). The soil texture is the proportion of these size groups within the soil. Texture is considered as a stable characteristic that provides a useful guide to a soil's potential of groundwater (Brown, 1998). The fine textured soils have good water-holding properties (low infiltration), whereas the coarse textured soils have a low water-holding capacity but are good at drainage (high recharge) (Stone and Myslik, 2007).

The texture of the soil is related to its porosity and permeability. Soil porosity is defined as the volume of pore spaces amongst soil grains per volume of soil. Coarse grains with large pores deliver better infiltration and fine grains with smaller pores deliver good water retention (Stone and Myslik, 2007). The average pore size determines how easy water can infiltrate through the soil. This process is known as the soil permeability. Sandy soils have a low porosity and, therefore, they have high permeability (Berry *et al*., 2007). On the other hand, clay soils have high porosity and low permeability. The surface water reaches the groundwater by moving through the soil pores. Thus, the soil texture determines the rate at which water drains through the saturated soil; the water moves more freely through a sandy soil than it does through a clay based soil (Stone and Myslik, 2007).

Twelve textural classes are based on the percentage of the sand, the silt and the clay in a sample of soil, which is defined by the soil textural triangle (Figure 6.3). Defining the soil without having to take percentages of the sand, the silt, and the clay into account is made easy by using the textural classes. The method of using the textural triangle is to locate the percentage of sand on the lowest side of the triangle and follow the line up to the left side of the triangle (Brown, 1998).The same is to be done with the percentages of clay or silt on the two other sides of the triangle (trace silt diagonally down to the bottom left and clay across from left to right). The textural class for that soil is where the two lines intersect (Berry *et al*., 2007). For example, a soil with 10% clay and 80% sand would have a sandy loam texture (A) and a soil with 35% clay and 30% silt would be clay loam (B).

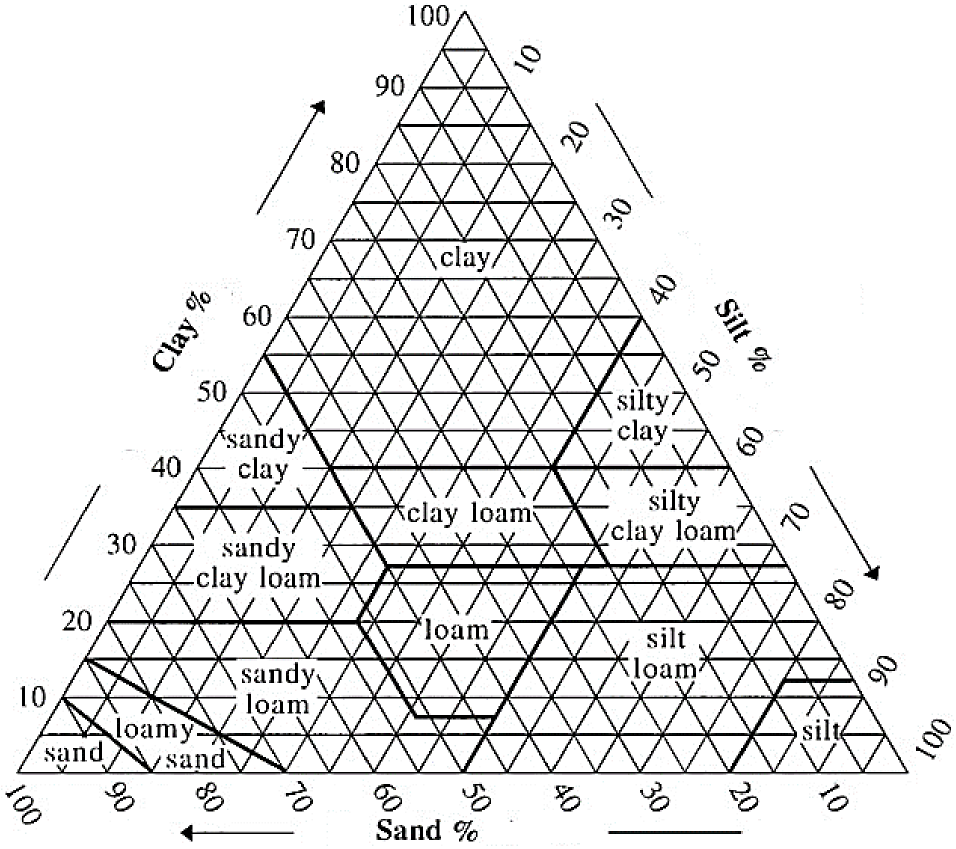


Figure 6.3. Soil texture triangle showing the percentages of sand, silt and clay in the different textural classes. Adapted from Berry *et al*., (2007)

As mentioned previously, soil texture is considered a key factor when selecting a site for groundwater recharge. The highest infiltration capacities are detected in sandy soils while heavy clay has considerably smaller infiltration capacities (Noman and Tahir, 2003). The distribution of the particle size is an important parameter in soil classification and genesis, which has implications for the soil, the water, the aeration, and the soil fertility. Two common procedures for particle size analysis involve either the hydrometer or the pipette gravimetric methods. Both methods rely on the effect of the particle size on the different settling velocities in a water column (USDA, 2012).The method of the hydrometer for the silt and the clay measurement depends on the outcome of the particle size in the different settling velocities in a water column. Ideally, the particles are meant to be spherical having an exact density of 2.65 g/cm^3. If all the other factors are kept constant, there is a proportional relationship between the settling velocity and the square of the radius of the particle (Stoke's Law). The settling velocity is also a function of viscosity, the temperature of liquid and the specific gravity of the falling particle. Therefore, in practice, corrections for liquid temperature should be made. A reduced viscosity is a result of greater temperatures, due to the expansion of the liquid and a more rapid decrease of the falling particles (USDA, 2012).

The methodology of Al-Amoush *et al*. (2012) was used to identify the soil texture for some selected sites and link the soil texture with the groundwater recharge suitability. As mentioned previously, sixteen surface soil samples were collected from eight sites located in the study area (Table 6.1). The hydrometer method of the particle size analysis was used in this stage, where the silt and the clay measurement depend on the outcome of the particle size in the different settling velocities in a water column. Two soil samples were collected from each site (Figure 6.4). The distance between the two samples was 50 m. The soil samples were collected from the top 30 cm.

Figure 6.4. Soil sampling in the laboratory

The results of the soil texture analysis showed that there is a link between the soil texture and the recharge as a result of the properties of the soil texture. If the soil texture consists of sand, it is a good indicator for a groundwater recharge suitability, while if it consists of clay there is a less chance of a groundwater recharge. Following the USDA soil texture calculator, the analysis is shown in Table 6.2. The results show that there are four types of soil texture in all of the sites visited. These are sandy clay loam, loam, clay loam and clay. In sites 1 and 8, the soil texture classification is sandy clay loam, suggesting improving infiltration properties. In sites 4 and 6, the classification of the soil texture is clay, suggesting lower infiltration properties. The soil texture classification of site 2 and 7 is loam, although the percentage of sand is large compared to silt and clay proportions. This indicates that these two sites are potentially suitable for a groundwater recharge. The type of soil texture in sites 3 and 5 is a clay loam. This indicates that these sites are generally not suitable for groundwater recharge.

Table 6.2. Soil textures analysis at the verification sites visited

Location	Sample	Sand (%)	Silt (%)	Clay (%)	Soil texture	Potential of GIS analysis
1	A	49	22	29	Sandy Clay Loam	Very high suitable1
	B	50	23	27		
2	C	42	33	25	Loam	High suitable1
	D	39	38	23		
3	E	33	39	28	Clay Loam	Moderate suitable 1
	F	33	40	27		
4	G	22	36	42	Clay	Low suitable 1
	H	24	36	41		
5	I	32	35	32	Clay loam	Moderate suitable 2
	J	35	26	36		
6	K	20	36	44	Clay	Low suitable 2
	L	24	34	42		
7	M	30	44	26	Loam	High suitable2
	N	38	36	26		
8	O	58	16	26	Sandy Clay Loam	Very high suitable2
	P	56	16	28		

6.3 Geophysical Investigations

A large dependence on groundwater as a primary drinking supply and also as a supply for agriculture and industrial use has been the concern of many developed and developing countries. The dependence on the groundwater is such that it is essential to make sure that there is significant amounts of water and that the water is of a high quality. Thanks to the rapid advances in microprocessors, geophysics can be used to map the groundwater resource and to evaluate the water quality, which has increased dramatically over the last 10 years (Kearey *et al*., 2009).

Geophysics is a science that deals with the ground by applying some physical theories on the surface of the earth. These theories are based on measuring the difference in some physical properties of the land of the areas to be explored including the density, the elasticity, the influential magnetic susceptibility, and the Electro resistivity or the Electro conductivity. The Hydrocarbon exploration, typically at depths greater than 1000m, has been the main use of geophysics in the geosciences. The science has evolved the hydrogeology in the past years by inventing methods to explore the aquifers (water-bearing layer).

Scientists were able to invent many devices to explore the aquifers, predominantly in the past two decades, taking into account the environmental aspects and the analysis. The techniques used for the geophysical exploration of the groundwater also used to track the motion of the groundwater depth in the earth, mining surface, reactors, artificial feeding of groundwater and nuclear contaminants. It was also used to study the effect of dams and reservoirs etch, where the above affects groundwater in terms of both quantity and quality (Kearey *et al*., 2009).

Many geophysical techniques were used for the groundwater investigations with some showing further success than the others. Previously, geophysics has been applied as a tool for mapping the groundwater resource and as a tool for the groundwater character discrimination. Regarding the groundwater resource mapping, the geological situation in which the water exists is the target of geophysics rather than the groundwater itself.

The following methods were used to map large-scale basin features such as the potential field methods, the gravity and the magnetics. They are also used to map the regional aquifers. Seismic methods have been used to delineate the fractured rock systems and the bedrock aquifers. The Electromagnetic and the electrical methods have been particularly useful for the groundwater studies since the electrical conductivity signatures being used to correlate many of the geological formation properties that are critical to the hydrogeology (the permeability and the porosity of rocks). Frequently methods of practice were created for the exploration of groundwater using geophysical techniques (Van Dongen and Woodhouse, 1994).

The desire to reduce the risk of drilling dry holes and the need to offset the costs associated with poor groundwater production has stimulated the use of geophysics for groundwater studies. Currently, geophysicists also provide useful parameters for the hydrogeological modelling of new groundwater materials and the assessment of the existing groundwater contamination. The benefits of using geophysical methods are the following (Kearey *et al*., 2009):

- These methods determine the nature of the geological formations below the earth's surface.
- Cohesive determining the thickness of the layers on the surface.
- Determining the level and depth of groundwater.
- Identify the geological structures in the ground, such as gravel and sediment layers of mud.

Some of the problems inherent in more conventional ground investigation techniques can be overcome by geophysical techniques. Many methods exist with the potential of providing profiles and sections, for example, the ground between boreholes can be tested to see whether the ground conditions at the boreholes are representative of that elsewhere. Geophysical techniques also help in locating cavities, backfilled mineshafts, and dissolution features in carbonate rocks.

The unevenness of the natural near-surface ground has already been noted, as has the limited finance available to make boreholes. Geophysical techniques can contribute very much to the process of ground investigation by allowing an assessment, in qualitative terms, of the lateral inconsistency of the near-surface materials beneath a site. Non-contacting techniques such as the ground conductivity, the magnetometry, and the gravity surveying are very useful, as are some surface techniques, for example, electrical resistivity traversing (Ranieri, 2000).

Vertical profiling also uses geophysical techniques. Here the objective is to determine the junctions between the different beds of soil or rock, in order, either to correlate among boreholes or to infill between them. Techniques used for this purpose include the electrical resistivity depth profiling, the seismic methods, the surface wave technique, and the geophysical borehole logging. Some of these methods are surface techniques, but the majorities are carried out down-hole (Ranieri, 2000).

Sectioning is done to provide cross-sections of the ground, mostly to give details of beds and layers. It is potentially useful when there are noticeable differences in the properties of the ground (as between the stiffness and strength of clay and rock), and the investigation is directed at finding the position of a geometrically complex interface, or when there is a need to find hard inclusions or cavities. Additionally, as with vertical profiling, these techniques can allow extrapolation of borehole data to areas of the site, which have not, been the subject of borehole investigation. Examples of such techniques are the seismic tomography, the ground probing radar, and the seismic reflection (Ranieri, 2000).

One of the main needs of any ground investigation is the classification of the subsoil into groups with similar geotechnical characteristics. Geophysical techniques are not generally of great use in this respect, except in limited circumstances. An example happens where there is a need to differentiate between cohesive and non-cohesive soils. If the salinity of the groundwater is low, it is usually possible to distinguish between these two groups of materials using either electrical resistivity or ground conductivity (Ranieri, 2000).

6.3.1 Time Domain Electromagnetic Method (TDEM)

The TDEM method has been widely developed and adapted over the last three decades to measure electrical resistivity. The method is categorised by its high sensitivity to electrically conductive targets, vertical and lateral resolutions, and the depth to the array size employed during acquisition (Ranieri, 2000).

TDEM methods have been used successfully in hydrogeological surveys, delineating aquifers, groundwater exploration and mapping contamination of reservoirs (El-Naqa, 2010; Fitterman and Hoekstra.1984; Fitterman and Stewart, 1986; Goldman *et al*., 1991; Goldstein *et al*., 1990; Hoekstra and Blohm, 1990; Hoekstra *et al*., 1992; Jansen *et al*., 2000; Jansen, 2000; Miamone *et al*., 1989; Mills *et al*., 1988; Paine *et al*., 2004; Papadopoulos *at el*., 2004; Stewart., 1982; Wolfe *et al*., 1999). The Earth is energised by a quickly shutting off current through a transmitter (Figure 6.5). According to Faraday's Law, currents are transported in the subsurface decays with time and produces secondary magnetic fields that create a measurable voltage in the receiver (Raiche, 1984).

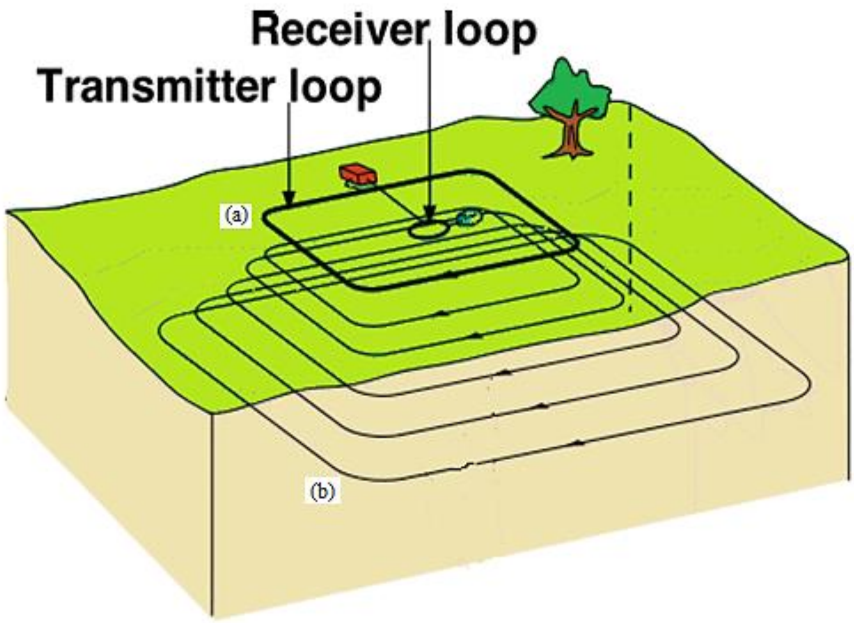


Figure 6.5. Eddy currents at progressively later times after turnoff. (a) Eddy Currents immediately after current turnoff, (b) Eddy Currents at later time. Adapted from El-Naqa (2010), and Meneill (1990)

TDEM survey involves the transmission of a current through a rectangular loop, normally laid on the ground (Figure 6.6) .The primary magnetic field spreads into the ground. By quickly reducing the transmitter current to zero, the changing primary magnetic field will induce eddy currents in the subsurface, which are reliant on the subsurface resistivity distributions. The eddy currents will produce a changing magnetic field that can be detected through a receiver coil on the exterior. The voltage created within the receiver coil, which is proportional to the difference of the secondary magnetic field generated by the eddy currents, is measured versus the time (Fitterman and Stewart, 1986).

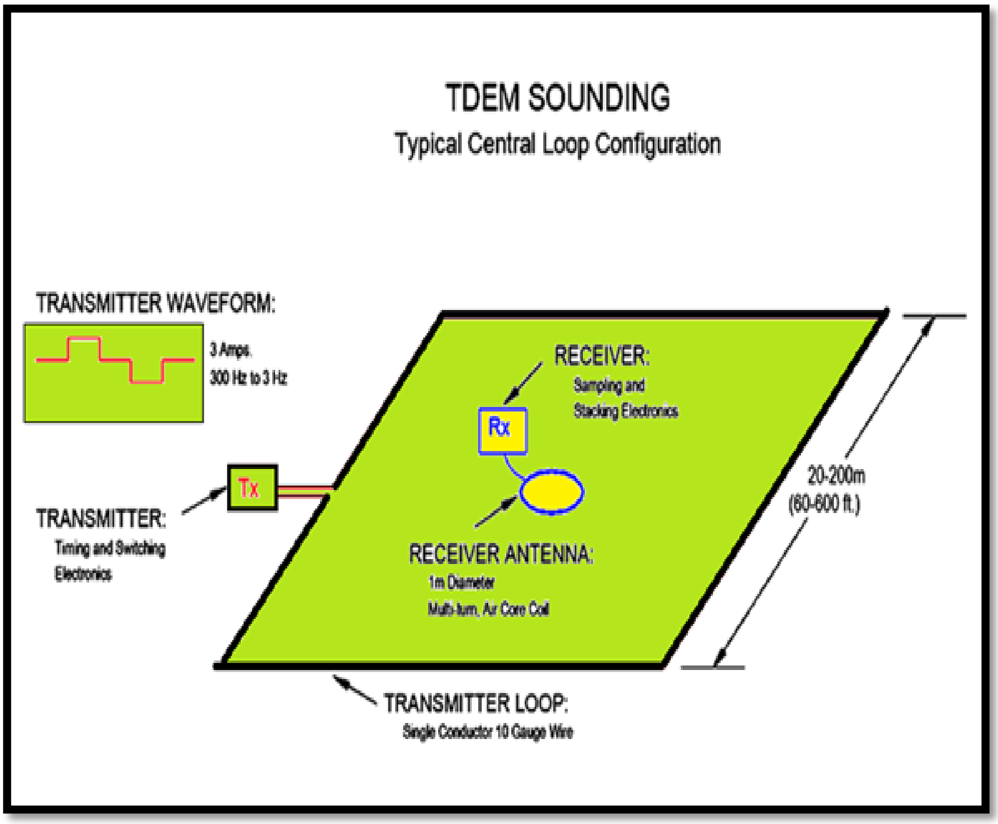


Figure 6.6. Typical central loop configuration (TDEM Field Setup). Adapted from El-Naqa (2010)

In poor conductors, secondary magnetic fields decay rapidly and in good conductors they decay slowly. Through determining the decay of the magnetic field, an approximation of the subsurface resistivity can be attained. The measured voltages can be converted into apparent resistivity values to represent the properties of the subsurface (Fitterman and Stewart, 1986). The principles of TDEM resistivity sounding are easy to conduct. According to Faraday's law, the process of sharply reducing the transmitter current to zero induces a voltage pulse in the ground with a short duration, which produces a flow of a loop of current in the immediate vicinity of the transmitter wire. Immediately after the transmitter current is turned off, the current loop passes into the ground directly below the transmitter and, because of the limited resistivity of the ground, the current immediately starts to decay. Similarly, the decaying current encourages a voltage pulse that causes additional current to flow at a larger distance from the transmitter loop, and additionally at larger depth. The deeper current flow also decays due to finite resistivity of the ground, encouraging even deeper current flow and so forth (Nabighian and Macanae, 1988).

To establish the voltage created at increasing time points, by the decaying magnetic field at the receiver coil, measurements are created from the current flow and thus also from the earth's electrical resistivity at increasingly larger depths. This process is what forms the base of resistivity. The decay characteristic of the voltage in the receiver is determined for a number of time gates (Figure 6.7), each measuring and recording the amplitude of the decaying voltage.

The time gating differs with time, to minimise measurement differences 'the early time gates' which are located where the transient changes rapidly with time are very narrow, whereas the later gates, where the amplitude of the transient decay diminishes, are much broader to improve the signal-to-noise ratio. The only (two) transients measured are the ones that arise when the transmitter current has just been switched off. For sounding at shallower depths, it is not necessary to measure the transient characteristics until a later time, with a period normally of the order of one millisecond or fewer, which means in an entire measurement time of a few seconds, measurements can be made and stacked on several thousand transient responses to improve signal-to-noise ratio.

To increase the depth, the differences must be recorded at a later time (by some seconds). Apparent resistivity in TDEM soundings allows the voltage response to be split into a premature stage (constant response with time), an intermediate stage (continually varying response shape with time) and a late stage (response is a linear line on log-log plot) (Fitterman and Stewart, 1986).

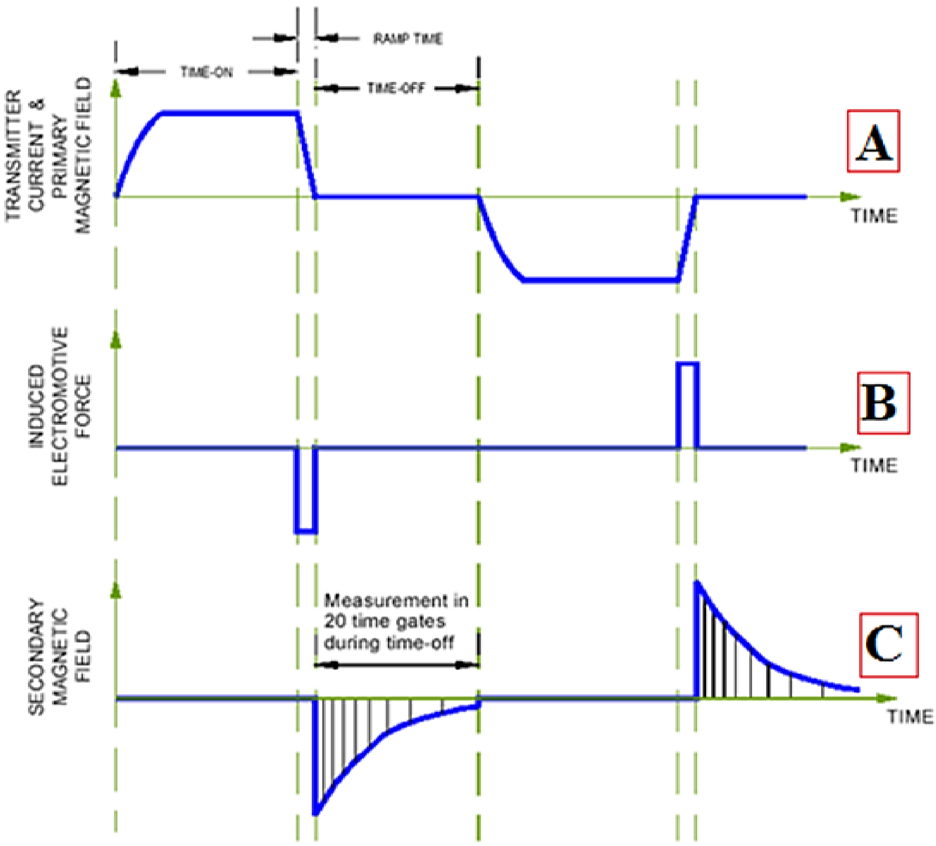


Figure 6.7. The TDEM waveforms at three different stages of measurements. Adapted from Mcneill (1990)

6.3.2 TDEM Equipment Characterisation

The TEM FAST 48HPC system comprises a single Transmitter– Receiver–Controller unit (b2 kg mass) managed by the HP IPAQ pocket computer. A single square (rectangular) loop is used both as a transmitter (Tx) and as receiver (Rx) antennae, so-called single or coincident loop configuration. The antenna is made of wire (0.5 mm2 for 20×20 m2loop was used here) providing high productivity in field conditions. A test ring controls system stability. Time of measurements from 4 to 16 ms includes 48 time windows, with frequency changing from 3.2 kHz to 11 Hz, respectively. The longer the transient time, the greater the distortion of measurement results caused by noise. The time range can be expanded as long as the measurement errors for a signal at maximum time do not exceed 10–20%. Ramp time (delay in starting the measurements) depends on loop size (usually, it varies from155 ns for a 10×10 m^2 loop to 1720 ns for a 100×100 m^2 loop). The dynamic range of voltage received (max/ min) is between 10 V and 100 V, which is the self-noise of the system (TEM-Researcher Software, 2007).

The TEM-RESEARCHER software is intended for modelling and inversion of the TEM sounding data acquired with the TEM FAST 48 HPC systems, (TEM-Researcher Software, 2007). There are two ways of creating a section, transformation and inversion. The transient curves ρa (t) =Res (t) are converted into a pseudo-section ρ (h) =Res (h). The layered model is chosen based on the transformation curve, and layered inversion is performed. The software allows processing data for coincident and central loop configurations. It contains an option for taking into account the Induced Polarization (IP) and Super Paramagnetic (SPM) effects. The software generates both, the transformation and the inversion sections and maps. It is designed for fast performance of "quasi" 2D and 3D pseudo- and inverse-resistivity sections and maps from multiple 1D sounding (tens–hundreds of soundings), which should be performed often under field conditions. The choice for estimating the equivalency and misfit error is not included in the software (TEM-Researcher Software, 2007).

The interpretation steps of the induction resistivity encounters the following:

1. Conventional apparent resistivity versus time curve ρa (t), which is an apparent resistivity of a homogenous medium. The response of which at a given moment coincides with the signal measured in the experiment. It is calculated by the asymptotic formula for late times in the near zone of the transient field.
2. The intermediate function ρf (t) (in contrast to ρa (t)) is introduced as an apparent resistivity valid at any stage of the transient process.
3. Transformation curve ρa (h) calculated from the function ρf (t) and its derivative ρf ' (t) in the TEM FAST methodology.
4. Inverse resistivity versus depth function is calculated from the transformation function in the TEMFAST methodology.
5. Resistivity versus depth functions, showing equivalent solutions for the same ρa (t) function.

6.3.3 TDEM Data Analysis and Interpretation

The Geophysical investigation was conducted according to the survey methods of El-Naqa, (2010). A coincident single turn of 20 m * 20 m loop was used in each location to gain a sufficient penetration depth (~60m). The system was set to transmit currents up to 2 ampere using 12 voltage source batteries with 48 active time gates (15360 µs –t centre). The stacking time was set to about 3 minutes with 50 Hz noise filter in order to avoid aliasing effects of possible galvanic interference.

The resistivity soundings are usually used to define the earth subsurface structures. The structures are multi-dimensional, so it is important to combine 1D inversion models to determine subsurface geologic structures (i.e. 1D inverted models and 2D representation by applying interpolation of the inverted 1D model) (Barsukov *et al*., 2007) .

The results shown below shows a layer up to a depth of 100m. These layers are based on the resistivity. In each site investigated by this method, there was a link between the recharge and the resistivity by means of the identification of the high resistivity zone and the depth of this zone. The solid line in each figure (red and green) represents the resistivity-depth inversion model. The solid lines that connect (plus and triangle symbols) represent the transformation of the resistivity function. The interpretation of each model is to consider the 2000 ohm-m as it is related to the basalt aquifer (Appendix B). If there is a high resistivity in some layers, this means that the layer is basalt. This is indicated by the basalt characters of fracture and faults thereby making it easy to infiltrate. In addition, the high resistivity indicates high porosity and therefore high infiltration.

Figure 6.8 and Table 6.3 show that there are four layers in site number 1, a site photo of which is shown in Figure 6.9. The high resistivity zone is at a depth of 15m from the surface of the Earth and the thickness of 30 to 40m with the resistivity of 2000 Ω.m. When there is a link between the depth of the high resistivity zone from the surface of the Earth and the high resistivity, it shows that high resistivity indicates high porosity and the depth is close to the surface, which indicates a high potential for groundwater recharge. This is because the water coming from the surface will easily and quickly reach the high resistivity zone and then the saturated zone.

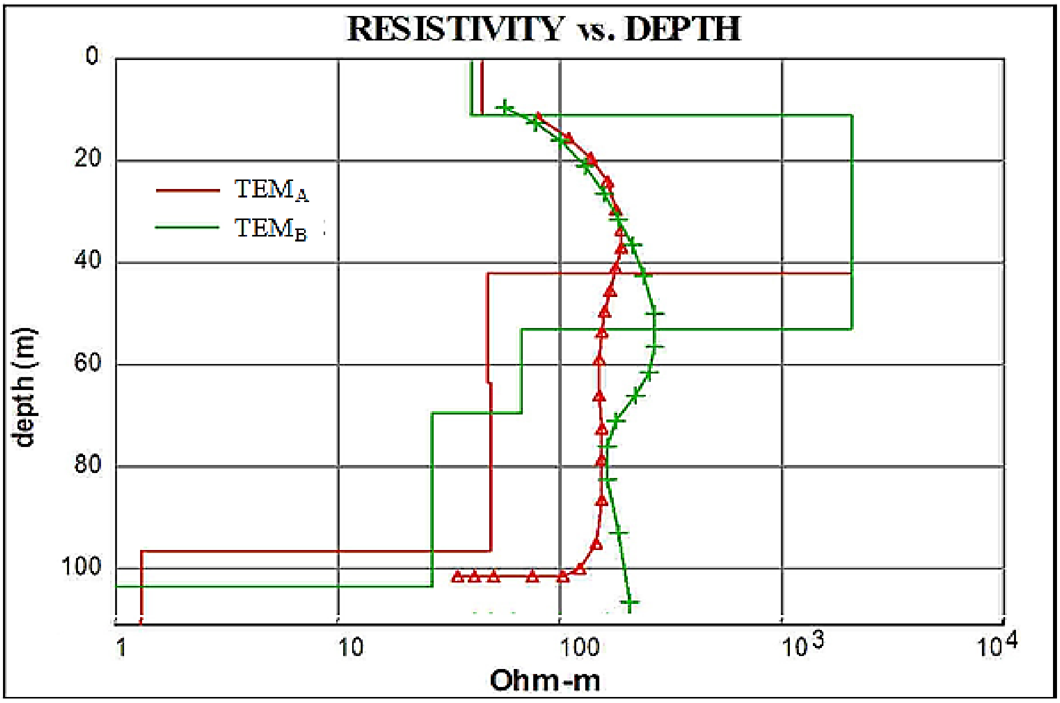


Figure 6.8. TEM resistivity model at site number 1 based on the geoelectrical cross section along (A, B) conducted sites

Table 6.3. Results of the resistivity soundings for site number 1 (A, B)

Layer	Thickness(m)	Resistivity(Ω.m)	Suggested Interpretation	Formation
1	11m	40-45	Thin soil cover/weathered basalt/wet layer	
2	30-40m	2000	Dense, hard basalt, belong to Fahda vesicular basalt (FA) Group (Bishriyya group)	Fahda vesicular basalt (FA)
3	50-55m	30-67	Low Resistivity zone (saturated layer, saturated wadi sediment and fractured basalts)	
4	<10	<10	Very Low Resistivity zone	

Figure 6.9. Field photo of site number 1

Figure 6.10 and Table 6.4 show that the thickness of the high resistivity zone of site number 2, illustrated in Figure 6.11 is 70 to 80 m with a depth of 16m from the surface. The high resistivity zone indicates a high porosity. The depth of the high resistivity zone is near the surface (about 16 m). This allows water moving quickly to the saturated zone. Therefore, this site has high potential for a groundwater recharge.

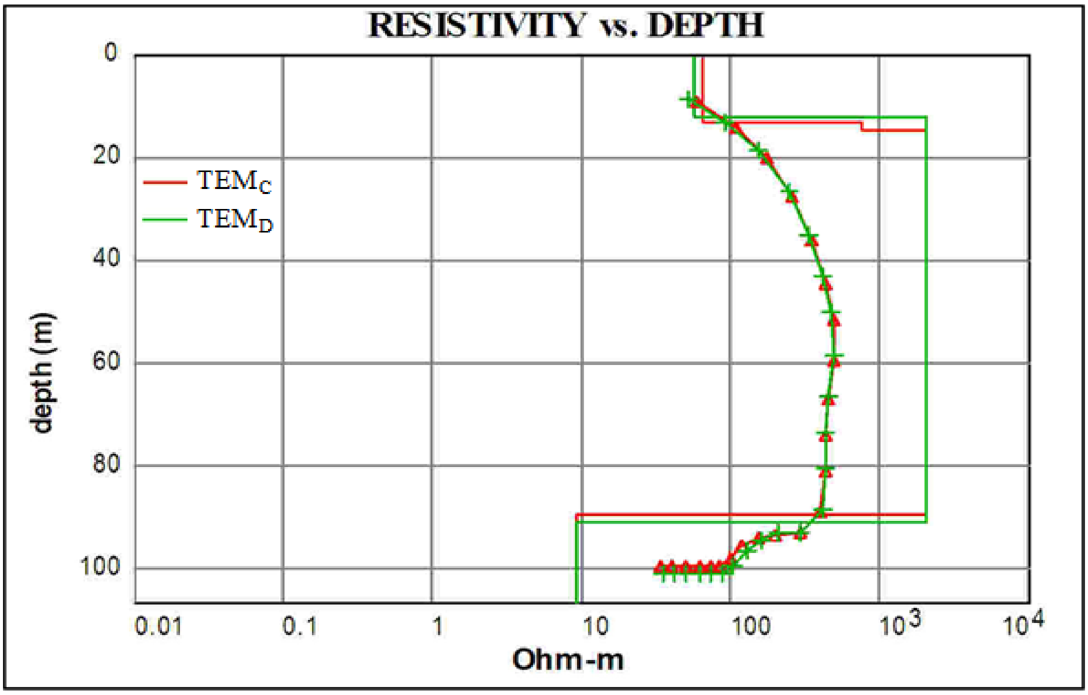


Figure 6.10. TEM resistivity model at site number 2 based on geoelectrical the cross section along (C, D) conducted TEM sites

Table 6.4. Results of the resistivity soundings for site number 2 (C, D)

Layer	Thickness(m)	Resistivity(Ω.m)	Suggested Interpretation	Formation
1	10-12m	50-60	Soil cover	
2	70-80m	700->2000	Dense, hard basalt, belong to Fahda vesicular basalt (FA) Group (Bishriyya group)	Fahda vesicular basalt (FA)
3	Unknown	10	Could be fractured basalt with high content of carbonate sediment, clay, silt	

Figure 6.11. Field photo of site number 2

The results from site 3 are shown in Figure 6.12 and Table 6.5, with a field photo shown in Figure 6.13. The results show that the zone resistivity is high and the depth is 18m from the surface. The thickness of the high resistivity zone is between 65m to 75m. This zone has high porosity where the depth of the unsaturated zone is about 18m of the surface. Thus, the water quickly reaches the high resistivity zone, which results in a good recharge.

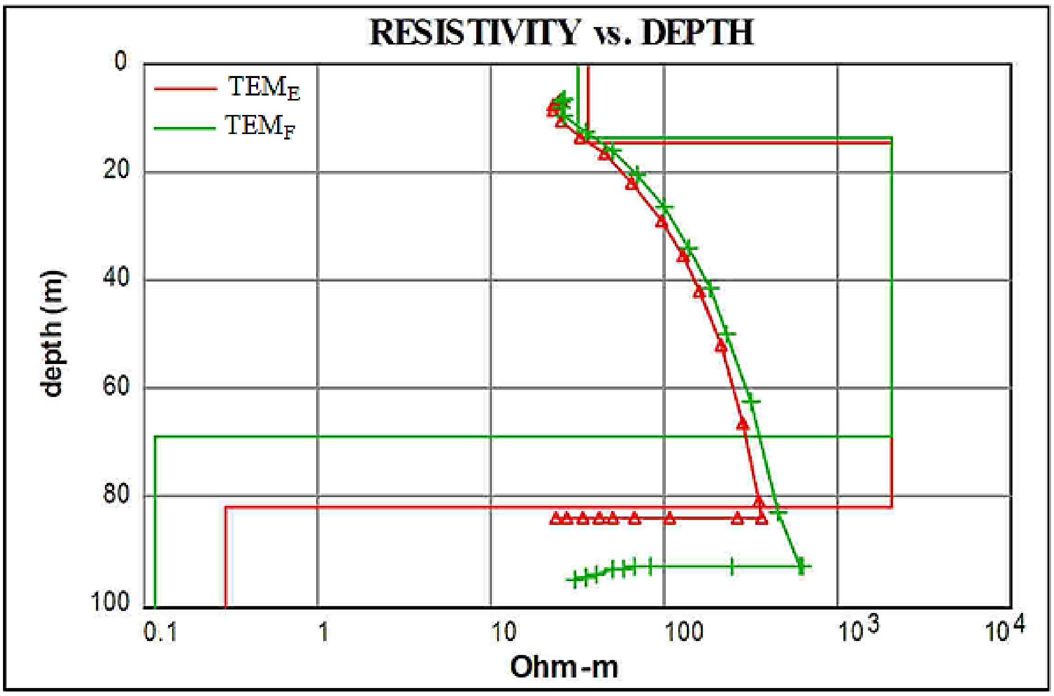


Figure 6.12. TEM resistivity model at site number 3 based on the geoelectrical cross section along (E, F) conducted TEM sites

Table 6.5. Results of resistivity soundings for site number 3 (E, F)

Layer	Thickness(m)	Resistivity(Ω.m)	Suggested Interpretation	Formation
1	12-14m	30-35	Thin soil cover/weathered basalt	
2	65-75m	2000	Massive basalt, boulders of basalt, belong to Madhala olivine phyric basalt formation (MOB)	Madhala Olivine phyric Basalt formation (MOB)
3	Unknown	Unknown	Low Resistivity zone	

Figure 6.13. Field photo of site number 3

At site 4, shown in Figure 6.14 and Table 6.6 and illustrated in Figure 6.15, the thickness of the high resistivity zone is between 6m to 9m and the depth is about 42m. The resistivity of this zone is about 2000 Ω.m, thus resulting in high porosity. In this site, the water must flow up to 42m to reach the high resistivity zone, where there is high infiltration. This can take a long time because the constant zone above the high resistivity zone is silt and clay, which means that this site is not good for groundwater recharge.

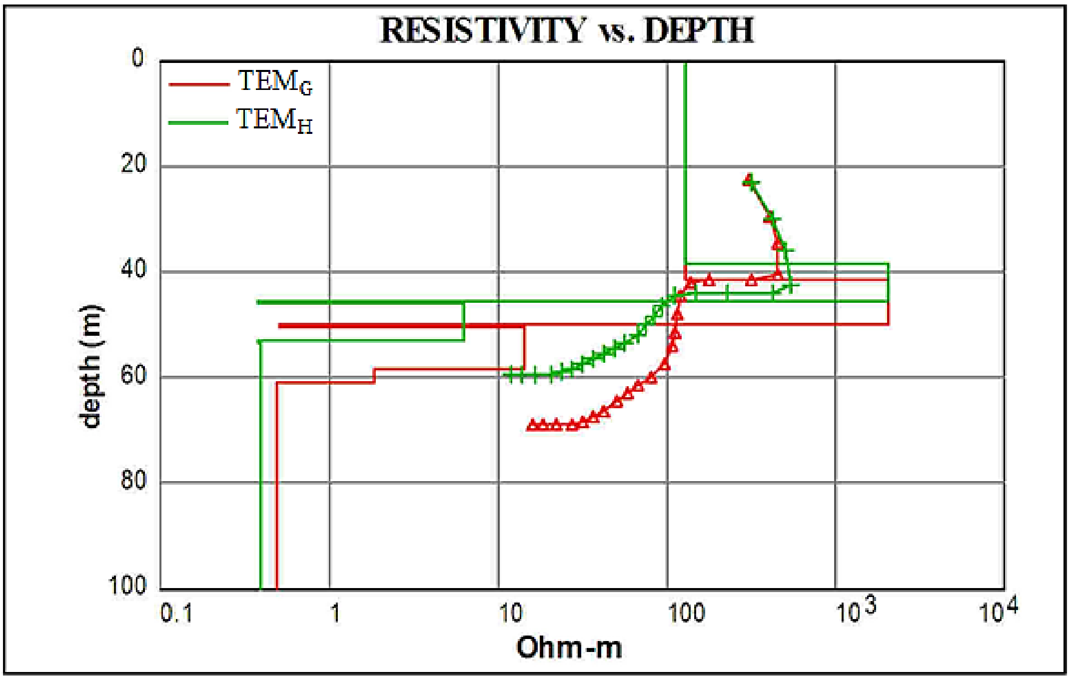


Figure 6.14. TEM resistivity model at site number 4 based on the geoelectrical cross section along (G, H) conducted TEM sites

Table 6.6. Results of resistivity soundings for site number 4 (G,H)

Layer	Thickness(m)	Resistivity(Ω.m)	Suggested Interpretation	Formation
1	38-42m	125-130	Wet, top soil, surface deposit. Basalt intercalated with soil, silt and clay	Madhala Olivine Basalt formation (MOB)
2	6-9m	2000	Massive basalt, boulders of basalt, belong to Madhala olivine phyric basalt formation (MOB)	
3	Unknown	1-10	Low Resistivity zone	

Figure 6.15. Field photo of site number 4

The results for site 5 is shown in Figure 6.16, Table 6.7. A field photo is shown in Figure 6.17. The data show that the depth of the high resistivity zone is about 50m and 15m thick. The zone above the high resistivity zone consists of silt and clay. This indicates that it is a low resistivity zone, and thus, less porosity. This site has low recharge capability, as the water needs time to reach the high resistivity zone.

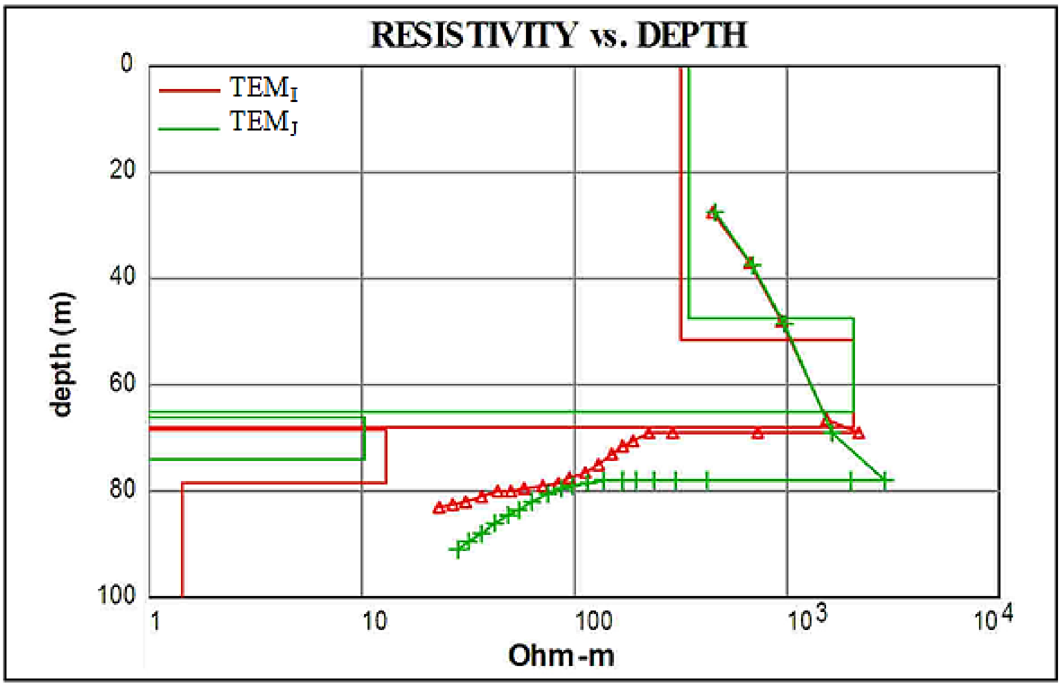


Figure 6.16. TEM resistivity model at site number 5 based on the geoelectrical cross section along (I, J) conducted TEM sites

Table 6.7. Results of resistivity soundings for site number 5 (I, J)

Layer	Thickness(m)	Resistivity(Ω.m)	Suggested Interpretation	Formation
1	45-52m	320-340	Basalt intercalated with soil, silt and clay	
2	15m	2000	Massive basalt, boulders of basalt, belong to Madhala olivine phyric basalt formation (MOB)	Madhala Olivine Basalt formation (MOB)
3	Unknown	Unknown	Low Resistivity zone	

Figure 6.17. Field photo of site number 5

The results for site 6 are shown in Figure 6.18 and Table 6.8. A field photo is shown in Figure 6.19. The results show that the thickness of the high resistivity zone is 40 to 45 m with the depth being 42m from the surface. The zone has a high resistivity of about 2000 Ω.m, which means there is high porosity. The depth of this zone is not close to the surface and the above contents of the zone are silt and clay; this means the water will need time to reach the high resistivity zone and therefore this means this site has low potential for groundwater recharge.

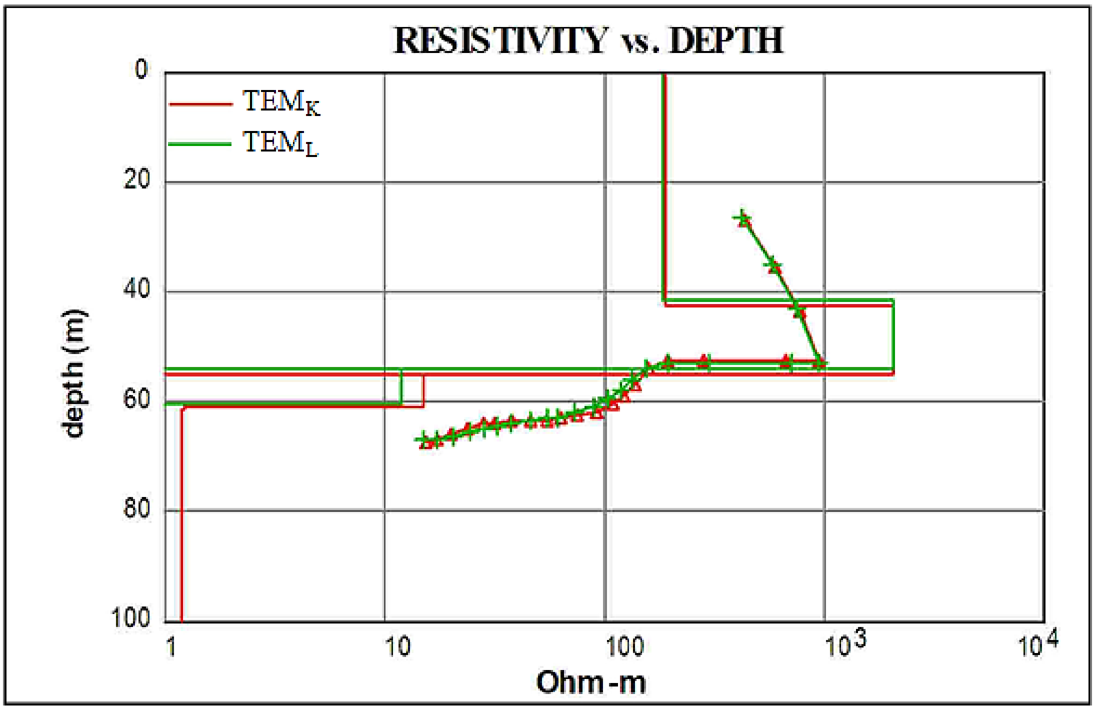


Figure 6.18. TEM resistivity model at site number 6 based on the geoelectrical cross section along (K, L) conducted TEM sites

Table 6.8. Results of resistivity soundings for site number 6 (K, L)

Layer	Thickness(m)	Resistivity(Ω.m)	Suggested Interpretation	Formation
1	40-45m	180-190	Basalt intercalated with soil, silt and clay	Ushayhib olivine pyroxene phyric basalt (UB,Se)
2	12-13m	2000	Massive basalt (UB)-Scoria	
3	Unknown	Unknown	Low Resistivity zone	

Figure 6.19. Field photo of site number 6

Site number 7, shown in Figure 6.20 and Table 6.9 and illustrated as a field photo in Figure 6.21, has a high a recharge capability since the thickness of the high resistivity zone is 20 to 24 m with the depth being 17 m from the surface. The zone has a high resistivity of about 2000 Ω.m, which indicates high porosity. The depth of the high resistivity zone is near the surface. This means that the water can easily and quickly reach the high resistivity zone and thus reach the saturated zone.

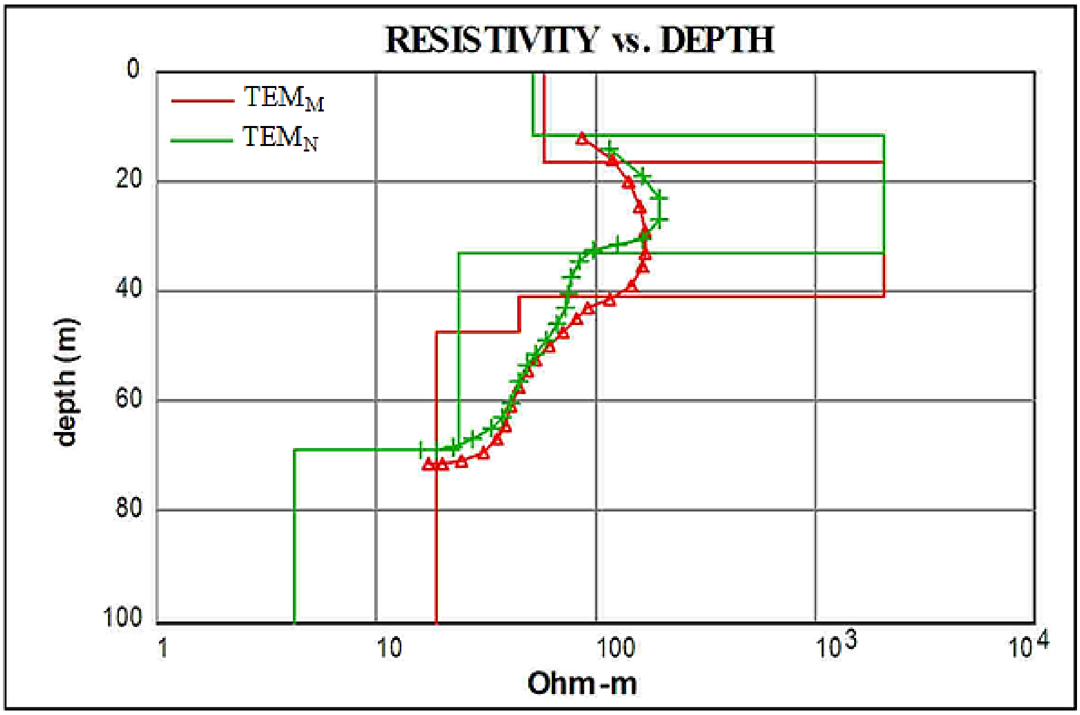


Figure 6.20. TEM resistivity model at site number 7 based on the geoelectrical cross section along (M, N)

Table 6.9. Results of resistivity soundings for site number 7 (M, N)

Layer	Thickness(m)	Resistivity(Ω.m)	Suggested Interpretation	Formation
1	10-16m	50-55	Alluvium mud flat	Alluvium mudflat (Alm), Abed Olivine phyric (AOB)-safawi group
2	20-24m	2000	Massive basalt (A0B)-Scoria	
3	Unknown	20-50	Saturated zone	

Figure 6.21. Field photo of site number 7

The results for site 8 are shown in Figure 6.22 and Table 6.10. A field photo is shown in Figure 6.23. The site has a high resistivity of about 2000 Ω.m with thickness of about 50 to 60m. The depth of the high resistivity zone is 18 meters from the surface of the Earth. The depth of the high resistivity zone is close to the surface. This indicates the water will take a short time to reach the high resistivity zone and then reach the saturated zone. Therefore, this site has high potential for groundwater recharge.

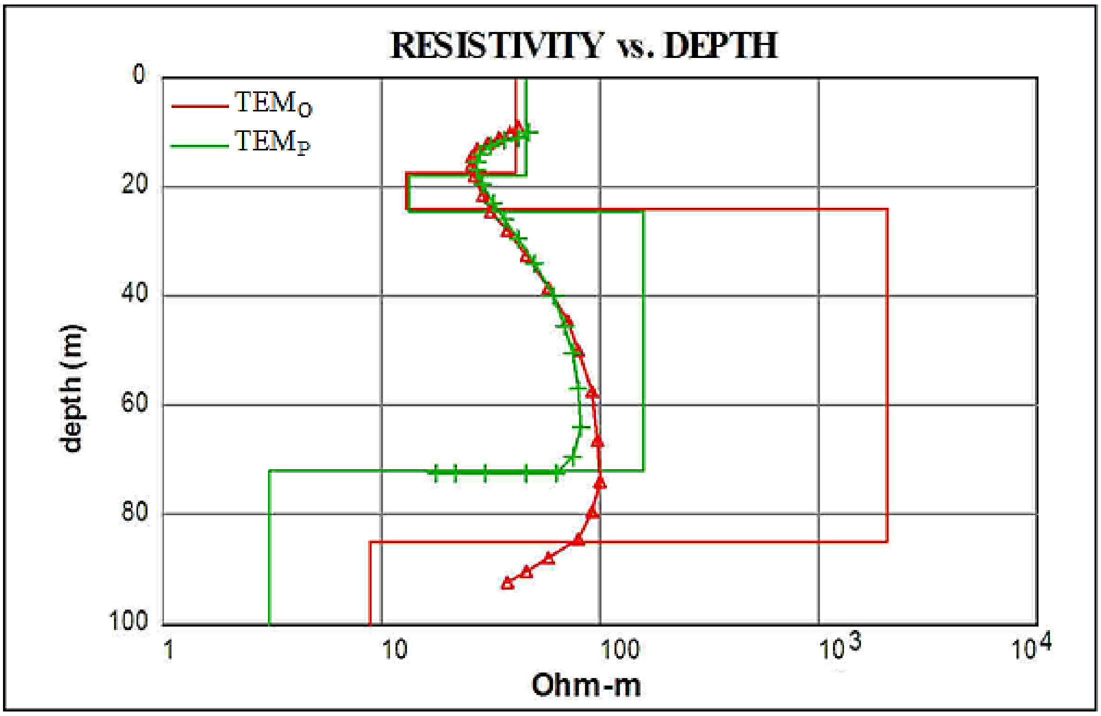


Figure 6.22. TEM resistivity model at site number 8 based on the geoelectrical cross section along (O,P)

Table 6.10. Results of resistivity soundings for site number 8 (O, P)

Layer	Thickness(m)	Resistivity(Ω.m)	Suggested Interpretation	Formation
1	20-24m	10-45	Soil cover	Abed Olivine phyric Basalt (AOB)-safawi
2	50-60m	160-2000	Massive basalt (UB)-Scoria	group
3	Unknown	<10	Saturated and wet layer	

Figure 6.23. Field photo of site number 8

6.4 Summary

The aim of conducting the geophysical investigation is to verify the outcomes of the GIS analysis. Eight sites were investigated, which represent the categories acquired by the GIS analysis (very high, high, moderate and low suitability for recharge). Two sites within each category were investigated with a TDEM and soil texture analysis. If the zone has a high resistivity, this indicates that the site has a high porosity, and thus, high infiltration. However, from site to site, this zone is different in depth from the surface of the Earth. The results show that there are sites close to the surface, such as site numbers 1, 2, 3, 7, and 8 with a range between 15 and 19 m from the Earth's surface. Site 4, 5 and 6 are between 43 and 55m from the surface. Sites 1,2,3,7 and 8 have good recharge potentiality through the depth of the high resistivity zones, whereas site 4, 5 and 6 are not suitable for groundwater recharge due to the depth and the zone type that are above the high resistivity zone. These findings indicate that there is compatibility between the results acquired by TDEM method and results of the GIS analysis as shown in Table 6.11. A comparison of the results acquired by the GIS analysis and the results of the conducted fieldwork investigation are illustrated. The results obtained by the fieldwork investigations were consistent to those acquired by the GIS analysis. This indicates that the conducted GIS analysis is valid in terms of classifying the study area based on the suitability for a groundwater recharge.

Table 6.11. Results of TDEM, soil texture and GIS analysis for all selected sites

Location	Sample	TDEM	Soil texture	Potential of GIS analysis
1	A	High recharge	Sandy Clay Loam	Very high Suitable1
	B			
2	C	High recharge	Loam	High Suitable1
	D			
3	E	High recharge	Clay Loam	Moderate Suitable 1
	F			
4	G	Not good to recharge	Clay	Low Suitable 1
	H			
5	I	Low recharge	Clay loam	Moderate Suitable 2
	J			
6	K	Low recharge	Clay	Low Suitable 2
	L			
7	M	High recharge	Loam	High Suitable2
	N			
8	O	High recharge	Sandy Clay Loam	Very high Suitable2
	P			

In this chapter, we have used field-based observations to verify the sites selected for ground water recharge using the GIS approaches developed in previous chapters. In particular, the following objective is addressed:

- Verify the outcomes of this analysis by making representative field measurements relevant to groundwater recharge that includes Time Domain Electromagnetic Methods (TDEM) and soil texture analysis.

The results, as shown in the various figures and tables, and summarised in Table 6.11 show that there is good correspondence between the sites identified through the GIS methods and suitability assessed through field measurements. In addressing this objective, it can be said that confidence has been gained in the usability and appropriateness of the approaches that have been developed in this study. The results presented in this chapter make a strong contribution to answering the research question that addresses whether the adaptations to existing approaches yield results that add value to existing knowledge and yield sites that are appropriate for groundwater recharge locations. The final chapter of this thesis brings together the collective of results and discusses the findings of this study in relation to existing literature and state of the art.

7 DISCUSSION & CONCLUSIONS

This chapter discusses the results that have been presented in Chapters 4, 5 and 6 against the research questions that were stated at the end of Chapter 2. Recommendations for areas of further research are presented.

In this study, modified Analytic Hierarchy Process (AHP) were used employed to generate a groundwater recharge suitability map of a study area located within the Azraq basin in Jordan which was followed up by field investigations at several sites within the study area to verify the acquired results.

Nine site selection criteria affecting the groundwater recharge in the study area were defined based on a literature review and discussions with relevant local experts (17 experts). These criteria were the Rainfall, the Material of the Vadose Zone, the Slope, the Lineament Density, the Soil Texture, the Drainage Density, the Static Water Level, the Aquifer Media and the Land use/ Land cover. In addition, five socio-economical factors that conflict with existing human activities, and thus, affecting the groundwater recharge were identified based on experts recommendations and literature review. These factors were the roads, the proximity of the international border, the urban, the farms, and the wells.

Following a review of the literature, a number of research questions were proposed.

7.1 Modified AHP to Address Groundwater Recharge Siting Options

The following research questions were stated following a review of the literature.

- Can we utilise the views and opinions of multiple experts in the field of groundwater recharge with a spatial analysis framework to identify the suitable site for groundwater recharge in the study area?

Results described in this thesis demonstrate that an effective interview and data collection campaign can be undertaken to acquire the opinions of multiple experts in the field of groundwater recharge and implemented in an AHP framework. The views of 17 experts were sought. These views contributed to the determination of the relative weights for each criterion considered to have an impact on site selection. Local experts' recommendations and their evaluations of the relevant importance of each individual criteria were acquired through a questionnaire. There was a difficulty in gathering all the experts in one place, and thus, expert opinions were taken individually. Each expert was asked to assess the importance of each criterion on a scale of 1 to 9, where 9 indicates a most significant criterion where 1 represents a minor criterion, there were a minor discrepancy in experts opinions with respect to the importance of each criterion. The pairwise comparison method (PCM) was applied for each expert opinion to identify the weight of each selection criterion and to assess the consistency between the experts' opinions. The results shows that the consistency ratio (CR) of each expert evaluation was less than or equal to 0.1, which indicated that expert opinions were consistent and could be used for the site selection of the groundwater recharge. Furthermore, the mean, the mode and the median of the weights were computed to further assess the compatibility between the opinions of the experts and identify the final weight for each criterion. The analysis results showed that the rainfall criterion was selected, as it was the most important criterion.

The findings of this research are in agreement with Anane *et al.* (2008); Han (2003); Krishnamurthy and Srinivas (1995); Krishnamurthy *et al.* (1996); Rahman *et al.* (2012); Rolland and Rangarajan (2013); and Saraf and Choudhury (1998). The original contribution of this research to the Analytical Hierarchy Process (AHP) is the use of individual opinion and merge them through the use of Mean, Mode and Median to check wither the experts opinions are consistent or not. The use of this novel approach mitigated against the need to gather all experts in one place. The advantage of this approach would be that expert opinion would reflect their expertise without influence. A dis-advantage of this approach would be the fact that the experts could not discuss or negotiate their position as a collective. However, for an application as important as groundwater recharge consensus may never have been reached.

- What is the consistency in these opinions and can they be represented spatially?

The Weighted Linear Combination (WLC) technique was used to identify the potential sites for groundwater recharge in the study area. This method is based on the collection of all the criteria after multiplying weights in rating, thereafter determining weights and unifying ranks for each criterion. The study area was classified into five classes in terms of the suitability for the groundwater recharge namely: very low suitability for groundwater recharge, low suitability for groundwater recharge, moderately suitable for groundwater recharge, high suitability for groundwater recharge and very high suitability for groundwater recharge. The Boolean technique was then used to eliminate these sites that are not suitable for the groundwater recharge within the study area including the roads, the urban, the farms, the wells and the close proximity of the international borders. The Boolean operation resulted in classifying the study area into two classes, suitable and not suitable for groundwater recharge, where the specified sites categories that are not suitable for groundwater recharge are eliminated. To identify the optimal sites for groundwater recharge in the study area, the results of the WLC analysis and the results of the Boolean technique were integrated to generate a final groundwater recharge suitability map of the study area. The study area was classified into no suitability, low suitability, moderate suitability, high suitability, and very high suitability in terms of groundwater recharge.

It was found in this study that there was consistency in the experts' opinions by checking the consistency ratio (CR) for each expert individually. The opinions of the experts were then merged using the Mean, Median and Mode that showed that all experts' opinions are in consistent and can be represented spatially. The outcome of this method is in agreement with Ezell (2001). In Chapter 5, it was determined that these views could be represented spatially. In this case, the views were found to meet the criteria for consistency. Future work may consider the scenario in the case when the experts cannot have a joint meeting to determine the appropriate weights for the selection criteria. It would be necessary to implement work-around solutions in this case.

- What novel adaptations to existing approaches can be made to support the merge of physical criteria and social factors to locate suitable sites for groundwater recharge potential?

Novel adaptations to existing approaches were implemented in this research to merge nine physical-based criteria with five social-based factors. The physical criteria are of great importance in determining the optimum site for groundwater recharge in the study area but not all selected sites can be utilized for groundwater recharge projects. Therefore, the social factors were introduced to eliminate sites that have other uses of socio-economic importance to the local community. The integration of both physical and social factors has been adopted by Al-Adamat, (2008), Al-Adamat et al., (2010) and Baban and Wan-Yusof, (2003).

There were two limitations in this stage, which are the use of medium map scale and the use of 2003 satellite imagery to generate the land use/cover map. Map data were available at a scale of 1:250,000. This may partially limit the identification of sites at the local level. Errors in map scale is equal to 0.1 mm which means that all maps used in this research is expected to have an error of 25m each. This might generate some errors in the final map. This scenario is mitigated against in this study due to the largely heterogeneous landscape that exists in the study area. The majority of the physical criteria are not varying at a high frequency which reduce the impact of securing absolute site location.

- Do these adaptations yield results that add value to existing knowledge and yield sites that are appropriate for groundwater recharge locations?

The results of the field investigations were consistent to the results acquired by the GIS analysis. The adaptations of AHP within GIS environment and based on experts opinions have yielded results that added value to the existing knowledge, especially the utilization of individual expert opinion and merge these opinions through the use of Mean, Median and Mode. Representing the consolidated views of a number of experts in groundwater hydrology and reflecting that information spatially is an incredibly difficult and politically charged task. Chapter 6 describes the verification method to establish that zones of suitability were in fact appropriate for groundwater recharge. The method used was a combination of Time Domain Electromagnetic Methods (TDEM) and soil texture analysis. Due to the expense, in terms of funding for lab and field support and time, of deploying this equipment in the field, it was necessary to restrict the number of sites visited to less than twenty. Although it would be recommended to visit many more sites (suitable and not suitable) for further investigation, this was not possible within the scope of the study and may not have eventually contributed to more knowledge if field analysis results were similar. Some sites were not accessible by car, which was needed to carry the geophysical equipment to these sites. Access to the laboratories of Al al-Bayt University, Jordan was financed for a period of only one month. We could use the equipment only for short periods of time.

The results of this fieldwork did establish that there was good correspondence between field derived suitability classification and the results derived from the GIS analysis. Future work on this task will be to close the loop and feedback to the experts the derived consensus view and discuss with them the implications of the informed opinion regarding the location of the study sites. One of the wider implications of this research is the provision to decision makers in Jordan of a set of verified map products that indicate relative zones of suitability. Jordan is one of the poorest countries in the world when it comes to water resources availability. This research will contribute to the enhancement of the available water resources in the country if the selected sites will be utilised for groundwater recharge. This will contribute to the sustainable socio-economic development of Jordan. Also, this will lead to have a better environment in the country through increasing the vegetation cover which will have a healthy environment in the future.

7.2 Uncertainties

It is important to establish and state some of the theoretical and practical uncertainties that sit within the results of this study. These uncertainties can often lead to the establishment of future research questions and objectives. The study design and methodology have mitigated against these uncertainties to a great extent. However, they need to be mentioned in case improved information and data is available to re-do this analysis in the future.

- Uncertainty with the slope map, that was generated from the what was believed to be the most accurate elevation model at the time of sourcing the data sets. Recent products from TerraSAR-X may offer better solutions.
- The satellite imagery data used in this study was from 2003 and there may have been more recent land use/cover changes not captured at this time. Post 2033, Landsat 7 TM was affected by the Scan Line Correction fault and the analysis was undertaken before Landsat TM 8 became available. The spatial resolution may also have been improved if funds were available to purchase commercial data sets such as RapidEye, WorldView or SPOT. No funds were available to do this.
- Maps data were available at a scale of 1:250,000, which may potentially limit site identification as previously discussed above.

- Number of verification sites as previously discussed above.
- The experts were mainly drawn from a hydrological sciences background. As social factors were included in the analysis, but not discussed, experts from a multi-disciplinary background could have been consulted. Other local actors and decision makers could have been further drawn into the debate. It was felt that local knowledge was captured by the process but the views of the local, non-expert may have been valuable.

7.3 Conclusions

The aim of this study, as stated in Section 1.4 was to identify potential sites for groundwater recharge in an aquifer in Jordan using an adapted AHP method that utilises the opinions of local experts.

Based on the results and discussion presented in Chapters 4 to 7 it is stated that the aim of the study has been met. Indeed, delineation of the study area into zones of suitability has been achieved after geographical consensus was achieved regarding the importance and weighting of physical factors that influence groundwater recharge potential. These zones have been further modified by a number of socio-economic factors that will affect where possible sites can be located. There is confidence in the results following a period of field investigations to support the evidence coming from the AHP analysis.

The novelty of this research is the generation and integration of a range of physical and socio-economic factors that have not been considered together as a whole before. And the method used to acquire the opinions of the experts in the absence of a formal meeting where consensus over the relative importance and weights of the factors would be determined. This study used the mean, the median and the mode values of experts' scores for selection criteria weights to overcome the problem of having outliers values. These values were also subjected to consistency ratio analysis to make sure that the experts' opinions are consistent. There is great value in applying this method to other geographical issues where opinions of experts of the factors that are important and their relative weights would be sought and analysed. The study described relatively quick methods verify the outcomes of the derived maps of suitability that supported the findings of the spatial analysis.

The study has major implications for the Jordanian agricultural and drinking water systems as much of the country's water resources are being exploited at maximum capacity beyond their safe yield. Agriculture in Jordan consumes more than 93% of the available water resources of which more than 36% comes from groundwater. The approach developed in this research can provide beneficial information in identifying groundwater recharge sites in the study area, which can be used by the decision makers in Jordan to establish new groundwater recharge projects within the Azraq basin in Jordan.

7.4 Future Work

Themes for future research on this study are:

- Feedback the findings to the experts and seek their critique and support.
- Update and revise the analysis when better underpinning data sets become available (e.g. DEM and land use/cover map).
- Apply the methods to other groundwater basins in Jordan.
- Seek the opinion of international experts in groundwater recharge for a wider perspective on the issue. A web site or an online questionnaire could be used for this purpose. Quality control of the completed submissions by the experts would be required.
- Implement a pilot groundwater recharge project in an area deemed to be Highly Suitable and make observations of water table to determine the effectiveness of recharge. A couple of related projects would be to observe the impact of the irrigation return flow on groundwater recharge and investigate the impact on the groundwater quality if surface water is artificially pumped directly into the ground.

Appendix A - Research Questionnaire

Questionnaire

Name: ……………………………………………………………..

Position: …………………………………………………………..

Email address: ………………………………………………

Dear Respected scientist/ Expert,

I am currently undertaken a PhDresearch at the university of Leicester, UK on the use of GIS in the selection of potential sites for Artificial Groundwater Recharge in the Azraq Basin. In this research, the selection criteria will be developed based on the literature review and the experience of selected scientists and experts in Jordan.

Based on your experience, please advice on the selection criteria below by suggesting the appropriate weight and ranking for each criterion.

Table A1: criteria that selected based on the literature review

Criteria	Weight	Explanations
Rainfall		
Lineament Density		
Static Water Level		
Aquifer Media		
Material of Vadose Zone		
Slope		
Land use/ Land cover		
Drainage Density		
Soil Texture		

Table A2: Other criteria (Please specify)

Criteria	Weight	Explanations
		1. 2. 3. 4.
		1. 2. 3. 4.
		1. 2. 3. 4.

Table A3: Pairwise comparison matrix for expert number 2

Criteria	A	B	C	D	E	F	G	H	I
A	1.000	1.125	1.500	1.286	1.800	1.800	2.250	2.250	3.000
B	0.889	1.000	1.333	1.143	1.600	1.600	2.000	2.000	2.667
C	0.667	0.750	1.000	0.857	1.200	1.200	1.500	1.500	2.000
D	0.778	0.875	1.167	1.000	1.400	1.400	1.750	1.750	2.333
E	0.556	0.625	0.833	0.714	1.000	1.000	1.250	1.250	1.667
F	0.556	0.625	0.833	0.714	1.000	1.000	1.250	1.250	1.667
G	0.444	0.500	0.667	0.571	0.800	0.800	1.000	1.000	1.333
H	0.444	0.500	0.667	0.571	0.800	0.800	1.000	1.000	1.333
I	0.333	0.375	0.500	0.429	0.600	0.600	0.750	0.750	1.000

Λ_{max} = 10.08, CI= 0.14, RI = 1.45, CR= 0.09. CR<0.1

Table A4: Pairwise comparison matrix for expert number 3

Criteria	A	B	C	D	E	F	G	H	I
A	1.000	1.125	1.500	1.286	1.800	1.800	2.250	2.250	3.000
B	0.889	1.000	1.333	1.143	1.600	1.600	2.000	2.000	2.667
C	0.667	0.750	1.000	0.857	1.200	1.200	1.500	1.500	2.000
D	0.778	0.875	1.167	1.000	1.400	1.400	1.750	1.750	2.333
E	0.556	0.625	0.833	0.714	1.000	1.000	1.250	1.250	1.667
F	0.556	0.625	0.833	0.714	1.000	1.000	1.250	1.250	1.667
G	0.444	0.500	0.667	0.571	0.800	0.800	1.000	1.000	1.333
H	0.444	0.500	0.667	0.571	0.800	0.800	1.000	1.000	1.333
I	0.333	0.375	0.500	0.429	0.600	0.600	0.750	0.750	1.000

Λ_{max} = 10.08, CI= 0.14, RI = 1.45, CR= 0.09. CR<0.1

Table A5: Pairwise comparison matrix for expert number 4

Criteria	A	B	C	D	E	F	G	H	I
A	1.000	1.500	1.125	1.800	2.250	3.000	1.800	3.000	2.250
B	0.667	1.000	0.750	1.200	1.500	2.000	1.200	2.000	1.500
C	0.889	1.333	1.000	1.600	2.000	2.667	1.600	2.667	2.000
D	0.556	0.833	0.625	1.000	1.250	1.667	1.000	1.667	1.250
E	0.444	0.667	0.500	0.800	1.000	1.333	0.800	1.333	1.000
F	0.333	0.500	0.375	0.600	0.750	1.000	0.600	1.000	0.750
G	0.556	0.833	0.625	1.000	1.250	1.667	1.000	1.667	1.250
H	0.333	0.500	0.375	0.600	0.750	1.000	0.600	1.000	0.750
I	0.444	0.667	0.500	0.800	1.000	1.333	0.800	1.333	1.000

Λ_{max} = 10.3, CI = 0.2, RI = 1.45, CR = 0.1

Table A6: Pairwise comparison matrix for expert number 5

Criteria	A	B	C	D	E	F	G	H	I
A	1.000	1.125	1.125	1.500	1.286	1.500	2.250	2.250	2.250
B	0.889	1.000	1.000	1.333	1.143	1.333	2.000	2.000	2.000
C	0.889	1.000	1.000	1.333	1.143	1.333	2.000	2.000	2.000
D	0.667	0.750	0.750	1.000	0.857	1.000	1.500	1.500	1.500
E	0.778	0.875	0.875	1.167	1.000	1.167	1.750	1.750	1.750
F	0.667	0.750	0.750	1.000	0.857	1.000	1.500	1.500	1.500
G	0.444	0.500	0.500	0.667	0.571	0.667	1.000	1.000	1.000
H	0.444	0.500	0.500	0.667	0.571	0.667	1.000	1.000	1.000
I	0.444	0.500	0.500	0.667	0.571	0.667	1.000	1.000	1.000

Λ_{max} =9.88, CI = 0.11, RI = 1.45, CR= 0.08, CR<0.1

Table A7: Pairwise comparison matrix for expert number 6

Criteria	A	B	C	D	E	F	G	H	I
A	1.000	2.250	1.125	2.250	1.800	1.500	2.250	1.286	1.500
B	0.444	1.000	0.500	1.000	0.800	0.667	1.000	0.571	0.667
C	0.889	2.000	1.000	2.000	1.600	1.333	2.000	1.143	1.333
D	0.444	1.000	0.500	1.000	0.800	0.667	1.000	0.571	0.667
E	0.556	1.250	0.625	1.250	1.000	0.833	1.250	0.714	0.833
F	0.667	1.500	0.750	1.500	1.200	1.000	1.500	0.857	1.000
G	0.444	1.000	0.500	1.000	0.800	0.667	1.000	0.571	0.667
H	0.778	1.750	0.875	1.750	1.400	1.167	1.750	1.000	1.167
I	0.667	1.500	0.750	1.500	1.200	1.000	1.500	0.857	1.000

Λ_{max} =9.79, CI= 0.1, RI= 1.45, CR= 0.07, CR<0.1

Table A8: Pairwise comparison matrix for expert number 7

Criteria	A	B	C	D	E	F	G	H	I
A	1.000	1.800	1.286	1.800	2.250	1.286	2.250	3.000	3.000
B	0.556	1.000	0.714	1.000	1.250	0.714	1.250	1.667	1.667
C	0.778	1.400	1.000	1.400	1.750	1.000	1.750	2.333	2.333
D	0.556	1.000	0.714	1.000	1.250	0.714	1.250	1.667	1.667
E	0.444	0.800	0.571	0.800	1.000	0.571	1.000	1.333	1.333
F	0.778	1.400	1.000	1.400	1.750	1.000	1.750	2.333	2.333
G	0.444	0.800	0.571	0.800	1.000	0.571	1.000	1.333	1.333
H	0.333	0.600	0.429	0.600	0.750	0.429	0.750	1.000	1.000
I	0.333	0.600	0.429	0.600	0.750	0.429	0.750	1.000	1.000

Λ_{max} = 10.3, CI = 0.2, RI= 1.45, CR= 0.1

Table A9: Pairwise comparison matrix for expert number 8

Criteria	A	B	C	D	E	F	G	H	I
A	1.000	1.000	1.600	1.333	1.600	1.143	2.000	1.143	2.667
B	1.000	1.000	1.600	1.333	1.600	1.143	2.000	1.143	2.667
C	0.625	0.625	1.000	0.833	1.000	0.714	1.250	0.714	1.667
D	0.750	0.750	1.200	1.000	1.200	0.857	1.500	0.857	2.000
E	0.625	0.625	1.000	0.833	1.000	0.714	1.250	0.714	1.667
F	0.875	0.875	1.400	1.167	1.400	1.000	1.750	1.000	2.333
G	0.500	0.500	0.800	0.667	0.800	0.571	1.000	0.571	1.333
H	0.875	0.875	1.400	1.167	1.400	1.000	1.750	1.000	2.333
I	0.375	0.375	0.600	0.500	0.600	0.429	0.750	0.429	1.000

Λ_{max} = 9.93, CI= 0.12, RI= 1.45, CR= 0.08. CR<0.1

Table A10: Pairwise comparison matrix for expert number 9

Criteria	A	B	C	D	E	F	G	H	I
A	1.000	1.125	1.800	1.500	2.250	1.500	1.500	3.000	3.000
B	0.889	1.000	1.600	1.333	2.000	1.333	1.333	2.667	2.667
C	0.556	0.625	1.000	0.833	1.250	0.833	0.833	1.667	1.667
D	0.667	0.750	1.200	1.000	1.500	1.000	1.000	2.000	2.000
E	0.444	0.500	0.800	0.667	1.000	0.667	0.667	1.333	1.333
F	0.667	0.750	1.200	1.000	1.500	1.000	1.000	2.000	2.000
G	0.667	0.750	1.200	1.000	1.500	1.000	1.000	2.000	2.000
H	0.333	0.375	0.600	0.500	0.750	0.500	0.500	1.000	1.000
I	0.333	0.375	0.600	0.500	0.750	0.500	0.500	1.000	1.000

Λ_{max} = 10.3, CI = 0.2, RI= 1.45, CR= 0.1

Table A11: Pairwise comparison matrix for expert number 10

Criteria	A	B	C	D	E	F	G	H	I
A	1.000	1.333	1.333	1.600	1.333	2.000	2.667	2.000	1.600
B	0.750	1.000	1.000	1.200	1.000	1.500	2.000	1.500	1.200
C	0.750	1.000	1.000	1.200	1.000	1.500	2.000	1.500	1.200
D	0.625	0.833	0.833	1.000	0.833	1.250	1.667	1.250	1.000
E	0.750	1.000	1.000	1.200	1.000	1.500	2.000	1.500	1.200
F	0.500	0.667	0.667	0.800	0.667	1.000	1.333	1.000	0.800
G	0.375	0.500	0.500	0.600	0.500	0.750	1.000	0.750	0.600
H	0.500	0.667	0.667	0.800	0.667	1.000	1.333	1.000	0.800
I	0.625	0.833	0.833	1.000	0.833	1.250	1.667	1.250	1.000

Λ_{max} = 9.70, CI= 0.09, RI= 1.45, CR= 0.06. CR<0.1

Table A12: Pairwise comparison matrix for expert number 11

Criteria	A	B	C	D	E	F	G	H	I
A	1.000	1.500	1.125	2.250	2.250	1.800	1.286	2.250	3.000
B	0.667	1.000	0.750	1.500	1.500	1.200	0.857	1.500	2.000
C	0.889	1.333	1.000	2.000	2.000	1.600	1.143	2.000	2.667
D	0.444	0.667	0.500	1.000	1.000	0.800	0.571	1.000	1.333
E	0.444	0.667	0.500	1.000	1.000	0.800	0.571	1.000	1.333
F	0.556	0.833	0.625	1.250	1.250	1.000	0.714	1.250	1.667
G	0.778	1.167	0.875	1.750	1.750	1.400	1.000	1.750	2.333
H	0.444	0.667	0.500	1.000	1.000	0.800	0.571	1.000	1.333
I	0.333	0.500	0.375	0.750	0.750	0.600	0.429	0.750	1.000

Λ_{max} = 10.2, CI= 0.1, RI= 1.45, CR= 0.1

Table A13: Pairwise comparison matrix for expert number 12

Criteria	A	B	C	D	E	F	G	H	I
A	1.000	0.750	0.667	1.500	0.750	1.200	2.000	1.200	0.857
B	1.333	1.000	0.889	2.000	1.000	1.600	2.667	1.600	1.143
C	1.500	1.125	1.000	2.250	1.125	1.800	3.000	1.800	1.286
D	0.667	0.500	0.444	1.000	0.500	0.800	1.333	0.800	0.571
E	1.333	1.000	0.889	2.000	1.000	1.600	2.667	1.600	1.143
F	0.833	0.625	0.556	1.250	0.625	1.000	1.667	1.000	0.714
G	0.500	0.375	0.333	0.750	0.375	0.600	1.000	0.600	0.429
H	0.833	0.625	0.556	1.250	0.625	1.000	1.667	1.000	0.714
I	1.167	0.875	0.778	1.750	0.875	1.400	2.333	1.400	1.000

Λ_{max} = 10.1, CI= 0.1, RI= 1.45, CR= 0.1

Table A14: Pairwise comparison matrix for expert number 13

Criteria	A	B	C	D	E	F	G	H	I
A	1.000	1.000	0.889	1.000	1.333	1.600	1.143	2.000	2.667
B	1.000	1.000	0.889	1.000	1.333	1.600	1.143	2.000	2.667
C	1.125	1.125	1.000	1.125	1.500	1.800	1.286	2.250	3.000
D	1.000	1.000	0.889	1.000	1.333	1.600	1.143	2.000	2.667
E	0.750	0.750	0.667	0.750	1.000	1.200	0.857	1.500	2.000
F	0.625	0.625	0.556	0.625	0.833	1.000	0.714	1.250	1.667
G	0.875	0.875	0.778	0.875	1.167	1.400	1.000	1.750	2.333
H	0.500	0.500	0.444	0.500	0.667	0.800	0.571	1.000	1.333
I	0.375	0.375	0.333	0.375	0.500	0.600	0.429	0.750	1.000

Λ_{max} = 10.2, CI= 0.1, RI= 1.45, CR= 0.1

Table A15: Pairwise comparison matrix for expert number 14

Criteria	A	B	C	D	E	F	G	H	I
A	1.000	1.125	1.000	1.800	1.125	1.125	1.125	1.000	1.000
B	0.889	1.000	0.889	1.600	1.000	1.000	1.000	0.889	0.889
C	1.000	1.125	1.000	1.800	1.125	1.125	1.125	1.000	1.000
D	0.556	0.625	0.556	1.000	0.625	0.625	0.625	0.556	0.556
E	0.889	1.000	0.889	1.600	1.000	1.000	1.000	0.889	0.889
F	0.889	1.000	0.889	1.600	1.000	1.000	1.000	0.889	0.889
G	0.889	1.000	0.889	1.600	1.000	1.000	1.000	0.889	0.889
H	1.000	1.125	1.000	1.800	1.125	1.125	1.125	1.000	1.000
I	1.000	1.125	1.000	1.800	1.125	1.125	1.125	1.000	1.000

Λ_{max} =9.28, CI= 0.04, RI= 1.45, CR= 0.02. CR<0.1

Table A16: Pairwise comparison matrix for expert number 15

Criteria	A	B	C	D	E	F	G	H	I
A	1.000	1.125	1.286	1.800	1.286	2.250	1.286	1.500	3.000
B	0.889	1.000	1.143	1.600	1.143	2.000	1.143	1.333	2.667
C	0.778	0.875	1.000	1.400	1.000	1.750	1.000	1.167	2.333
D	0.556	0.625	0.714	1.000	0.714	1.250	0.714	0.833	1.667
E	0.778	0.875	1.000	1.400	1.000	1.750	1.000	1.167	2.333
F	0.444	0.500	0.571	0.800	0.571	1.000	0.571	0.667	1.333
G	0.778	0.875	1.000	1.400	1.000	1.750	1.000	1.167	2.333
H	0.667	0.750	0.857	1.200	0.857	1.500	0.857	1.000	2.000
I	0.333	0.375	0.429	0.600	0.429	0.750	0.429	0.500	1.000

Λ_{max} =10. 05, CI= 0.13, RI= 1.45, CR = 0.09. CR<0.1

Table A17: Pairwise comparison matrix for expert number 16

Criteria	A	B	C	D	E	F	G	H	I
A	1.000	1.286	2.250	2.250	2.250	1.800	1.800	1.286	3.000
B	0.778	1.000	1.750	1.750	1.750	1.400	1.400	1.000	2.333
C	0.444	0.571	1.000	1.000	1.000	0.800	0.800	0.571	1.333
D	0.444	0.571	1.000	1.000	1.000	0.800	0.800	0.571	1.333
E	0.444	0.571	1.000	1.000	1.000	0.800	0.800	0.571	1.333
F	0.556	0.714	1.250	1.250	1.250	1.000	1.000	0.714	1.667
G	0.556	0.714	1.250	1.250	1.250	1.000	1.000	0.714	1.667
H	0.778	1.000	1.750	1.750	1.750	1.400	1.400	1.000	2.333
I	0.333	0.429	0.750	0.750	0.750	0.600	0.600	0.429	1.000

Λ_{max} =10.03, CI= 0.13, RI= 1.45, CR= 0.09, CR<0.1

Table A18 Pairwise comparison matrix for expert number 17

Criteria	A	B	C	D	E	F	G	H	I
A	1.000	1.125	1.800	1.286	3.000	2.250	1.800	1.500	2.250
B	0.889	1.000	1.600	1.143	2.667	2.000	1.600	1.333	2.000
C	0.556	0.625	1.000	0.714	1.667	1.250	1.000	0.833	1.250
D	0.778	0.875	1.400	1.000	2.333	1.750	1.400	1.167	1.750
E	0.333	0.375	0.600	0.429	1.000	0.750	0.600	0.500	0.750
F	0.444	0.500	0.800	0.571	1.333	1.000	0.800	0.667	1.000
G	0.556	0.625	1.000	0.714	1.667	1.250	1.000	0.833	1.250
H	0.667	0.750	1.200	0.857	2.000	1.500	1.200	1.000	1.500
I	0.444	0.500	0.800	0.571	1.333	1.000	0.800	0.667	1.000

Λ_{max} = 10.08, CI= 0.14, RI= 1.45, CR= 0.09, CR<0.1

Appendix B - TDEM raw data

#Set 1

Time-Range 3 Stacks 5 deff= 3 us I=1.0 A FILTR=50 Hz AMPLIFER=OFF

T-LOOP (m) 20.000 R-LOOP (m) 20.000 TURN= 1

Comments: PPC HP IPAQ 2190

Location:x= +0.000 y= +0.000 z= +0.00

Channel	Time	E/I[V/A]	Err[V/A]	Res[Ohm-m]
1	4.06	0.000e+000	0.000e+000	99999.99
2	5.07	1.285e-001	1.920e-005	48.96
3	6.07	7.310e-002	1.175e-005	52.78
4	7.08	4.385e-002	1.357e-005	57.43
5	8.52	2.371e-002	5.010e-006	63.55
6	10.53	1.178e-002	6.661e-006	71.14
7	12.55	6.685e-003	6.884e-006	77.51
8	14.56	4.128e-003	5.018e-006	83.43
9	17.44	2.343e-003	2.522e-006	90.06
10	21.46	1.254e-003	3.242e-006	96.64
11	25.49	7.724e-004	2.780e-006	100.26
12	29.50	5.174e-004	2.952e-006	102.62
13	35.28	3.181e-004	1.791e-006	105.38

14	43.30	1.791e-004	1.869e-006	109.82
15	51.40	1.123e-004	1.604e-006	112.65
16	59.41	7.400e-005	1.802e-006	116.87
17	70.95	4.692e-005	7.470e-007	117.77
18	87.07	2.750e-005	6.443e-007	119.54
19	103.16	1.727e-005	7.245e-007	122.89
20	119.22	1.107e-005	6.776e-007	129.89
21	142.33	8.444e-006	3.782e-007	115.81
22	174.54	5.625e-006	3.640e-007	108.06
23	206.71	4.031e-006	4.400e-007	101.79
24	238.83	4.580e-006	4.301e-007	73.48

#Set 2

Time-Range 3 Stacks 5 deff= 3 us I=1.0 A FILTR=50 Hz AMPLIFER=OFF

T-LOOP (m) 20.000 R-LOOP (m) 20.000 TURN= 1

Comments: PPC HP IPAQ 2190

Location:x= +20.000 y= +0.000 z= +0.00

Channel	Time	E/I[V/A]	Err[V/A]	Res[Ohm-m]
1	4.06	0.000e+000	0.000e+000	99999.99
2	5.07	1.636e-001	1.400e-005	41.68
3	6.07	9.434e-002	1.291e-005	44.52
4	7.08	5.778e-002	1.303e-005	47.79
5	8.52	3.180e-002	5.864e-006	52.26

6	10.53	1.581e-002	5.903e-006	58.48
7	12.55	8.735e-003	5.058e-006	64.85
8	14.56	5.172e-003	7.151e-006	71.79
9	17.44	2.707e-003	2.515e-006	81.79
10	21.46	1.293e-003	2.891e-006	94.69
11	25.49	7.194e-004	2.966e-006	105.13
12	29.50	4.525e-004	3.534e-006	112.21
13	35.28	2.672e-004	1.507e-006	118.36
14	43.30	1.460e-004	1.609e-006	125.84
15	51.40	9.193e-005	1.452e-006	128.72
16	59.41	6.252e-005	1.784e-006	130.77
17	70.95	3.811e-005	9.917e-007	135.28
18	87.07	2.212e-005	7.779e-007	138.22
19	103.16	1.525e-005	6.984e-007	133.54
20	119.22	8.747e-006	8.013e-007	151.98
21	142.33	6.521e-006	4.423e-007	137.58
22	174.54	3.676e-006	3.853e-007	143.49
23	206.71	3.290e-006	4.186e-007	116.55
24	238.83	3.738e-006	3.813e-007	84.14

#Set 3

Time-Range 3 Stacks 5 deff= 3 us I=1.0 A FILTR=50 Hz AMPLIFER=OFF

T-LOOP (m) 20.000 R-LOOP (m) 20.000 TURN= 1

Comments: PPC HP IPAQ 2190

Location:x= +0.000 y= +10.000 z= +0.00

Channel	Time	E/I[V/A]	Err[V/A]	Res[Ohm-m]
1	4.06	0.000e+000	0.000e+000	99999.99
2	5.07	1.801e-001	2.131e-005	39.09
3	6.07	9.414e-002	1.472e-005	44.58
4	7.08	5.075e-002	1.672e-005	52.10
5	8.52	2.286e-002	8.131e-006	65.11
6	10.53	8.750e-003	5.275e-006	86.74
7	12.55	4.024e-003	6.077e-006	108.72
8	14.56	2.161e-003	6.505e-006	128.46
9	17.44	1.081e-003	3.175e-006	150.82
10	21.46	5.253e-004	3.611e-006	172.64
11	25.49	2.978e-004	3.255e-006	189.29
12	29.50	1.848e-004	2.495e-006	203.85
13	35.28	1.078e-004	1.456e-006	216.76
14	43.30	6.178e-005	1.528e-006	223.30
15	51.40	3.979e-005	1.686e-006	224.97
16	59.41	2.887e-005	1.668e-006	218.88
17	70.95	1.910e-005	7.869e-007	214.41
18	87.07	1.453e-005	7.362e-007	182.90
19	103.16	1.088e-005	8.135e-007	167.25
20	119.22	9.396e-006	7.726e-007	144.90

21	142.33	6.388e-006	5.170e-007	139.49
22	174.54	5.569e-006	4.348e-007	108.78
23	206.71	4.760e-006	4.327e-007	91.11
24	238.83	4.480e-006	4.481e-007	74.58

#Set 4

Time-Range 3 Stacks 5 deff= 3 us I=1.0 A FILTR=50 Hz AMPLIFER=OFF

T-LOOP (m) 20.000 R-LOOP (m) 20.000 TURN= 1

Comments: PPC HP IPAQ 2190

Location:x= +20.000 y= +10.000 z= +0.00

Channel	Time	E/I[V/A]	Err[V/A]	Res[Ohm-m]
1	4.06	0.000e+000	0.000e+000	99999.99
2	5.07	1.969e-001	1.723e-005	36.84
3	6.07	1.041e-001	1.703e-005	41.68
4	7.08	5.637e-002	1.045e-005	48.58
5	8.52	2.545e-002	5.846e-006	60.62
6	10.53	9.673e-003	5.773e-006	81.14
7	12.55	4.436e-003	5.900e-006	101.88
8	14.56	2.348e-003	6.212e-006	121.56
9	17.44	1.166e-003	2.906e-006	143.41
10	21.46	5.559e-004	3.089e-006	166.25
11	25.49	3.112e-004	2.363e-006	183.80
12	29.50	1.968e-004	3.598e-006	195.48

13	35.28	1.121e-004	1.583e-006	211.23
14	43.30	6.276e-005	1.284e-006	220.95
15	51.40	3.863e-005	1.249e-006	229.43
16	59.41	3.026e-005	1.401e-006	212.15
17	70.95	2.056e-005	7.859e-007	204.18
18	87.07	1.456e-005	7.620e-007	182.65
19	103.16	1.064e-005	7.806e-007	169.75
20	119.22	8.319e-006	8.293e-007	157.14
21	142.33	6.077e-006	3.960e-007	144.20
22	174.54	5.555e-006	4.022e-007	108.96
23	206.71	4.109e-006	4.213e-007	100.49
24	238.83	4.865e-006	4.113e-007	70.58

#Set 5

Time-Range 3 Stacks 5 deff= 3 us I=1.0 A FILTR=50 Hz AMPLIFER=OFF

T-LOOP (m) 20.000 R-LOOP (m) 20.000 TURN= 1

Comments: PPC HP IPAQ 2190

Location:x= +0.000 y= +20.000 z= +0.00

Channel	Time	E/I[V/A]	Err[V/A]	Res[Ohm-m]
1	4.06	0.000e+000	0.000e+000	99999.99
2	5.07	2.386e-001	1.708e-005	32.41
3	6.07	1.625e-001	1.691e-005	30.98
4	7.08	1.178e-001	1.203e-005	29.73

5	8.52	8.004e-002	6.195e-006	28.24
6	10.53	5.063e-002	5.467e-006	26.92
7	12.55	3.349e-002	5.945e-006	26.47
8	14.56	2.264e-002	6.645e-006	26.83
9	17.44	1.319e-002	2.621e-006	28.46
10	21.46	6.450e-003	2.929e-006	32.44
11	25.49	3.244e-003	2.697e-006	38.52
12	29.50	1.673e-003	3.219e-006	46.93
13	35.28	6.794e-004	1.750e-006	63.53
14	43.30	2.132e-004	1.493e-006	97.77
15	51.40	7.847e-005	1.759e-006	143.06
16	59.41	3.570e-005	1.649e-006	189.99
17	70.95	1.742e-005	7.964e-007	228.02
18	87.07	9.750e-006	7.658e-007	238.65
19	103.16	7.235e-006	7.378e-007	219.51
20	119.22	6.807e-006	7.616e-007	179.63
21	142.33	5.107e-006	4.338e-007	161.94
22	174.54	4.906e-006	3.722e-007	118.37
23	206.71	4.674e-006	4.151e-007	92.22
24	238.83	4.616e-006	3.465e-007	73.09

#Set 6

Time-Range 3 Stacks 5 deff= 3 us I=1.0 A FILTR=50 Hz AMPLIFER=OFF

T-LOOP (m) 20.000 R-LOOP (m) 20.000 TURN= 1

Comments: PPC HP IPAQ 2190

Location:x= +20.000 y= +20.000 z= +0.00

Channel	Time	E/I[V/A]	Err[V/A]	Res[Ohm-m]
1	4.06	0.000e+000	0.000e+000	99999.99
2	5.07	2.515e-001	2.205e-005	31.30
3	6.07	1.682e-001	1.686e-005	30.28
4	7.08	1.181e-001	2.051e-005	29.67
5	8.52	7.672e-002	7.599e-006	29.05
6	10.53	4.585e-002	8.397e-006	28.75
7	12.55	2.891e-002	8.064e-006	29.20
8	14.56	1.876e-002	8.056e-006	30.41
9	17.44	1.049e-002	3.402e-006	33.15
10	21.46	4.926e-003	3.283e-006	38.83
11	25.49	2.434e-003	3.305e-006	46.65
12	29.50	1.251e-003	3.567e-006	56.96
13	35.28	5.274e-004	2.547e-006	75.22
14	43.30	1.804e-004	2.259e-006	109.28
15	51.40	7.501e-005	2.005e-006	147.42
16	59.41	3.813e-005	2.055e-006	181.84
17	70.95	2.272e-005	1.009e-006	190.98
18	87.07	1.505e-005	9.214e-007	178.70
19	103.16	1.215e-005	8.521e-007	155.33

20	119.22	1.041e-005	8.267e-007	135.33
21	142.33	7.923e-006	4.655e-007	120.83
22	174.54	4.661e-006	5.071e-007	122.48
23	206.71	5.361e-006	5.169e-007	84.16
24	238.83	4.888e-006	5.195e-007	70.36

#Set 7

Time-Range 3 Stacks 5 deff= 3 us I=1.0 A FILTR=50 Hz AMPLIFER=OFF

T-LOOP (m) 20.000 R-LOOP (m) 20.000 TURN= 1

Comments: PPC HP IPAQ 2190

Location:x= +0.000 y= +30.000 z= +0.00

Channel	Time	E/I[V/A]	Err[V/A]	Res[Ohm-m]
1	4.06	0.000e+000	0.000e+000	99999.99
2	5.07	5.638e-002	1.789e-005	84.80
3	6.07	2.752e-002	1.688e-005	101.22
4	7.08	1.437e-002	1.290e-005	120.82
5	8.52	6.779e-003	6.369e-006	146.43
6	10.53	3.294e-003	7.537e-006	166.39
7	12.55	2.080e-003	5.753e-006	168.79
8	14.56	1.468e-003	6.477e-006	166.20
9	17.44	9.862e-004	3.721e-006	160.36
10	21.46	6.241e-004	3.286e-006	153.91
11	25.49	4.284e-004	3.564e-006	148.53

12	29.50	3.142e-004	4.075e-006	143.11
13	35.28	2.111e-004	2.043e-006	138.51
14	43.30	1.396e-004	1.595e-006	129.65
15	51.40	1.024e-004	1.413e-006	119.79
16	59.41	7.808e-005	1.861e-006	112.76
17	70.95	6.004e-005	7.504e-007	99.92
18	87.07	4.186e-005	9.149e-007	90.35
19	103.16	3.380e-005	6.970e-007	78.55
20	119.22	2.886e-005	9.273e-007	68.58
21	142.33	2.254e-005	4.643e-007	60.19
22	174.54	1.694e-005	4.463e-007	51.81
23	206.71	1.585e-005	4.363e-007	40.85
24	238.83	1.300e-005	4.611e-007	36.65

#Set 8

Time-Range 3 Stacks 5 deff= 3 us I=1.0 A FILTR=50 Hz AMPLIFER=OFF

T-LOOP (m) 20.000 R-LOOP (m) 20.000 TURN= 1

Comments: PPC HP IPAQ 2190

Location:x= +20.000 y= +30.000 z= +0.00

Channel	Time	E/I[V/A]	Err[V/A]	Res[Ohm-m]
1	4.06	0.000e+000	0.000e+000	99999.99
2	5.07	5.389e-002	1.572e-005	87.39
3	6.07	2.626e-002	1.629e-005	104.44

4	7.08	1.358e-002	1.137e-005	125.47
5	8.52	6.182e-003	5.349e-006	155.71
6	10.53	2.836e-003	4.915e-006	183.86
7	12.55	1.716e-003	6.114e-006	191.90
8	14.56	1.226e-003	5.923e-006	187.47
9	17.44	8.419e-004	3.051e-006	178.19
10	21.46	5.687e-004	2.935e-006	163.74
11	25.49	4.188e-004	2.785e-006	150.78
12	29.50	3.241e-004	3.041e-006	140.19
13	35.28	2.397e-004	1.594e-006	127.27
14	43.30	1.677e-004	1.679e-006	114.73
15	51.40	1.283e-004	1.488e-006	103.10
16	59.41	1.086e-004	1.499e-006	90.48
17	70.95	8.162e-005	7.679e-007	81.43
18	87.07	6.528e-005	7.672e-007	67.18
19	103.16	5.159e-005	6.988e-007	59.25
20	119.22	4.227e-005	8.685e-007	53.17
21	142.33	3.442e-005	4.143e-007	45.38
22	174.54	2.653e-005	3.360e-007	38.42
23	206.71	2.323e-005	4.348e-007	31.66
24	238.83	2.023e-005	3.251e-007	27.30

#Set 9

Time-Range 3 Stacks 5 deff= 3 us I=1.0 A FILTR=50 Hz AMPLIFER=OFF

T-LOOP (m) 20.000 R-LOOP (m) 20.000 TURN= 1

Comments: PPC HP IPAQ 2190

Location:x= +0.000 y= +40.000 z= +0.00

Channel	Time	E/I[V/A]	Err[V/A]	Res[Ohm-m]
1	4.06	0.000e+000	0.000e+000	99999.99
2	5.07	3.809e-002	1.587e-005	110.13
3	6.07	1.625e-002	1.303e-005	143.81
4	7.08	6.789e-003	1.279e-005	199.20
5	8.52	2.041e-003	4.668e-006	325.97
6	10.53	5.195e-004	4.886e-006	569.97
7	12.55	2.898e-004	6.023e-006	628.12
8	14.56	2.516e-004	4.713e-006	538.70
9	17.44	1.996e-004	3.099e-006	465.25
10	21.46	1.541e-004	3.157e-006	390.98
11	25.49	1.200e-004	3.051e-006	346.92
12	29.50	1.011e-004	3.467e-006	304.69
13	35.28	6.926e-005	1.740e-006	291.15
14	43.30	5.433e-005	1.610e-006	243.24
15	51.40	4.496e-005	1.416e-006	207.38
16	59.41	3.496e-005	2.004e-006	192.68
17	70.95	3.018e-005	8.209e-007	158.07

18	87.07	2.512e-005	7.905e-007	126.99
19	103.16	1.994e-005	6.398e-007	111.65
20	119.22	1.655e-005	7.364e-007	99.33
21	142.33	1.319e-005	4.695e-007	86.03
22	174.54	9.906e-006	4.458e-007	74.10
23	206.71	9.337e-006	4.136e-007	58.14
24	238.83	7.169e-006	4.286e-007	54.51

#Set 10

Time-Range 3 Stacks 5 deff= 3 us I=1.0 A FILTR=50 Hz AMPLIFER=OFF

T-LOOP (m) 20.000 R-LOOP (m) 20.000 TURN= 1

Comments: PPC HP IPAQ 2190

Location:x= +20.000 y= +40.000 z= +0.00

Channel	Time	E/I[V/A]	Err[V/A]	Res[Ohm-m]
1	4.06	0.000e+000	0.000e+000	99999.99
2	5.07	3.556e-002	1.369e-005	115.31
3	6.07	1.533e-002	1.754e-005	149.53
4	7.08	6.445e-003	1.521e-005	206.23
5	8.52	1.884e-003	7.280e-006	343.79
6	10.53	3.973e-004	6.663e-006	681.54
7	12.55	1.721e-004	6.541e-006	889.05
8	14.56	1.342e-004	6.690e-006	818.98
9	17.44	1.277e-004	2.808e-006	626.46

10	21.46	1.009e-004	2.471e-006	518.63
11	25.49	8.515e-005	3.366e-006	436.10
12	29.50	6.916e-005	3.278e-006	392.54
13	35.28	6.129e-005	1.716e-006	315.86
14	43.30	4.863e-005	1.511e-006	261.90
15	51.40	4.245e-005	1.812e-006	215.48
16	59.41	3.756e-005	1.570e-006	183.66
17	70.95	2.834e-005	8.442e-007	164.84
18	87.07	2.237e-005	8.804e-007	137.21
19	103.16	1.784e-005	8.075e-007	120.26
20	119.22	1.413e-005	6.673e-007	110.38
21	142.33	1.179e-005	4.827e-007	92.71
22	174.54	9.066e-006	3.788e-007	78.61
23	206.71	7.519e-006	5.021e-007	67.17
24	238.83	5.729e-006	4.692e-007	63.29

#Set 11

Time-Range 3 Stacks 5 deff= 3 us I=1.0 A FILTR=50 Hz AMPLIFER=OFF

T-LOOP (m) 20.000 R-LOOP (m) 20.000 TURN= 1

Comments: PPC HP IPAQ 2190

Location:x= +0.000 y= +50.000 z= +0.00

Channel	Time	E/I[V/A]	Err[V/A]	Res[Ohm-m]
1	4.06	0.000e+000	0.000e+000	99999.99

2	5.07	3.872e-002	2.927e-005	108.94
3	6.07	1.789e-002	2.248e-005	134.88
4	7.08	8.398e-003	2.323e-005	172.86
5	8.52	3.341e-003	6.506e-006	234.71
6	10.53	1.407e-003	7.313e-006	293.41
7	12.55	8.720e-004	7.589e-006	301.34
8	14.56	6.840e-004	6.069e-006	276.59
9	17.44	4.776e-004	4.157e-006	260.03
10	21.46	3.184e-004	3.649e-006	241.05
11	25.49	2.246e-004	3.710e-006	228.42
12	29.50	1.740e-004	4.441e-006	212.19
13	35.28	1.337e-004	2.618e-006	187.77
14	43.30	9.749e-005	2.566e-006	164.73
15	51.40	8.166e-005	2.825e-006	139.30
16	59.41	7.020e-005	2.707e-006	121.05
17	70.95	5.885e-005	1.086e-006	101.26
18	87.07	4.525e-005	1.269e-006	85.77
19	103.16	3.874e-005	1.140e-006	71.72
20	119.22	3.566e-005	1.228e-006	59.56
21	142.33	2.662e-005	7.061e-007	53.86
22	174.54	1.960e-005	7.248e-007	47.01
23	206.71	1.832e-005	7.384e-007	37.10
24	238.83	1.407e-005	8.231e-007	34.77

#Set 12

Time-Range 3 Stacks 5 deff= 3 us I=1.0 A FILTR=50 Hz AMPLIFER=OFF

T-LOOP (m) 20.000 R-LOOP (m) 20.000 TURN= 1

Comments: PPC HP IPAQ 2190

Location:x= +20.000 y= +50.000 z= +0.00

Channel	Time	E/I[V/A]	Err[V/A]	Res[Ohm-m]
1	4.06	0.000e+000	0.000e+000	99999.99
2	5.07	4.060e-002	1.461e-005	105.54
3	6.07	1.872e-002	1.403e-005	130.88
4	7.08	8.779e-003	1.449e-005	167.82
5	8.52	3.456e-003	6.664e-006	229.47
6	10.53	1.402e-003	6.006e-006	294.06
7	12.55	8.763e-004	6.753e-006	300.36
8	14.56	6.631e-004	6.972e-006	282.36
9	17.44	4.680e-004	3.316e-006	263.59
10	21.46	3.260e-004	3.382e-006	237.27
11	25.49	2.302e-004	3.255e-006	224.73
12	29.50	1.825e-004	3.289e-006	205.60
13	35.28	1.333e-004	1.809e-006	188.16
14	43.30	1.027e-004	1.741e-006	159.08
15	51.40	8.474e-005	1.836e-006	135.90
16	59.41	6.855e-005	1.583e-006	122.98

17	70.95	5.843e-005	1.142e-006	101.75
18	87.07	4.702e-005	6.910e-007	83.61
19	103.16	3.898e-005	9.329e-007	71.42
20	119.22	3.189e-005	7.132e-007	64.16
21	142.33	2.554e-005	4.122e-007	55.38
22	174.54	2.032e-005	4.313e-007	45.89
23	206.71	1.678e-005	4.557e-007	39.33
24	238.83	1.458e-005	4.145e-007	33.96

#Set 13

Time-Range 3 Stacks 5 deff= 3 us I=1.0 A FILTR=50 Hz AMPLIFER=OFF

T-LOOP (m) 20.000 R-LOOP (m) 20.000 TURN= 1

Comments: PPC HP IPAQ 2190

Location:x= +0.000 y= +60.000 z= +0.00

Channel	Time	E/I[V/A]	Err[V/A]	Res[Ohm-m]
1	4.06	0.000e+000	0.000e+000	99999.99
2	5.07	1.191e-001	1.704e-005	51.52
3	6.07	6.813e-002	1.515e-005	55.31
4	7.08	4.119e-002	9.724e-006	59.88
5	8.52	2.236e-002	6.616e-006	66.08
6	10.53	1.129e-002	7.254e-006	73.21
7	12.55	6.539e-003	6.593e-006	78.66
8	14.56	4.166e-003	5.337e-006	82.93

9	17.44	2.441e-003	2.557e-006	87.65
10	21.46	1.366e-003	2.937e-006	91.30
11	25.49	8.781e-004	2.590e-006	92.05
12	29.50	6.147e-004	2.412e-006	91.49
13	35.28	4.087e-004	1.386e-006	89.16
14	43.30	2.637e-004	1.362e-006	84.86
15	51.40	1.860e-004	1.857e-006	80.47
16	59.41	1.353e-004	1.655e-006	78.14
17	70.95	9.551e-005	8.600e-007	73.33
18	87.07	6.633e-005	6.516e-007	66.47
19	103.16	4.692e-005	6.276e-007	63.12
20	119.22	3.507e-005	6.474e-007	60.22
21	142.33	2.531e-005	3.642e-007	55.71
22	174.54	1.824e-005	3.753e-007	49.33
23	206.71	1.371e-005	4.099e-007	45.00
24	238.83	1.196e-005	3.302e-007	38.75

#Set 14

Time-Range 3 Stacks 5 deff= 3 us I=1.0 A FILTR=50 Hz AMPLIFER=OFF

T-LOOP (m) 20.000 R-LOOP (m) 20.000 TURN= 1

Comments: PPC HP IPAQ 2190

Location:x= +20.000 y= +60.000 z= +0.00

Channel Time E/I[V/A] Err[V/A] Res[Ohm-m]

1	4.06	0.000e+000	0.000e+000	99999.99
2	5.07	1.062e-001	1.524e-005	55.60
3	6.07	5.792e-002	1.211e-005	61.64
4	7.08	3.352e-002	1.161e-005	68.70
5	8.52	1.766e-002	6.287e-006	77.35
6	10.53	9.009e-003	6.505e-006	85.08
7	12.55	5.495e-003	5.383e-006	88.33
8	14.56	3.737e-003	5.460e-006	89.17
9	17.44	2.371e-003	2.596e-006	89.35
10	21.46	1.442e-003	2.964e-006	88.07
11	25.49	9.595e-004	3.020e-006	86.76
12	29.50	6.919e-004	3.258e-006	84.55
13	35.28	4.560e-004	1.553e-006	82.88
14	43.30	2.916e-004	1.499e-006	79.35
15	51.40	2.007e-004	1.621e-006	76.49
16	59.41	1.498e-004	1.949e-006	73.03
17	70.95	1.039e-004	6.655e-007	69.33
18	87.07	7.003e-005	5.913e-007	64.11
19	103.16	5.027e-005	7.081e-007	60.28
20	119.22	3.701e-005	6.860e-007	58.09
21	142.33	2.771e-005	4.032e-007	52.44
22	174.54	1.939e-005	4.120e-007	47.36
23	206.71	1.592e-005	4.831e-007	40.74

24 238.83 1.289e-005 4.343e-007 36.87

#Set 15

Time-Range 3 Stacks 5 deff= 3 us I=1.0 A FILTR=50 Hz AMPLIFER=OFF

T-LOOP (m) 20.000 R-LOOP (m) 20.000 TURN= 1

Comments: PPC HP IPAQ 2190

Location:x= +0.000 y= +70.000 z= +0.00

Channel	Time	E/I[V/A]	Err[V/A]	Res[Ohm-m]
1	4.06	0.000e+000	0.000e+000	99999.99
2	5.07	1.424e-001	3.080e-005	45.73
3	6.07	9.420e-002	2.928e-005	44.56
4	7.08	6.694e-002	2.796e-005	43.32
5	8.52	4.490e-002	6.556e-006	41.52
6	10.53	2.885e-002	6.480e-006	39.16
7	12.55	2.011e-002	6.739e-006	37.19
8	14.56	1.468e-002	7.504e-006	35.82
9	17.44	9.878e-003	5.649e-006	34.51
10	21.46	6.186e-003	4.651e-006	33.35
11	25.49	4.102e-003	4.396e-006	32.94
12	29.50	2.870e-003	5.389e-006	32.75
13	35.28	1.787e-003	2.938e-006	33.35
14	43.30	1.008e-003	2.793e-006	34.70
15	51.40	6.148e-004	2.917e-006	36.26

16	59.41	3.911e-004	2.937e-006	38.52
17	70.95	2.242e-004	1.182e-006	41.52
18	87.07	1.172e-004	1.365e-006	45.49
19	103.16	7.105e-005	1.191e-006	47.87
20	119.22	4.544e-005	1.511e-006	50.66
21	142.33	2.639e-005	7.233e-007	54.17
22	174.54	1.520e-005	8.243e-007	55.70
23	206.71	1.174e-005	8.687e-007	49.91
24	238.83	7.110e-006	8.171e-007	54.81

#Set 16

Time-Range 3 Stacks 5 deff= 3 us I=1.0 A FILTR=50 Hz AMPLIFER=OFF

T-LOOP (m) 20.000 R-LOOP (m) 20.000 TURN= 1

Comments: PPC HP IPAQ 2190.

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