

EVALUATION OF GROUNDWATER CONTAMINATION RISK FROM PETROLEUM PRODUCTS IN BLANTYRE

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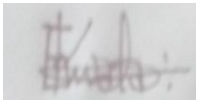
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ABSTRACT

The purpose of this study is fill the missing data in Groundwater risk from petroleum products in Blantyre city. Groundwater is a very important source of water and is used for domestic purposes in many areas of Malawi including Blantyre City hence it needs to be taken care of. But due to human activities such as building of filling stations and use of Petroleum products has made groundwater to be vulnerable to contamination. Using the DRASTIC model, this Paper has a main objective to assess groundwater contamination risk from petroleum products such petrol, Diesel and lubricants which are sold in filling station within Blantyre city. This research involved the use of secondary data which has been obtained from different sources from internet websites, it is more of desktop work and It used the quantitative and qualitative approach. ArcGIS software has been used in order to come up with parameter maps (D.R.A.S.T.I.C) and data has been retrieved from USGS dataset portal, Africa groundwater website, MASDAP, Literature, Soil Map of Malawi. The seven parameters of this Model include; Depth to water table(D), Net recharge(R), Aquifer Media(A), Soil Media(S), Topography(T), Impact of Vadose(I) and Hydraulic. The fixed weights assigned to the parameters are 5,4,3,2,1,5 and 3 respectively. The data processing involved raster conversion, reclassifying each parameter Map, rating the parameters and using the weighted sum, overlying the parameters and come up with the DRASTIC index and Vulnerability Map. The DRASTIC map produced was classified into very low, low, moderate and high vulnerable zones, and indicated that more areas in Blantyre city falls within very low and low vulnerable zones and in those areas its where a lot of filling stations are belt. The areas where filling stations are more close to each to each the risk to contamination is high because the source of contamination is more e.g. Limbe compared to those areas with filling stations far from each other e.g. along the High way from Chichiri to Clock tower.

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ACRONYMS/ABBREVIATIONS

DRASTIC: Depth to water table, Net Recharge, Aquifer media, Soil Media, Topography, Impact of Vadoze and Hydraulic Conductivity.

UST: Underground Storage Tanks

GUP: Getting Up to Speed

FD: Filling Station Density

USEPA: US Environmental Protection Agency

MERA: Malawi Energy Regulatory Authority

DEM: Digital Elevation Model

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CHAPTER 1

Introduction

Groundwater has been considered as an important source of water supply due to its relatively low susceptibility to pollution compare to surface water (Ersoy2013). A Risk is the measure of the magnitude of damage along with its probability of occurrence (Chandrasekaran, 2016). In other words, it is the product of the chance that a specific undesired event will occur and the severity of the consequences of the event (Chandrasekaran, 2016). Risk assessment is the quantitative or qualitative value of risk, which is related to a situation and a recognized hazard (Chandrasekaran, 2016). Risk assessment can also be defined as the process for estimating the potential impact of a chemical, biological or physical agent on humans, animals and the ecology (NEPC, 1999). Groundwater risk assessment from petroleum products involves evaluating the measure of the magnitude of the damage influenced by petroleum products e.g. petrol and Diesel along with its probability of occurrence. This groundwater contamination risk assessment can be done by using the concept of groundwater vulnerability to contamination which was introduced in 1960s in France (Margat, 1968). Groundwater vulnerability defines the sensitivity of an aquifer to get contaminated from anthropogenic activities on the land surface (Vrba and Zeporozec 1994). Foster (1987) defined vulnerability as the intrinsic characteristics which determine the sensitivity of various parts of an aquifer to being adversely affected by an imposed contamination load. However, there is a difference between vulnerability and pollution risk. Pollution risk is defined as the interaction between the natural vulnerability of the aquifer and the pollution loading that is being or will be applied on the surface environment as a result of human activities (Foster 1987). It is possible that an area with high aquifer vulnerability may have low pollution risk, if there is no significant pollution load. However, petroleum Industries in Blantyre city (Filling stations and service stations) located in a low vulnerable area may render high pollution risk if they are creating a significant pollution.

A problem was identified when there was groundwater being contaminated with Diesel in Limbe market, as a result this research is aims at assessing the groundwater contamination

risk from petroleum products such as petrol, diesel and paraffin sold in different filling stations found in Blantyre City.

This chapter will provide an introduction to the study by first discussing the background, followed by the research problem statement, the main aim and specific objectives, research questions and finally the significance of this study.

1.1 Background

Groundwater vulnerability is a burning issue all over the world due to the deterioration of groundwater level and increasing contamination which poses serious detrimental risk to the environment (Shirazi & Akib, 2012). To identify this risk, extensive research has been carried out to assess the groundwater vulnerability by using different methods. Generally, the process-based method, statistical method, and overlay & index methods are used in this regard which are well explained in the literature review and Methodology. Groundwater has a major contribution to agricultural, industrial, drinking, and other municipal uses, particularly in the region where other sources of water are lacking (Shirazi & Akib, 2012). Estimates show that 65% of the population in Malawi depends on groundwater for domestic supply: in rural areas, this rises to 82%, while in urban areas it is closer to 20% (UPGro, 2020). Unfortunately, groundwater is vulnerable to pollution because it dissolves in a wide variety of substances and it is also known as a universal solvent (Multipure, 2021). Groundwater contamination is a hidden surface-subsurface process since it is not directly invisible from the surface. It can be noticed only once a spring or a well becomes contaminated, or the contaminant is released into surface waters (Jang et al. 2017). Groundwater can be protected from pollution by the early identification of areas more vulnerable to contamination and the implementation of protective measures (Moges et al. 2020).

Vehicles uses petroleum products such as petrol, diesel, kerosene and lubricants for locomotion and underground storage tanks are used to store them for safety reasons (Duncan K & Bailey B, 1993). But when these petroleum products (e.g. petrol and Diesel) are not properly handled they may end up polluting groundwater. Groundwater contamination from petroleum products is when groundwater is polluted by petroleum

products from leaking underground oil tanks and landfills. According to getting up to speed (GUP, 2015) groundwater generally moves slowly because of this the contaminants tend to remain concentrated in the form of a plume and flows the same path as the groundwater. Contaminant plume is the body of groundwater that has been affected by the presence of pollutants in the soil or aquifer and moves away from the source with the flowing groundwater. The plumes can end up covering a larger area due to percolation.

Figure 1 shows the contaminant plume.

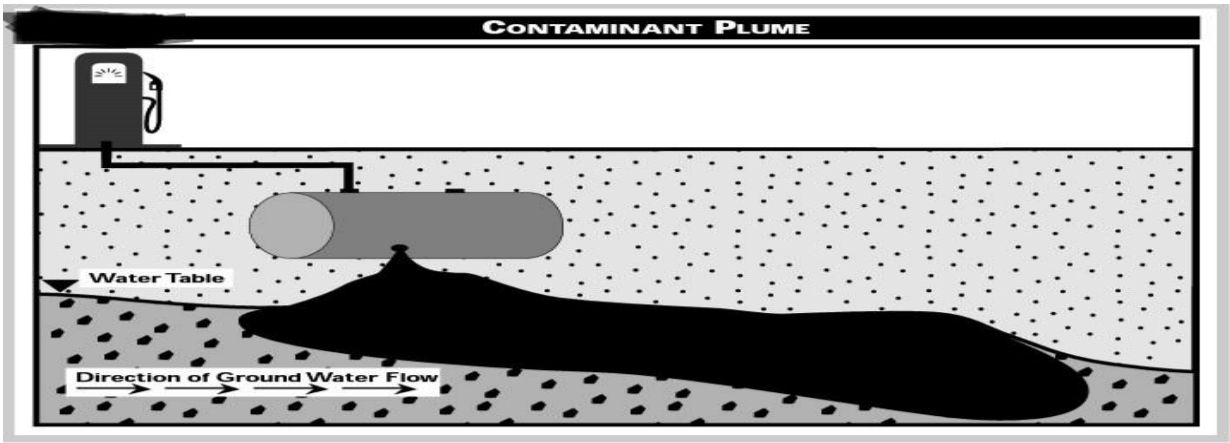


Figure 1: *contamination plume*

Vehicles service station and underground oil tanks are among the main polluting sites for groundwater because of leakage of oil tanks and oil transshipment spills (Bai et al 2019). If the underground tanks are made of material that is not resistance to corrosion, the tank may corrode away and petroleum products may leak into the ground and contaminate groundwater source. Oil spills from leaking underground storage tanks (USTs) at gas stations due to corrosions and other factors such as improper installation, spills during product delivery and piping failure are some of the largest threat to groundwater quality. It is very difficult and hence expensive to clean groundwater which has been contaminated with the petroleum products to drinking water standards. A lot of people uses groundwater directly from the source without purifying it. Benzene, ethylbenzene, dichloroethane and other organic contaminants from petroleum are carcinogenic risk factors that threatens the safety of people drinking a water source contaminated by

petroleum products (Bai et al 2019). Benzene is also classified as a known human carcinogen based on occupational studies in humans (ATSDR, 2007). Polycyclic aromatic hydrocarbons found in oil cause symptoms such as nausea, vomiting and skin and eye irritation following acute, high-level exposures (Cal OEHHA, 2003). Hence, the study has been taken up to address the vulnerable area of different potential and also the identification of concentration areas due to Petroleum products in Blantyre city. The DRASTIC method has been most commonly used for mapping vulnerability in porous aquifers (Aller et al., 1987). The hydrogeological parameters were processed and mapped to delineate areas susceptible to contamination producing a risk assessment map of Blantyre city.

The purpose of this research is to assess the groundwater for contamination from petroleum products. Different activities will be carried out in order to complete this research. By carrying out all the activities explained in the methodology that will help to manage the filling stations properly so that the risk of contamination with groundwater can be reduced, and it will also help on safety and planting of underground oil tanks. The main area of study of this research is Blantyre city because this is where there's a lot of petrol stations hence there is high risk of contamination with groundwater.

1.2 Problem Statement

The problem that has been identified is that there is a contamination of underground water from petroleum products such as Petrol and diesel in Blantyre due to leaky landfills and underground storage oil tanks. A case seen in Limbe where people (vendors) claimed to have find an oil reservoir by seeing the oil floating on groundwater is feature that points to groundwater contamination but the laboratory analysis done by the ministry of mining revealed that there is no crude oil in Limbe (Sabola T, 2020). Due to formation of contamination plumes the aquifers in Blantyre city may be affected and contaminated. So because there are many petrol stations in Blantyre city and others built long time ago, there is a potential of groundwater contamination if the underground tanks corrode away and leaks.



Figure 2: *A picture showing groundwater contaminated from Diesel in Limbe*

1.3 Main and Specific Objectives

The main goal of this research is to evaluate the groundwater contamination risk from petroleum products such as petrol, diesel and paraffin in different filling stations found in Blantyre City.

There are several ways on how this main objective can be achieved, so the specific objectives of this study include;

1. Determining the filling stations Density.
2. Developing a risk assessment model of Blantyre.

1.4 Research Questions

1. How many filling stations are there per square kilometer distance?
2. How will the risk assessment model of Blantyre be developed?

1.5 Significant of the study

The research is very important because it will help to develop a risk model that will be used to determine contamination risk from petroleum products. This study will also help proper management of the filling stations and thereby reducing the groundwater contamination risk from leaking underground petrol and diesel tanks. it will also help on

how we can ensure safety and planting of underground oil tanks and deciding the type of material to be used for making underground oil storage tanks so that it does not corrode easily. The research will also insure Proper management of the landfills so that the petroleum products should not contaminate the underground water. According to Getting up to Speed (GUP,2015),The new landfills are required to have a clay or synthetic liners and leachate (liquid from a landfill containing contaminats) collection systems to protect groundwater from contamination. This study provides theoretical support for the protection of a dispersed drinking water source such as groundwater and also address the current shortage of research in this area here in Malawi. The research will also help the decision making process for groundwater and soil environment improvement in all areas vulnerable to oil contamination in Blantyre.

CHAPTER 2

Literature review

The study area of this research is Blantyre, which is a place situated in southern Malawi and its geographical coordinates are 15° 47' 0" South, 35° 0' 0" East (Maplandia, 2016). According to Population Statistics (2022), there are 982,828 people living in urban area of Blantyre and 584,877 living in city area. Blantyre experiences extreme seasonal variation in monthly rainfall (Weatherspark, 2022). The rain period of the year lasts for 7 months, from October to May and January are the months with the most rain with an average rainfall of 9.6 inches. This period groundwater percolation is high hence there's high transportation of contaminated water to different locations of Blantyre.

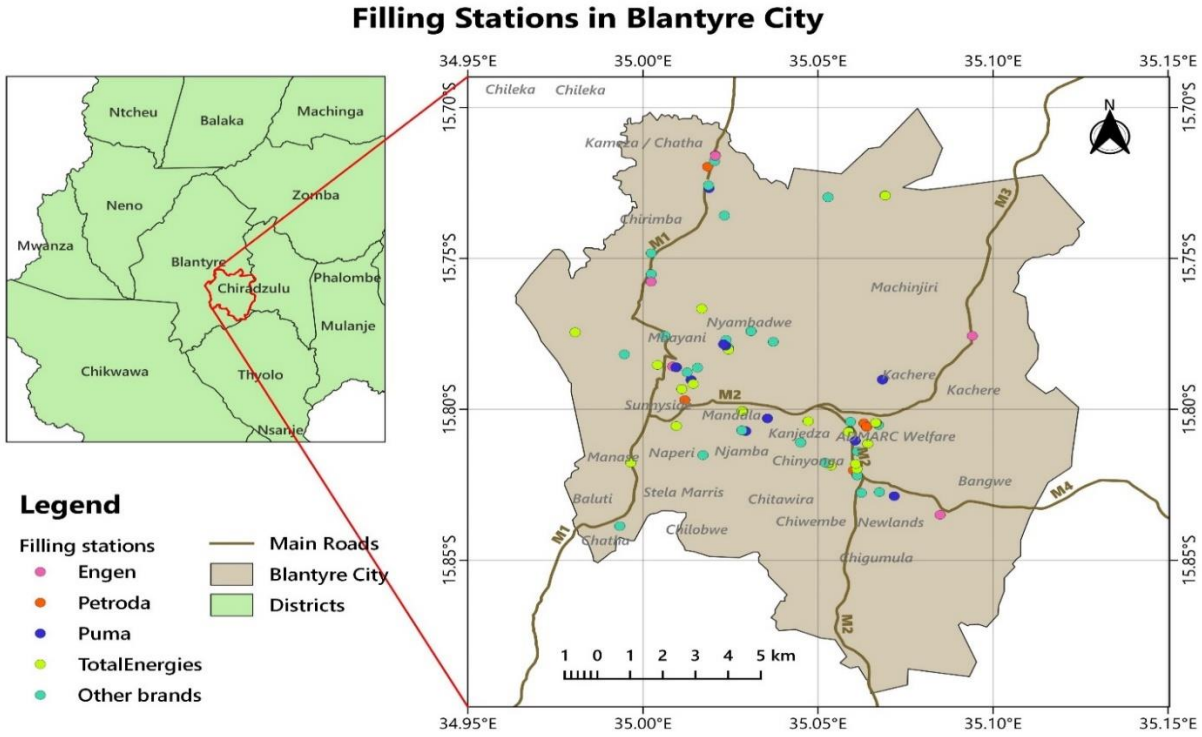


Figure 3: *The study area Map of Blantyre City*

According to Total Energies (2022), there are more than 70 service stations in Malawi of which most of them are found in Blantyre. Apart from Total service stations some of the filling stations found in Blantyre are; Puma, Meru, Petroda, Engen and Simso.

2.1 Oil tank Leakages

The environmental risk of oil tank leakage increases as the tanks ages (Bai, X., & Song, K., 2019), this highlights that filling station that were built long ago have high risk of tank leakages. According to the US Environmental Protection Agency's (USEPA) statistics for 2011, 71% of the buried oil tanks in the USA that have operated for more than 10 years have leaked and no information has been found on how many underground tanks have leaked in Malawi. When the underground oil tank leaks there is leaching of petroleum hydrocarbons from soils and downward flow of dissolved phase hydrocarbons through the unsaturated zone to the water table (Claire, 2017). If drinking water sources are close to a source of pollution, human health can be harmed through drinking contaminated water. Several receptors have been identified for example Human receptor and ecological receptor. According to previous research, the composition of stored oil products at service stations or underground oil tanks is complex and controlled by production processes and standard requirements (Adeniji et al., 2017).

Adeniji et al, studied the types and composition of oil pollutants. Innocent et al, Lueders et al (2017), Wade et al (2016), and Meyer et al (2015), studied the main organic pollutants in oil, including methyl tertbutylether, benzene series, total petroleum hydrocarbons, and polycyclic as well as their migration in the environment. After entering the ecological environment, pollutants contained in oil will affect the growth and development of animals and plants.

According to the research that was done by Xue Bai, Kai Song and their friends in 2019, they collected soil and groundwater samples on oil depots and analyzed for pollutants and found that there were more heavy contaminants with high carcinogenic risk around these depots (Bai et al 2019). In order to construct the hydrogeological model of the study area (Sichuan, China), Bai and his friends conducted an exploratory drilling and other physical explorations were used to obtain the structural information about the aeration zone (i.e.,

Vadoze zone) and the aquifer. Pollution of the soil by leakage from the buried oil tank is mainly concentrated in the oil storage area. Pollutants leaked from the oil tank also have penetrated groundwater in the vicinity of the station. Their research indicated that the oil leakage is associated with the age of the filling stations, older filling stations are likely to be at risk of leakages compared to newly built filling stations.

2.2 Models

Models that predict groundwater dynamics can be used to calculate the migration path and concentration trend of pollutants in the environment by generalizing hydrogeological conditions and designing various working conditions. Process-based method, statistical method, and overlay & index methods are generally used to assess groundwater vulnerability in many parts of the world. The limitations of process-based method are availability of adequate data and quality for the capture of physical, chemical and biological reactions which occur from the surface through the groundwater regimes (Shirazi & Akib, 2012). The statistical method includes uncertainty and tries to minimize the error and used parameters coefficient instead of weight (Shirazi & Akib, 2012). The lack of this method is proper monitoring data this method is only applicable to those regions where the groundwater contamination is governed by similar factors. Overlay & index methods are the most suitable method for groundwater vulnerability assessment overcoming all the limitations mentioned above. DRASTIC is the most widely applied scheme for vulnerability assessment which was developed by the US Environmental Protection Agency (USEPA) (Aller et al., 1987). DRASTIC is a model that considers the main hydrological and geological factors with the potential impact on aquifer pollution (Barbulescu A, 2020). The DRASTIC model is a straightforward method and generally it is applicable where the hydrological data are available.

DRASTIC method was derived from rating and weights associated with the seven parameters, these are: Depth to groundwater (D), Net recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of the vadose zone (I) and Hydraulic conductivity (C) (Abdullah, T.O.2017). According to Alina (2020), the depth to water table (D) is the

thickness of the layers crossed by the pollutant before reaching the aquifer and it is defined as the distance between the ground surfaces to the water table and it is the actual distance that is covered by contaminants and pollutants before dissolution in the groundwater (Aller et al., 1987). The depth to groundwater affects the time available for contaminants to undergo chemical and biological reaction i.e. dispersion and oxidation. Areas with greater depth are less susceptible to vulnerability because there is so much time taken for the contaminants to reach the groundwater thereby giving more room for contaminants attenuation hence low vulnerability rating compared to areas with shallow depth to groundwater. The aquifer vulnerability is inverse proportional to the depth of the water table. The net recharge (R) [mm/year] represents the volume of infiltrated water that reaches the aquifer. Generally, areas with higher volume of annual recharge are more likely to have the groundwater quality compromised because if the recharge is higher the aquifer is more vulnerable to contamination originating from surface (Aller et al 1987). Net recharge depends on various factors such as slope, permeability, rainfall, land cover, amount of water seeping in (Shirazi et al., 2013). The contamination possibility increases if the net recharge increases (Barbulescu A, 2020). Aquifer media(A) is the consolidated formation and unconsolidated rocks and pebbles in which the water is contained, this include pores and fractures (Fraser 2020). The aquifer media consists of different types of rocks serving as an aquifer. The aquifer has a potential to store water and controls the attenuation process. The transportation of the pollutants in the aquifer depends mainly on the thickness and permeability of the formation. Lower permeability and greater thickness of the formation is categorized by lower risk of contamination with higher dissolution and dilution of the contaminants (Edet 2004). The longer the time it takes during transportation the more the attenuation of the pollutants will be. The upper part of the vadose zone with intense biological activity, is defined to be the soil media (S). The areas with soils that allows contaminants to infiltrates easily are said to be more vulnerable to contaminants compared to soils which resist to infiltration. The topography (T) (%) is defined by the terrain slope together with its variation. A low slope will determine a small surface flow and a high pollution risk. The vadose zone impact (I)—the unsaturated or discontinuously saturated layer situated above the water table is called vadose. The

pollutant's transfer is influenced by the vadose zone's lithology. The aquifer hydraulic conductivity (C) is the aquifer materials' capacity to leave the water to pass through it. The aquifer vulnerability is low for reduced hydraulic conductivities (Barbulescu A, 2020) therefore The higher the conductivity values, the high vulnerability to contaminant and vice versa. Hydraulic conductivity controls the rate at which groundwater will flow under a given hydraulic gradient (Baalousha, 2006. In this DRASTIC model, GIS database is develop using the input information such as borehole data, meteorological data, hydrological data, geology data, soil data, lithology data, contour map, and topography map. This research uses the Geographic Information System (GIS) based DRASTIC method.

The rating and weighting of the seven parameters are due to their relative importance to contamination (Shirazi 2012). Weighting and rating ranges were considered from 1 to 5 and 1 to 10, respectively. A multiplier defined as weight is multiplied with each parameter rating for each interval and then the products were summed up to calculate the final DRASTIC index. The equation used is as shown below

DRASTIC Index (DI) = $D_rD_W + R_rR_W + A_rA_W + S_rS_W + T_rT_W + I_rI_W + C_rC_W$

R and W is rate and weight respectively assigned to the seven parameters. Where:

D_R = numerical rating of depth to water

D_W = numerical weight of depth to water

R_R = numerical rating of net recharge

R_W = numerical weight of net recharge

A_R = numerical rating of aquifer media

A_W = numerical weight of aquifer media

S_R = numerical rating of soil media

S_W = numerical weight of soil media

T_R = numerical rating of topography

T_W= numerical weight of topography

I_R = numerical rating of impact of Vadoze zone media

I_W = numerical weight of impact of Vadoze zone media

C_R = numerical rating of hydraulic conductivity

C_W= numerical weight of hydraulic conductivity

The DRASTIC index simply indicates the degree of groundwater vulnerability of an area. The higher the index value the greater the possibility of contamination. The highest weight has been assigned to the depth of water and impact of the Vadoze zones because the shallower the water table, the higher the chance of pollutants to reach to groundwater(Linan et al., 2012).

Recently, geographic information system (GIS) techniques have been widely used in aquifer vulnerability mapping. The major advantage of GIS-based mapping is the combination of data layers and rapid change in the data parameters used in vulnerability classification (Wang Y., & Merkel B. J. 2007). Not only that but also DRASTIC method is more economic and less time consuming to assess a wide range of regional groundwater vulnerability, overcoming sloppy, uncontrolled development of land, and undesirable activities. Statistical methods are used to easily obtain the relationships between the selected variables and the actual occurrence of pollutants in the groundwater. The other advantage of DRASTIC model is that it provides a basis of evaluating the vulnerability to pollution of groundwater resources based on hydrogeological parameters. This is inexpensive method to identify areas that need more investigation (Twana Abdullah, 2017). However, the assessment results are easily influenced by the selected data or methods. Geographic Information System (GIS) is a very efficient tool for analyzing, interpreting, manipulating and incorporating the geological, hydrogeological and geomorphological data (Jha and Peiffer 2006; Jha et al. 2007). According to the findings of the study that was done by Shirazi & Akib in 2012, indicate that the combination of GIS and DRASTIC are more viable for groundwater vulnerability assessment hence this is the proper method chosen to be used for groundwater vulnerability assessment from petroleum in Blantyre.

In Qatar, a research was done by Riyadh Al-Raoush, Stephane Ngueleu & Philippe van Cappellen to assess groundwater pollution by petroleum derived contaminants in coastal semiarid environment (AL-Raoush R., Ngueleu S., et al 2018), the research was aim at developing a reactive transport model for groundwater pollution by petroleum hydrocarbons. Other researches, studied the types and composition of oil pollutants (Innocent, I., & Massetti, F., 2014). Twana Abdullah researched on groundwater vulnerability using the DRASTIC model and the DRASTIC model was considered the most proper and useful method for assessment of groundwater vulnerability (Abdullah, T.O.2017). DRASTIC index model was employed in the assessment of the intrinsic groundwater vulnerability to contamination in Kaduna metropolis, Nigeria and it was effective (Ahmed M. S., Tanko A. I., et al 2017). Others studied the main organic pollutants in oil including methyl tert-butyl ethane, Benzene series, total petroleum hydrocarbons, and polycyclic aromatic hydrocarbons (Wade et al., 2016). But no research has been made in Malawi assessing the groundwater contamination risk from petroleum products in Blantyre city using the DRASTTC method so this will help in finding better ways on how groundwater contamination from petroleum products in Blantyre city can be reduced in order to have clean groundwater. Figure below is a schematic diagram.

https://www.researchgate.net/figure/Schematic-diagram-of-light-nonaqueous-phase-liquids-LNAPL-leakage-from-underground_fig1_331155377.

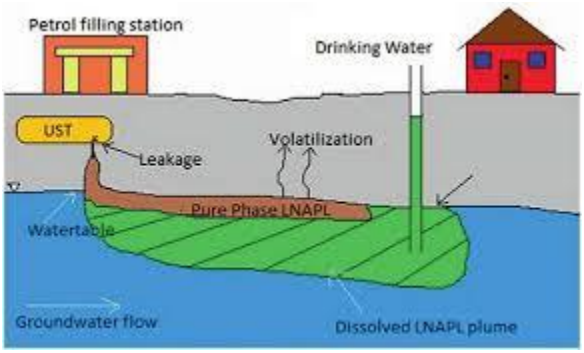


Figure 4: *schematic diagram of light non aqueous phase liquids (LNAPL) leakage from underground storage tanks (UST) and its migration in the subsurface.*

CHAPTER 3

Methodology

3.1 Research Design

This research is designed as both quantitative and qualitative study, aiming at assessing the groundwater contamination from petroleum products. The research is quantitative because it focuses on analysis of spatial patterns through quantitative attributes (numerical values) such as filling stations density, topography, hydraulic conductivity, depth to water table. At the same time is qualitative research because it involves mapping features that are not necessarily based on numerical values such Soil type, Aquifer Media, Vadose zone. Therefore, the research used a mixed method (quantitative and qualitative) that has been applicable in order to assess the contamination risk from petroleum products.

Figures below shows the study area Map and the service stations

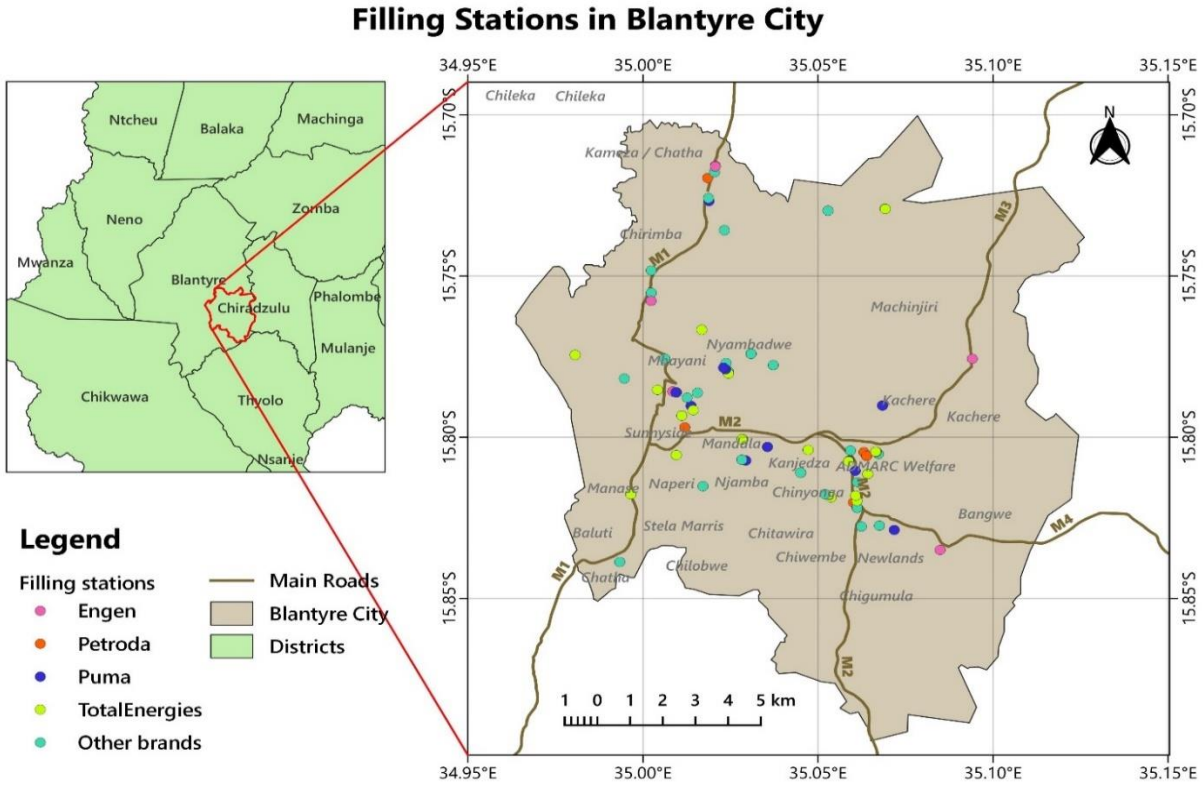


Figure 5: *The Study Area Map and Filling Station distribution*

3.2 Material and methods

This research will use secondary data and is more of a desk research. Soil maps of Blantyre city will be used, remote sensing data will help to understand the spatial distribution of the filling stations using ARCGIS, and Hydrological map of Blantyre was used to create Aquifer media map for Blantyre city. Using the DRASTIC Method, the groundwater vulnerability to contaminants of Blantyre city has been estimated, by calculating the depth, recharge, soil media, topography, impact of Vadose, and Conductivity. A software known as Q GIS and ARCGIS have been used to make a map of filling stations in Blantyre at same time knowing their spatial distribution of the filling stations and the help to make a risk assessment model. Some of the data has been taken from literature i.e. Malawi government reports and some from different websites all these sources have been recognized.

The diagram below shows the simplified DRASTIC method from collected data to processing and the final output. The raw data is used to make parameter maps which are later processed using ArcGIS tools and the final output is produced which is the vulnerability map,

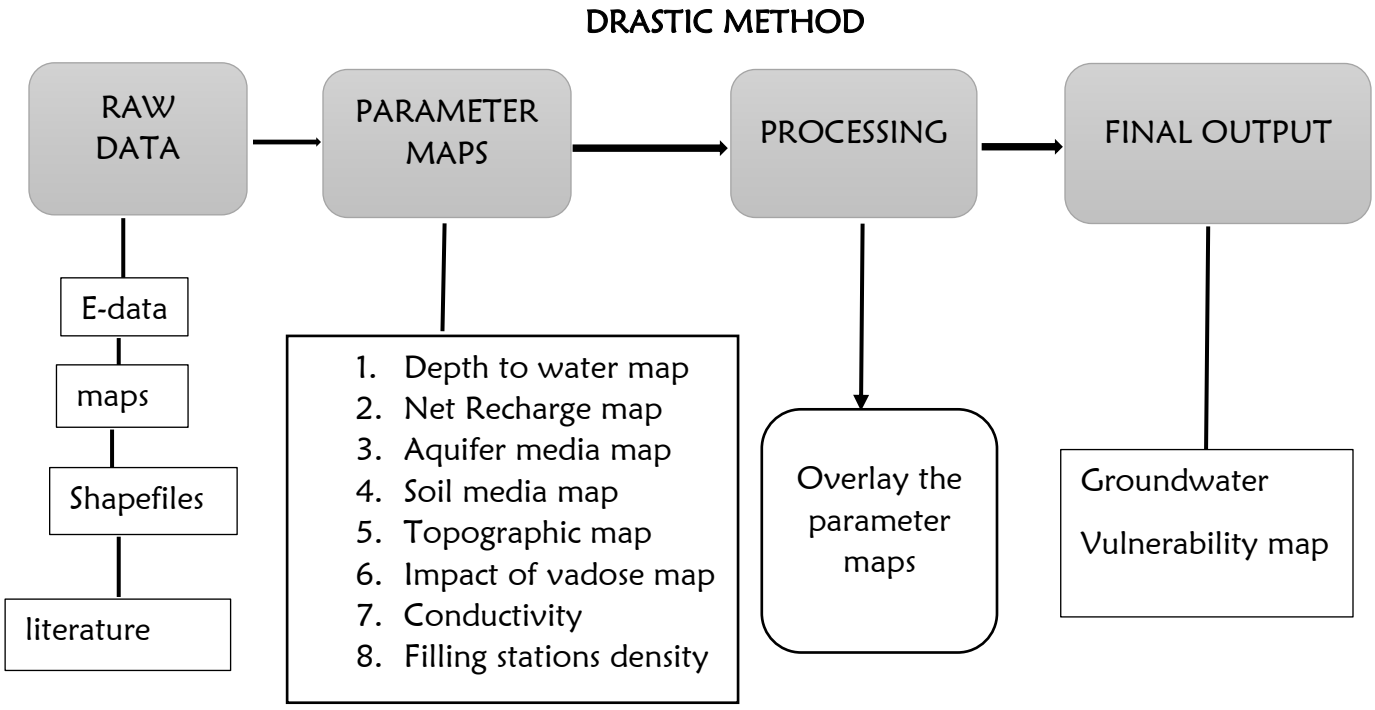


Figure 6: *Schematic Diagram showing the DRASTIC method*

These seven Parameters were developed by Aller et.al (1987) and each of the parameters contributes to the evaluation of groundwater vulnerability (Prasad, et al., 2010). An eighth parameter has been added to this DRASTIC method and that's filling Station Density(Fd). Filling stations density is dealing with how close the filling stations are from one another per square kilometer because where there are a lot of filling stations the vulnerability of groundwater to fuel must be high. The main source of petroleum contaminants such as petrol, diesel and lubricants(Lubes) are the filling stations/ service stations in Blantyre city. So adding this filling station Density (Fd) to the DRASTIC index equation it becomes;

DRASTIC Index (DI) = $D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w + Fd_rFd_w$

The DRASTIC Index will be calculated using the weighted sum tool that is found ArcGIS and this will help to classify the vulnerability of the groundwater to petroleum contaminants such petrol and diesel in Blantyre city. Each parameter has got its own Weight and Range, and the tables below are the fixed weights, ranges and ratings for each of the parameters.

Table 1*: The weights assigned the Parameters*

Parameters	Assigned DRASTIC weights
Depth to Water	5
Net Recharge	4
Aquifer Media	3
Soil Media	2
Topography	1
Impact of Vadoze zone Media	5
Hydraulic Conductivity of the Aquifer	3
Filling Stations Density	5

Using these fixed weights, the DRASTIC index equation will look as below;

DRASTIC Index (DI) = $5D_r + 4R_r + 3A_r + 2S_r + T_r + 5I_r + 3C_r + 5Fd_r$

Table 2: *A list of parameter ranges and ratings for the DRASTIC mode*

Parameters	Range	Rates
Aquifer Media	Fractured Basement(FB)	5
Depth to Water table	20 m	6
Net Recharge	15-50 mm/yr 50-80 mm/yr 80-100 mm/yr	3 6 9
Topography (Slope %)	0-2 2-10 10-20 20-33 >33	10 8 5 2 1
Soil Media	Loamy sand Sandy Loam Sandy Clay Loam Rock Outcrops/Hills	8 6 5 1
Saturated hydraulic Conduction	0.5 - 1.5 m/day	1
Vadose Media	fluvial and colluvial deposits gneiss gravel	8 7 5

	Syenite	4
Filling Station Density	0	1
	1	2
	2	3
	4	5
	5	7
	6	8

According to Aller 1987, the deeper the Depth to groundwater table (D) the safe it is from pollutants than shallow depth to water table. On the other hand, the higher the annual recharge rates (R) indicates that more contaminants infiltrate into the groundwater. The aquifer media(A) determines chances of resistance against the contaminant transport. The soil media (S) exposes the pollutants moving time from the surface to the water table while the topography (T) indicates that high slope there's more runoff and that results to less chance of contaminants infiltrating into the ground. The Vadoze zone (I) thickness and matrix affects the contamination intensity and transport timing and finally the hydraulic Conductivity of the aquifer indicates the quantity of the water percolation through the aquifer.

The data for 8 parameters used in this study was collected from different sources. The Depth to water table data was obtained from literature and one value was estimated for the whole Blantyre city in ArcGIS. The Net recharge data was also collected from Literature from Malawi government report (Ministry of agriculture, irrigation). The aquifer media data was downloaded from Africa Hydrogeological map. The Soil media data was extracted from the Malawi Soil Map similarly the Vadose Zone map of Blantyre. Digital Elevation Model(DEM) of Blantyre was downloaded from USGS-Earth Explorer and the it was converted to slope(Topography) in ArcGIS. The Hydraulic Conductivity was obtained in literature and then assigned to the whole map of Blantyre city. Using the google map, the coordinates for each filling station in Blantyre city was obtained and compiled in an excel. The coordinates were imported into ArcGIS and QGIS was used to make a filling station density map per square kilometer.

All these parameter maps, were converted to Raster files so that they could be used in DRASTIC modelling. The conversion involved the use of the Raster conversion tool in

ARCGIS which converted the features to raster and then to assign rating to the parameter maps, the maps were reclassified using reclassifying tool (Spatial analysis tool). Using the Weighted sum tool, the DRASTIC model for the parameters was developed. The weights were assigned to each parameter accordingly and then the index was produced which was later classified into four classes.

CHAPTER 4

Results and Discussion

1. Depth to groundwater

The depth to water table determines the depth of material through which a contaminant such petrol/diesel must travel before reaching the aquifer. The depth to water table in the study area varies from 15m to 25m and this range was obtained from literature (Fraser 2020). A value of 20m was assigned to the whole study area because it is a middle value. This depth of 20m can only be categorized as a shallow depth here in Malawi hence the vulnerability rating of 6 was assigned due to its significant effect as shown in figure 7 & 8 below, and the DRASTIC weight is 5. Therefore, the whole study area has a relatively shallow depth which is less susceptible to vulnerability.

Table 3: *The DRASTIC Rating, weighting and Index for Depth to water table*

Depth(m)	Rating	Weight	Index D_rD_w
20	6	5	30

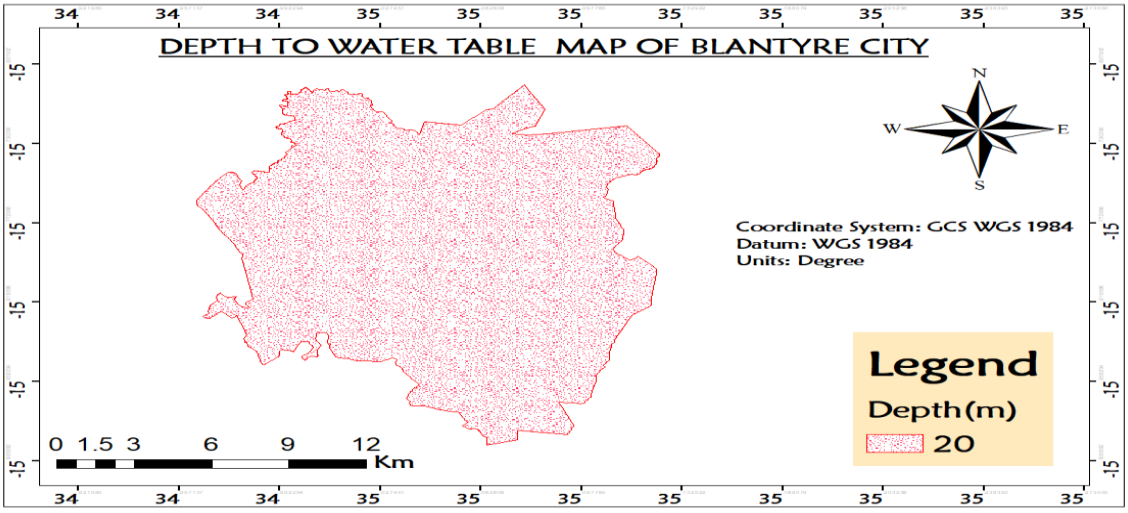


Figure 7: *Depth to water table map of Blantyre city*

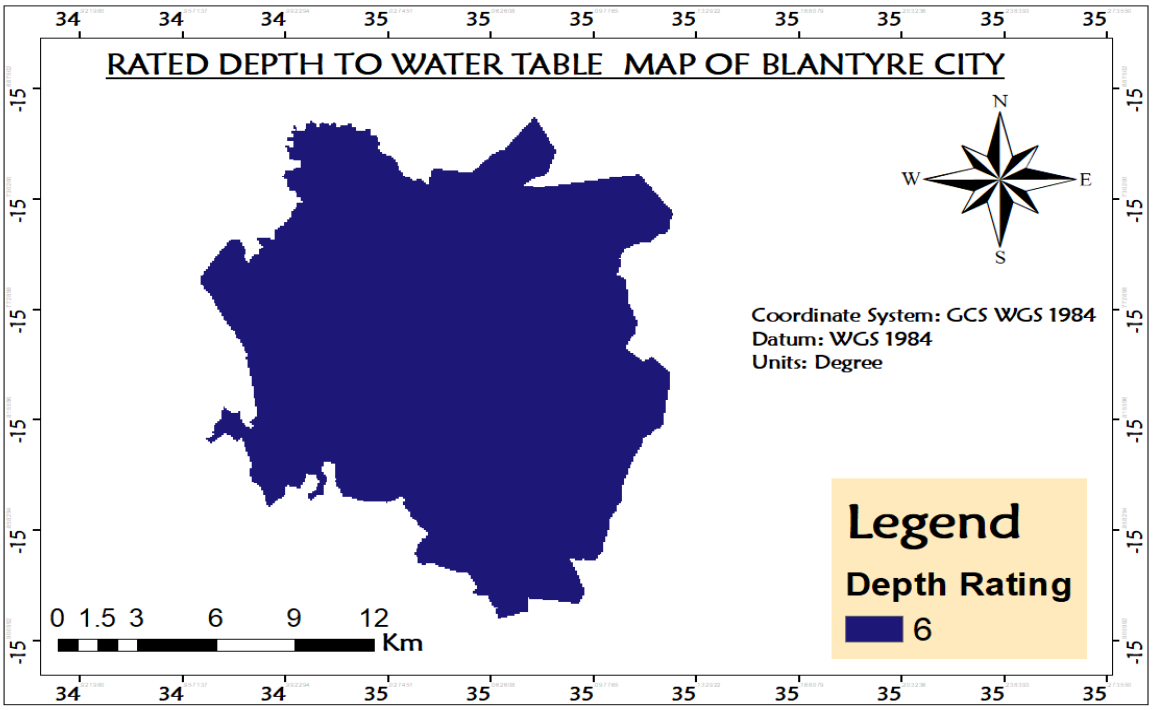


Figure 8: *Depth to water table map rating for Blantyre City*

2. Net Recharge

The net recharge is low where there is high slope because the runoff is high leading to low infiltration. The Malawi Government has not yet developed a hydrogeological map showing the distribution of groundwater recharge in the country (Pavelic et al 2012). Therefore, recharge rate of the study area was obtained from literature available about Malawi Net recharge. According to Scheidegger et. al (2015) the Net recharge to complex basement aquifer ranges from 15mm/year to 80 mm/year and according to department of Lands, valuation and water (1983) the net recharge of Altered basement aquifer ranges from 10mm/year to 100mm/year. According to the Project for National Water Resources Master Plan in the Republic of Malawi final Report (2020), the recharge tends to be higher than 100mm/year at the bottom of mountain areas such as hills in Blantyre. From these literatures, a range of Net recharge was established from 15mm/year to 100mm/year.

Table 4: *The DRASTIC Rating, weighting and Index for Net Recharge*

Net Recharge(mm/yr)	Rating	Weight	Index R_rR_w
15-50	3	4	12
50-80	6		24
80-100	9		36

Using the slope map, areas at bottom of the mountain were given higher recharge and away from the mountain the recharge value increases. This is so because hills in Blantyre receives a lot of rainfall and due to steep slope the runoff is higher and these waters easily infiltrates at the feet of these hills.

The net recharge was classified into three classes 15-50 mm/year, 50-80mm/year and 80-100mm/year and there rating was 3,6 and 9 respectively. The DRASTIC weighting was 4 for net recharge. The net recharge map rating shows that the groundwater vulnerability is high below the hills with a rating 9. The figures below show the maps for net recharge and the rating.

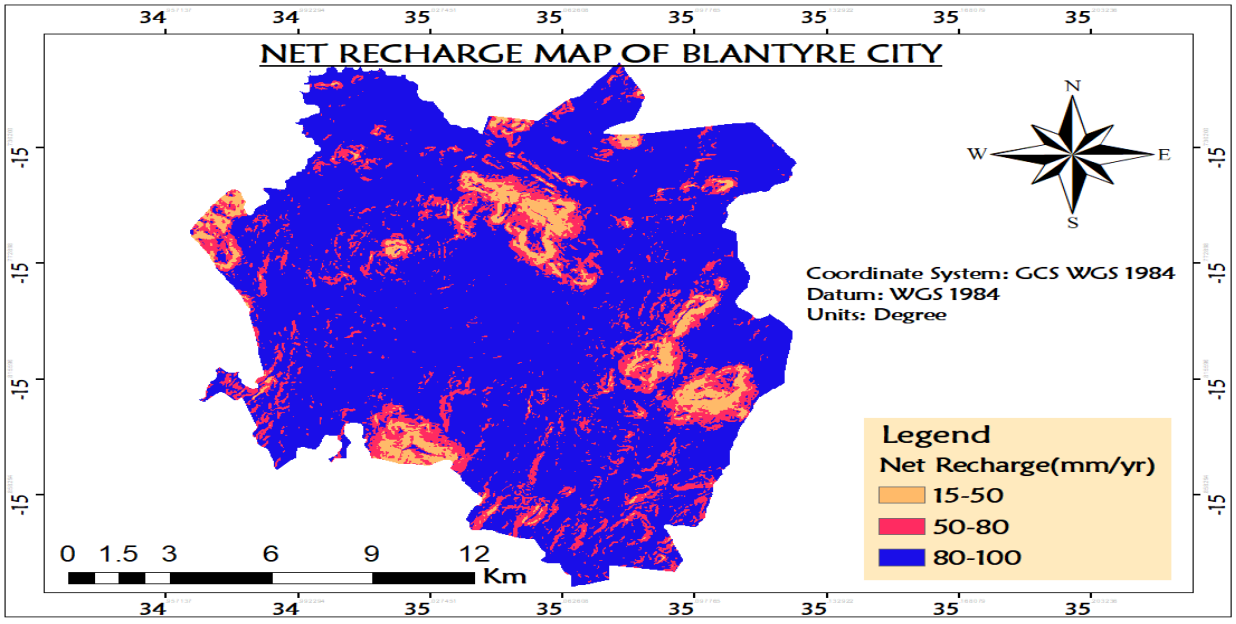


Figure 9: *The net recharge Map of Blantyre city*

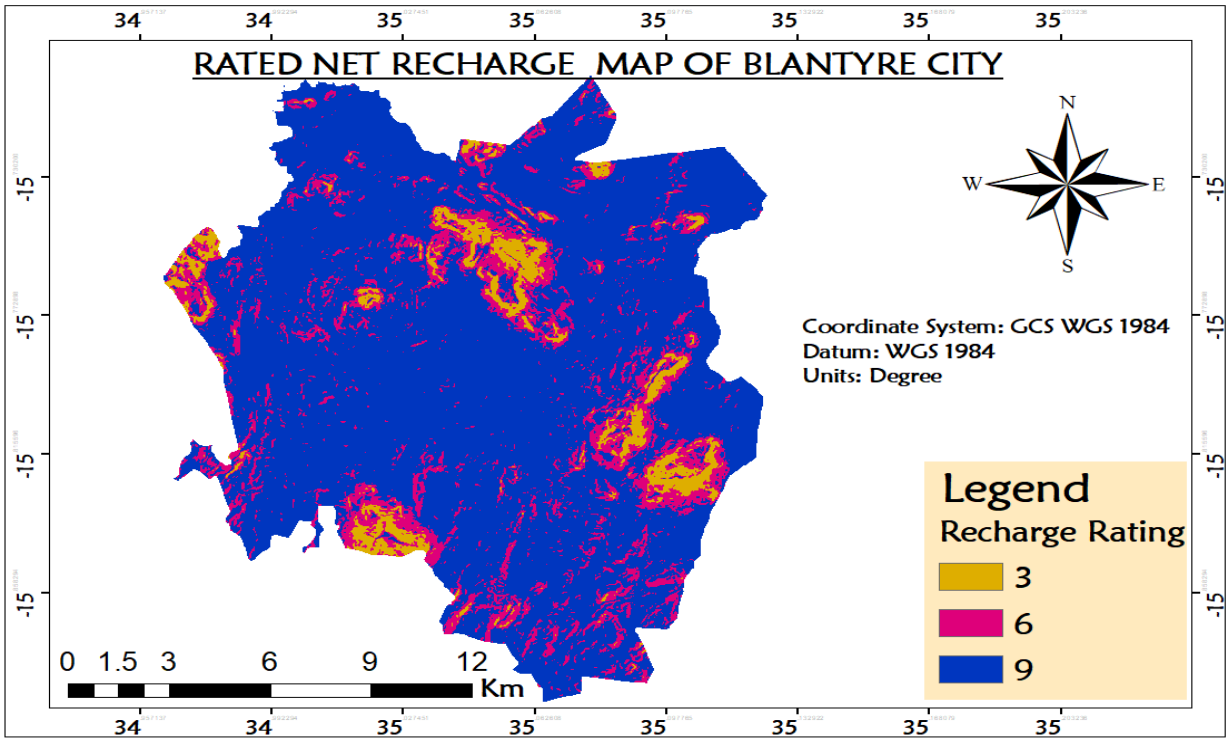


Figure 10: *Rating Net charge map*

3. Aquifer Media

According to the hydrogeological map of Malawi gotten from Africa Groundwater Atlas, Blantyre has got a Basement Aquifer type. This basement aquifer is divided into weathered and fractured basement aquifers (Robins et al., 2013). Blantyre city has Fractured Basement aquifer which mainly composed of these rocks; Gneiss, Marbles and Quartzite (Fraser 2020). the fractured Rock Aquifers often have a fast, turbulent flow and are less isotropic than porous media (The Ministry of Agriculture, Irrigation and Water Development, 2016). the fractured basement aquifer that is found on the steep slopes of the escarpments or the uplands rising from plateau are rarely significant because of low storage and low permeability (Smith, 1983). Due to this Blantyre Fractured Basement aquifer has been rated as 5 because it has more steep slopes hence the vulnerability to contaminants is not that high and the DRASTIC Weight assigned to it is 3. The rating of 5 and weight of 3 indicates that the aquifer media does not contribute much to groundwater vulnerability because the permeability is low hence the contaminants are attenuated as it takes longer

during transportation. The maps and table below show the Aquifer type of Blantyre City and the Rating assigned to the aquifer type of Blantyre.

Table 5: *The DRASTIC Rating, weighting and Index for Aquifer media*

Aquifer media	Rating	Weight	Index A_rA_w
Fractured Basement	5	3	15

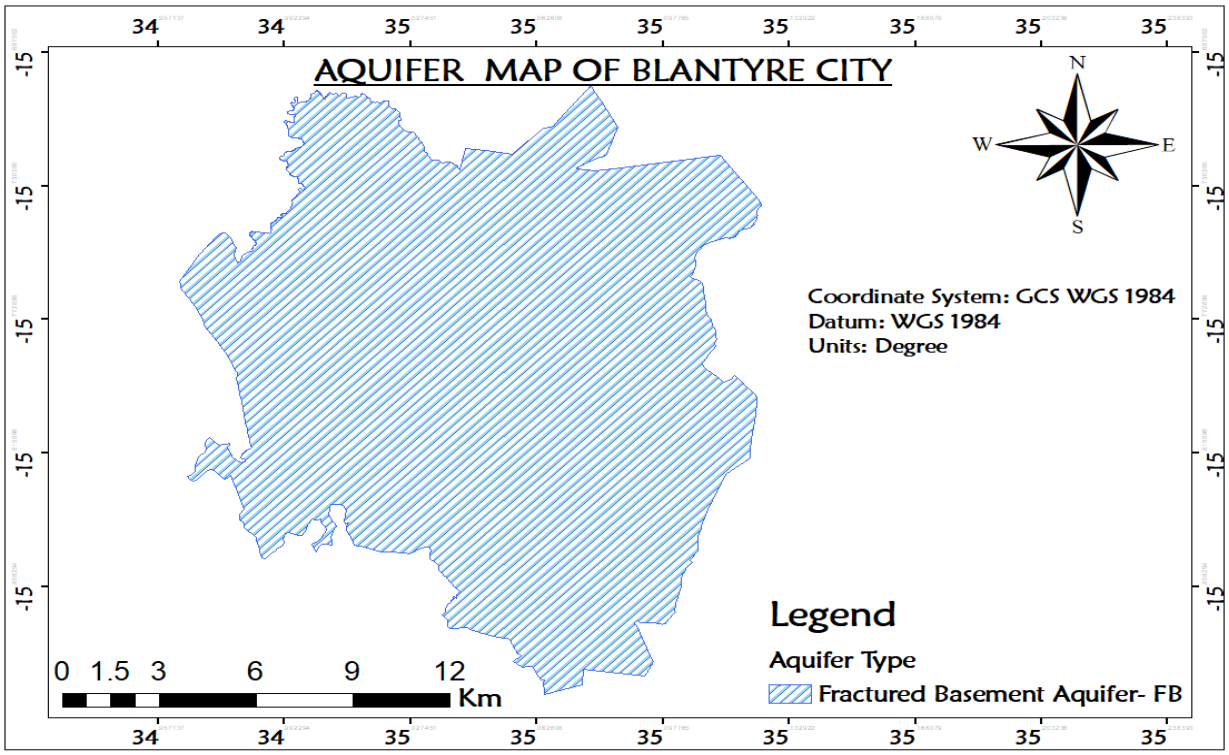


Figure 11: *The aquifer media of Blantyre city*

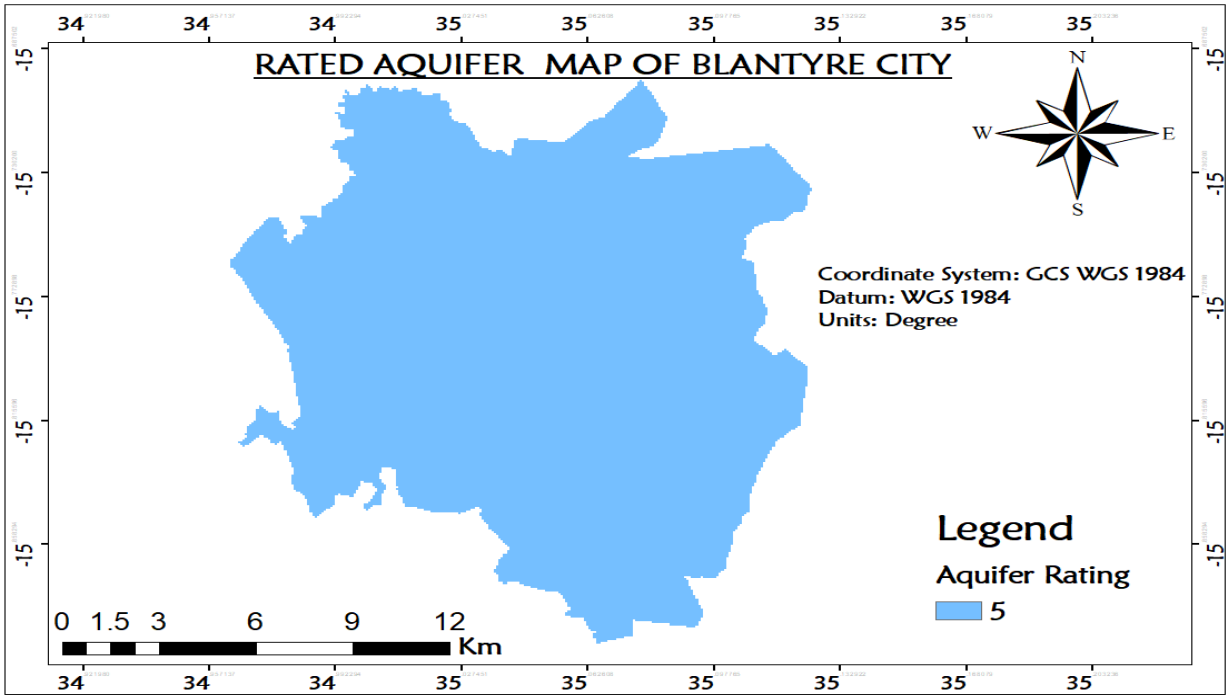
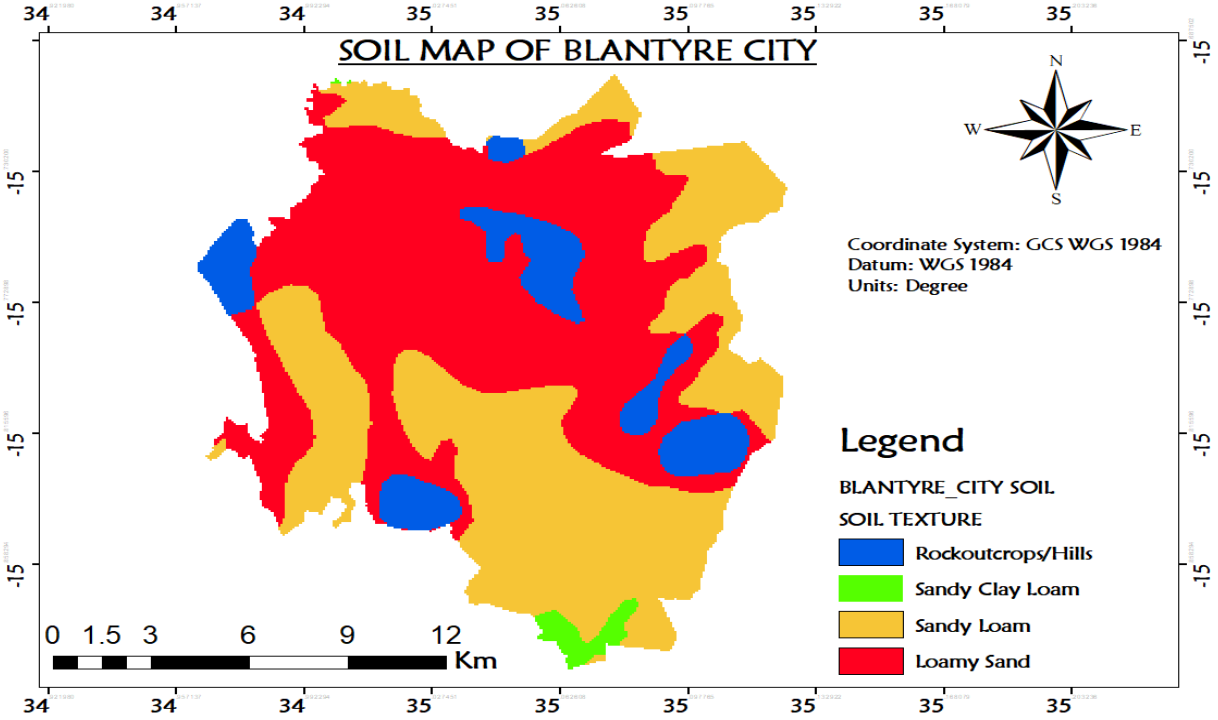


Figure 12: *Rating Aquifer Map of Blantyre*

4. Soil Media

The soil media refers to the uppermost part of the ground which is characterized by significant biological activity (Aller et al 1987). The areas with soils that allows contaminants to infiltrates easily are said to be more vulnerable to contaminants compared to soils which resist to infiltration. So Based on Aller et al. (1987) method, the soils types for Blantyre City have been classified and the rates were assigned (from table 2).

Figure 13: *The soil Media of Blantyre city*



According to Shakoor et al (2018), the soil media provides the first defense against pollutants infiltration and the soil media map reflects pollutant infiltration rates. The soil characteristics such as soil texture and soil compaction controls the infiltration rate. Based on soil texture of Blantyre city, the soil map was classified into 4 classes and further reclassified based on infiltration and porosity rate by using the DRASTIC rating. The first class of Blantyre city soil is rock outcrops which include all hills, the other classes include Sandy clay loam, sandy loam and loamy sand. With the rating 1, 5, 6 and 8 respectively and soil media has a fixed DRASTIC weight of 2. The soil maps show that small percentage of Blantyre city has low rating (hills) compared to sandy loam soils and loamy sand soils which have high rating and prone to contaminants infiltration. The hills are lesser vulnerable to contamination because they have Rockoutcrops which resist infiltration and the slope increases runoff. The north side and west of Blantyre city have loamy sand which allows more infiltration hence it is more vulnerable to contamination.

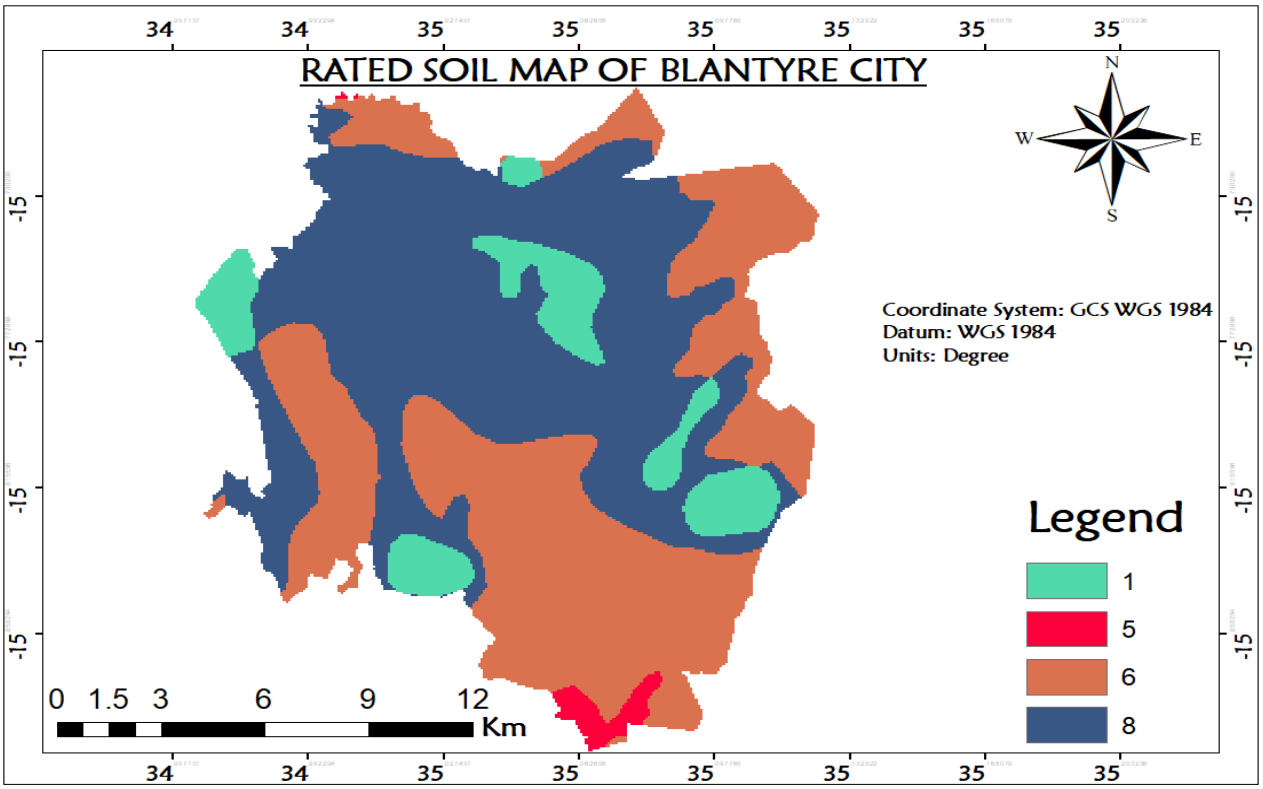


Figure 14: *Rating of soil map of Blantyre City*

The soil index is high for loamy sand as shown in table 7 hence the groundwater vulnerability is high in these loamy sands locations in Blantyre city.

Table 6: *The DRASTIC Rating, weighting and Index for Soil Media*

Soil Class	Rating	Weight	Index (SrSw)
Rockoutcrops	1	2	2
Sandy Clay Loam	5		10
Sandy Loam	6		12
Loamy Sand	8		16

5. Topography(Slope)

Topography refers to the slope of land surface and slope variability of the land surface. Topography has a significant effect on water movement and influences the rainfall runoff and hence affecting the infiltration process in the Blantyre's hydrogeological system. The Digital Elevation Model(DEM) of Blantyre city was downloaded from USGS portal and then converted into raster in ArcGIS.

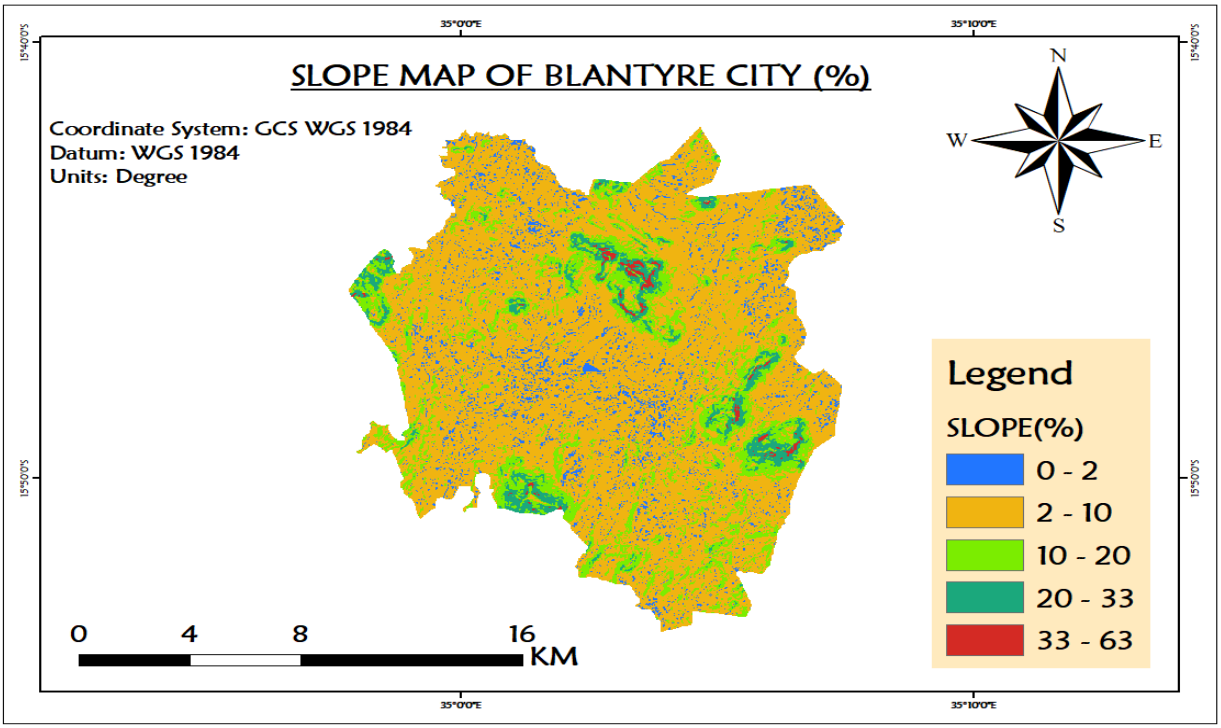


Figure 15: *Topographic of Blantyre City*

The slope of Blantyre city ranges from 0 to 63% and it has been divided into five classes according to Aller et.al (1987)

Significant parts of Blantyre city have got a gentle slope (2-10%) and some parts have a very gentle slope (0-2%), the central part of the study area has more of gentle slopes. These areas are more prone to contamination because there's less runoff hence the contaminants infiltrate, the rating of 10 and 8 has been assigned to 0-2% and 2-10% respectively. A rating of 5 has been assigned to a moderate slope that ranges from 10% to 20% as shown figures 16 And 17 a slope from 20-30% and 33-63% can be classified as

very steep slope because these are hilly areas and the runoff is always high in these areas. For such reason the contamination is low and therefore the rating is low, 2 and 1 respectively. Where there is low slope the DRASTIC Rating is high because the contaminant released is less likely to become run off hence much of it infiltrates into the aquifer while where there is steep slope DRASTIC rating is low as the contaminants infiltrates into the aquifers. The fixed weight of 1 is assigned to topography

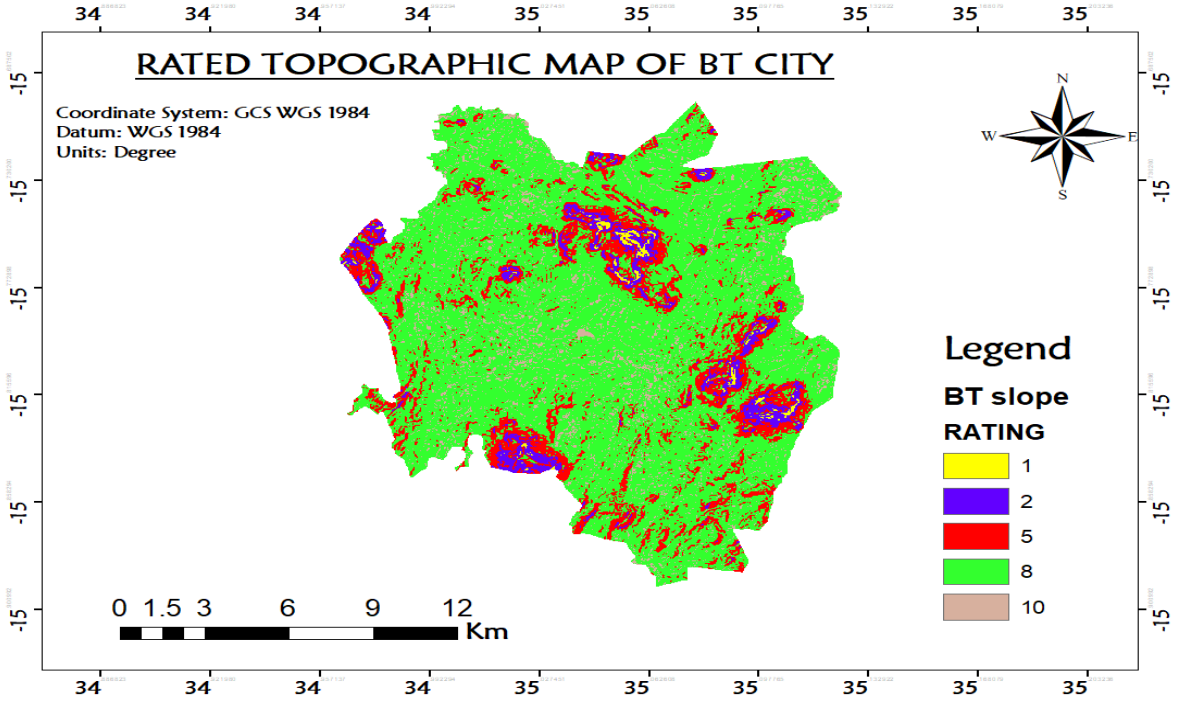


Figure 16: *Rated Topographical Map of Blantyre City*

Table 7: *The DRASTIC Rating, weighting and Index for Topography of BT city*

Slope Range(%)	Rating	Weight	Index T_rT_w
0-2	10		10
2-10	8		8
10-20	5		5
20-33	2		2
>33	1	1	1

6. Impact of Vadoze zone

The Vadoze zone is the layer above the water table and completely unsaturated (Aller et.al 1987). The type of vadose zone media determines the attenuation characteristics of the material above the water table and it influences the amount of contaminant rich water percolating down. A lot of processes takes place in this zone such straining, bio chemical degradation and filtration. The parameter map was prepared from well lithology data using the Malawi Soil map. In this study, it was assumed that the unsaturated zone is a continuation and extension of the parent material of this location (Blantyre city). The zones include fluvial and colluvial deposits, gneiss, gravel and syenite with the DRASTIC rating 8,7,5 and 4 respectively. The same shapefiles used to make soil map was used to make vadose zone map and the weight for the vadose zone was 5. The figures and a table below shows the vadose zones and the rating to each zone in Blantyre city. The areas of Blantyre city which have the Gravel, Gneiss and the fluvial & colluvial deposits Vadoze zone are more susceptible to contamination. From these results, it shows that a large area of Blantyre city which is the southern part and northeastern part that contains gneiss area more vulnerable to contamination as the zone allows more contaminants to sink into the aquifer.

Table 8: *The DRASTIC Rating, weighting and Index for vadose Zone*

Vadose Zone	Rating	Weight	Index Irlw
fluvial and colluvial deposits	8		40
Gneiss	5		25
Gravel	3		15
Syenite	4	5	20

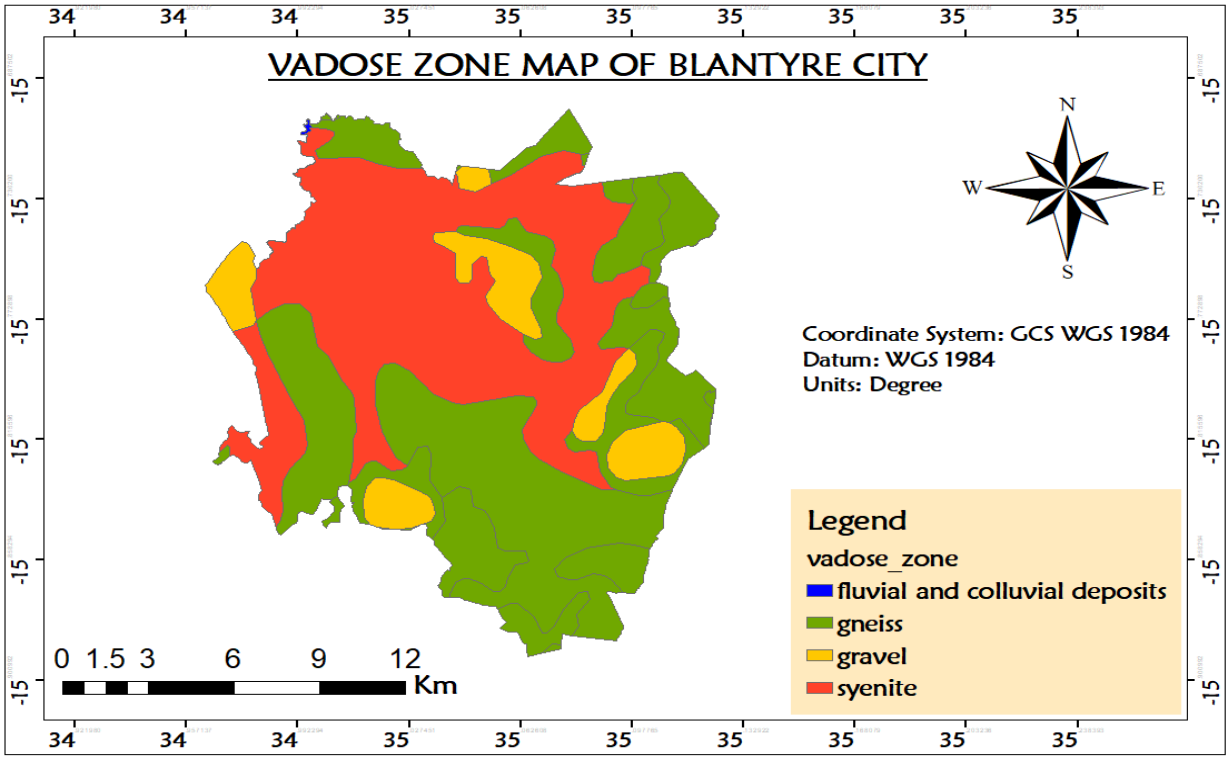


Figure 17: *The Impact Of Vadoze Zone map*

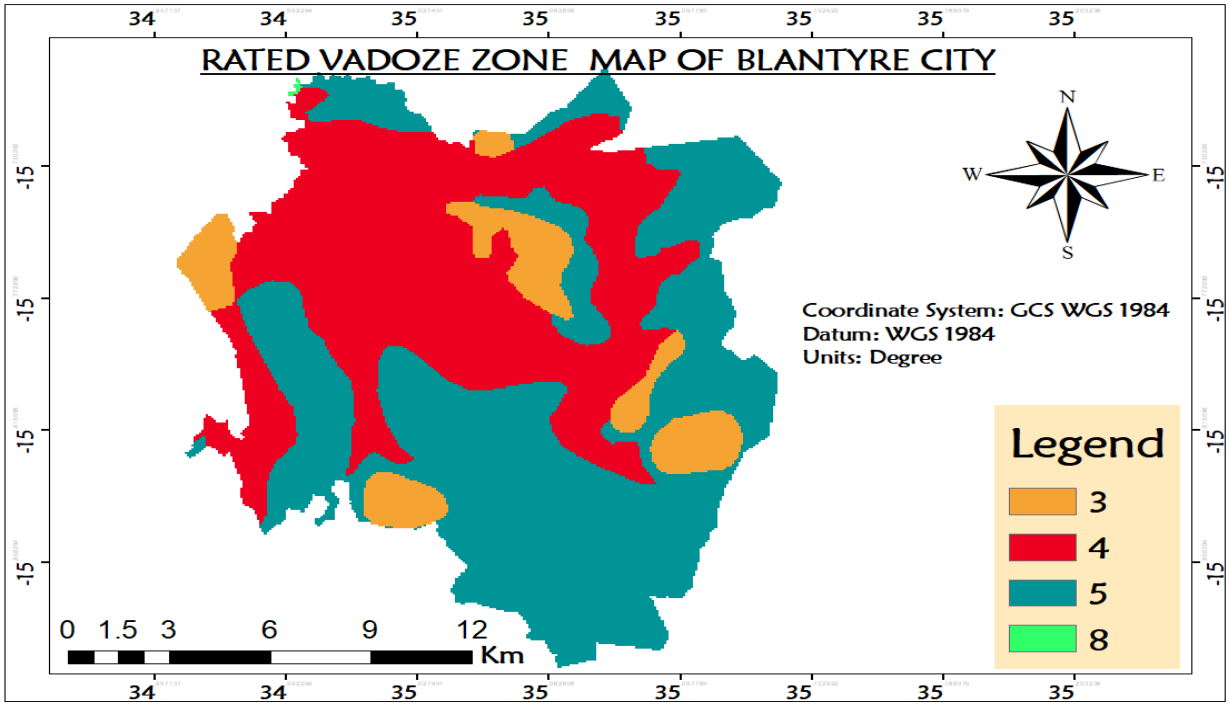


Figure 18: *Rating of the impact of vadose zone*

7. Conductivity

The hydraulic conductivity value was obtained from literature which was collected by Ministry of Agriculture, irrigation and water development (2016). The values of hydraulic conductivity of Blantyre city ranges from 0.5m/d to 1.5 m/d and these values have a minimal impact to groundwater vulnerability and it only fit into one class (0.5-1.5 m/d) hence the rating is 1 while the DRASTIC weight assigned to it is 3. The mapped saturated hydraulic conductivity was reclassified based on the rating scheme in ArcGIS and the whole Study area was assigned a rate of 1. In relation with hydraulic conductivity, Blantyre city is less susceptible to contamination.

Table 9: *The DRASTIC Rating, weighting and Index for Hydraulic Conductivity*

Conductivity(m/d)	Rating	Weight	Index C_rC_w
0.5- 1.5	1	3	3

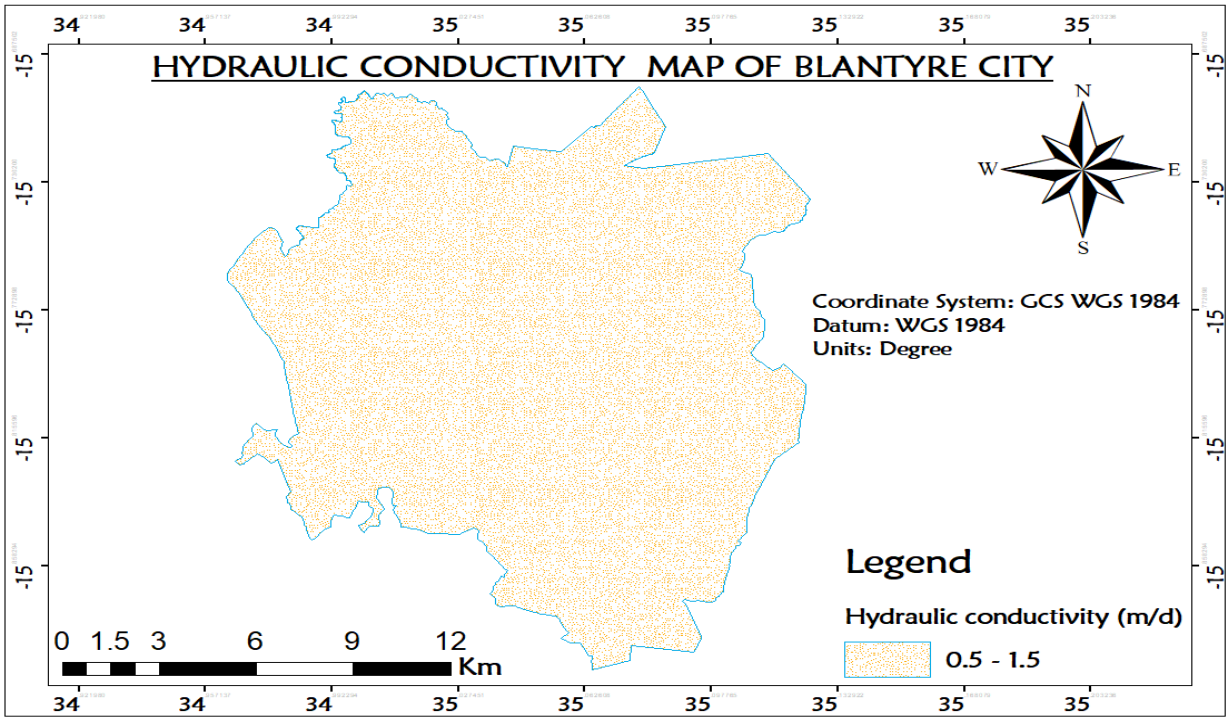


Figure 19: *The Hydraulic conductivity map of Blantyre city*

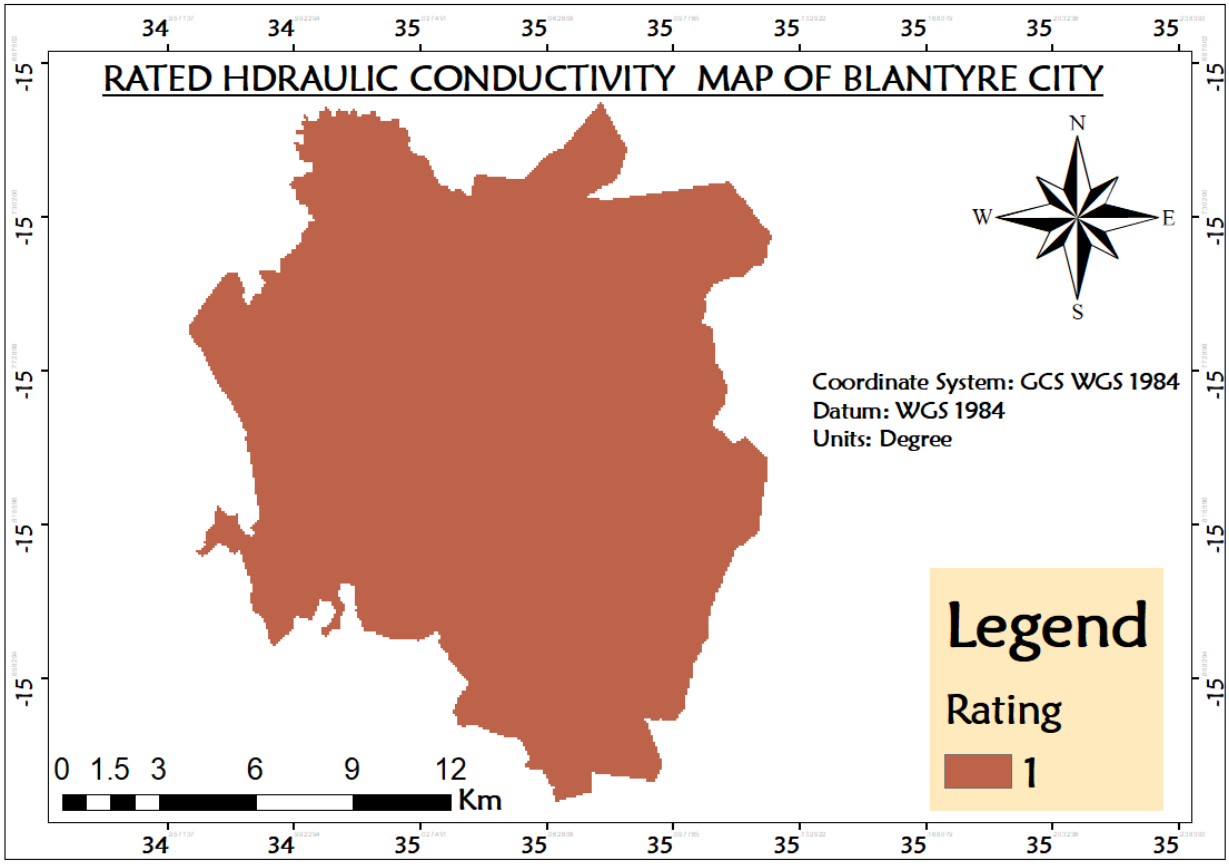


Figure 20: *Rating of the hydraulic Conductivity Map*

8. Filling station Density (Fd)

The filling station density was calculated per km². according to Malawi Regulatory Authority (2014) guidelines for constructing filling stations it allows construction of a service station within one kilometer of an existing service station and 100m away from public institution or 50m from a residential area, however according to this study the results shows (**figure 27**) that a lot of filling stations were built close to each other for example in Limbe and this increases the risk to groundwater contamination from petroleum products. A map was developed to show the filling stations per km² (figure 21). The table below shows the rating, weighting and the index for filling station density.

Table 10: *Rating, Weighting and Index for Filling Station Density*

Filling Station density(km²)	Rating	Weight	Index FdrFdw
0	1		5
1	2		10
2	3		15
4	5		25
5	7		35
6	8	5	40

Within a square kilometer the number of filling stations differs, the range starts from 0-6 filling stations per square kilometer. A higher rating was given to location where there are more filling stations. 8 was the highest rating which was assigned to location which has 6 filling stations within a square kilometer. In this research, filling stations are considered as the main source of contamination hence the DRASTIC weight assigned to it was 5 due to its significant effect on the aquifer.

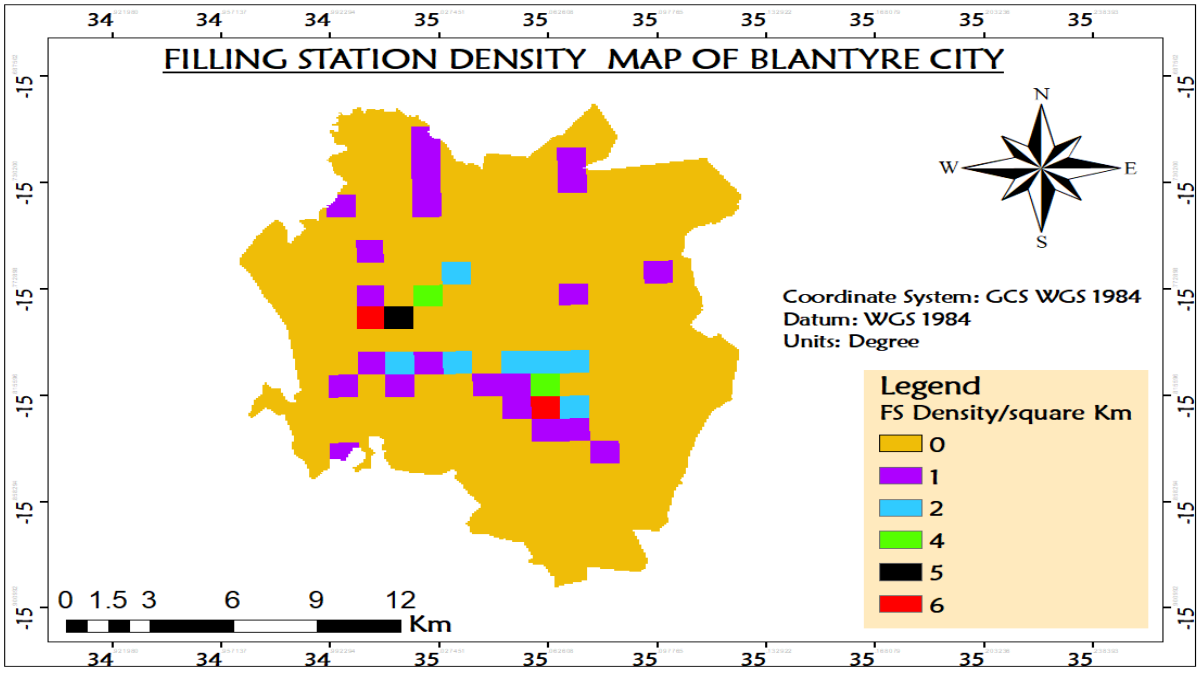


Figure 21: *Filling station Density Per Square Kilometer*

From the figure 22 above, the 0 is the region where there's no filling stations and vulnerability is low, and from this map it clearly shows that a lot of locations there is only one filling station per square kilometer followed by 2 filling stations per km^2. There are two locations with dense filling station per square kilometer of approximately 6 filling stations. In this location the risk to groundwater contamination is likely to be higher because there are more sources of contaminants. Figure 22, shows the Filling Station Density Rating according to the number of filling stations per square kilometer. The lowest rating is 1 where there's is no filling station and the maximum rating is 8 where there are 6 filling stations.

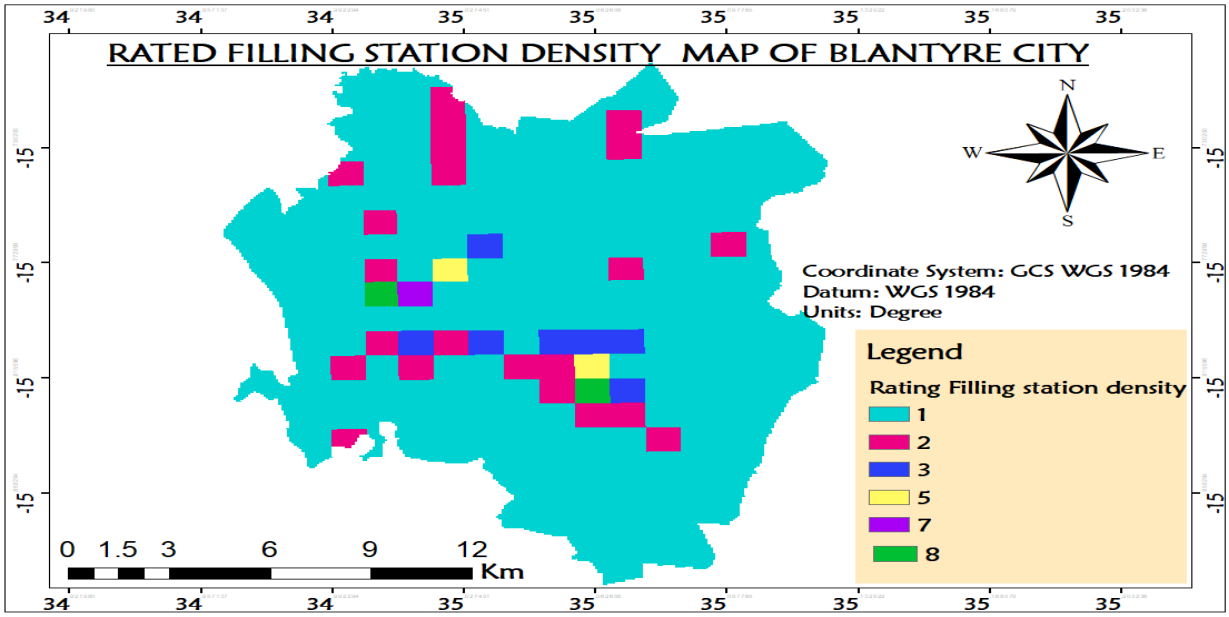


Figure 22: *Filling Station Density Rating*

The DRASTIC index

The DRASTIC index is highly Sensitive to the parameter scores, weightings and the numerical values assigned. Using the ArcGIS tool (weighted sum), all seven parameters were added and the weight was assigned to each parameter accordingly then the DRASTIC index was produced. In this research two DRASTIC index have been produced, one for the seven DRASTIC parameter and the other index contains all 8 parameters (Including the

Filling station density). This has been done in order to appreciate the effect of the 8th parameter on the aquifer vulnerability to contaminants.

1. Index for the seven Parameters

The DRASTIC index for the 7 parameters (Depth to water table, Net Recharge, Aquifer media, Soil Media, Topography, impact of vadose and Hydraulic conductivity) ranges from 78 to 150 and using the Natural Breaks(Jenks) classification method the Index was classified into 4 classes as shown in figure 23. From the vulnerability risk map shown in figure 24, Index ranges (78-99, 99-118, 118-130 and 130-150) have been classified as Very low, low, moderate and High vulnerable zones respectively. A very large area of Blantyre city located in northern, western and some part of east and southern sides area covered by a moderate vulnerable zones which index ranges from 118 to 130. The hills the contamination is very low because the net recharge is low due to steep slope and rocky outcrops. The central part of the study area which contains areas like Limbe, Nyambadwe, Mbayani and Blantyre town are more vulnerable to contamination and they have the index that ranges from 130 to 150.

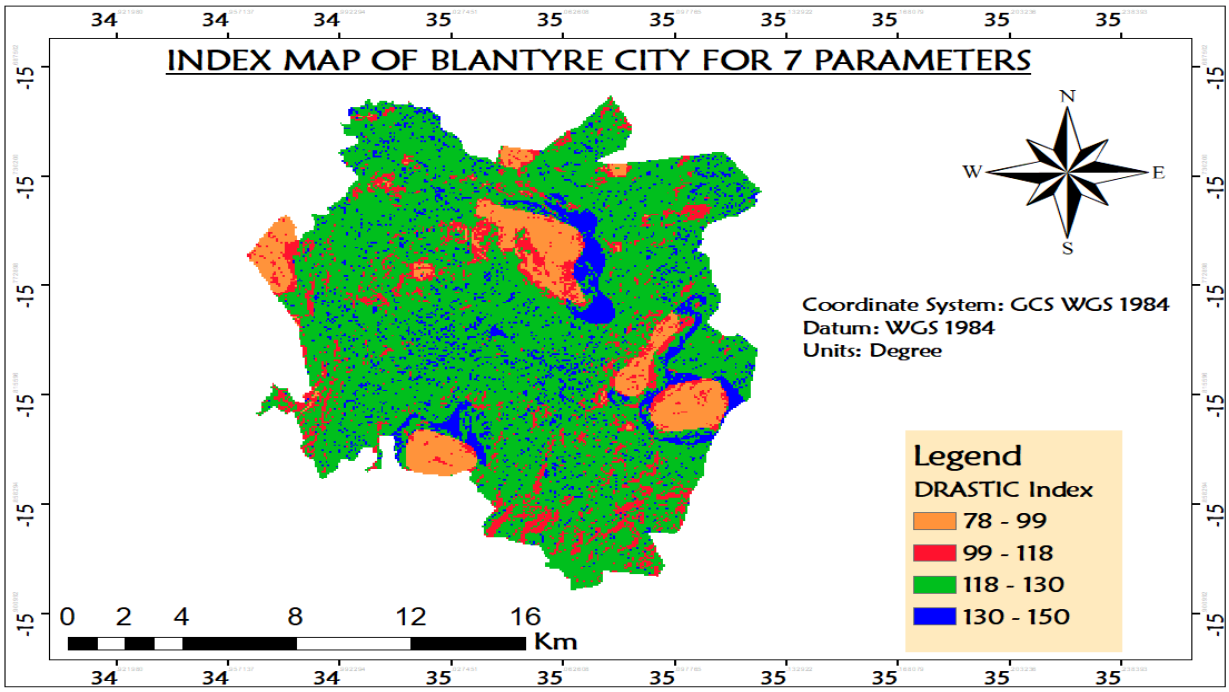


Figure 23: *DRASTIC Index Map of Blantyre City (7 Parameters)*

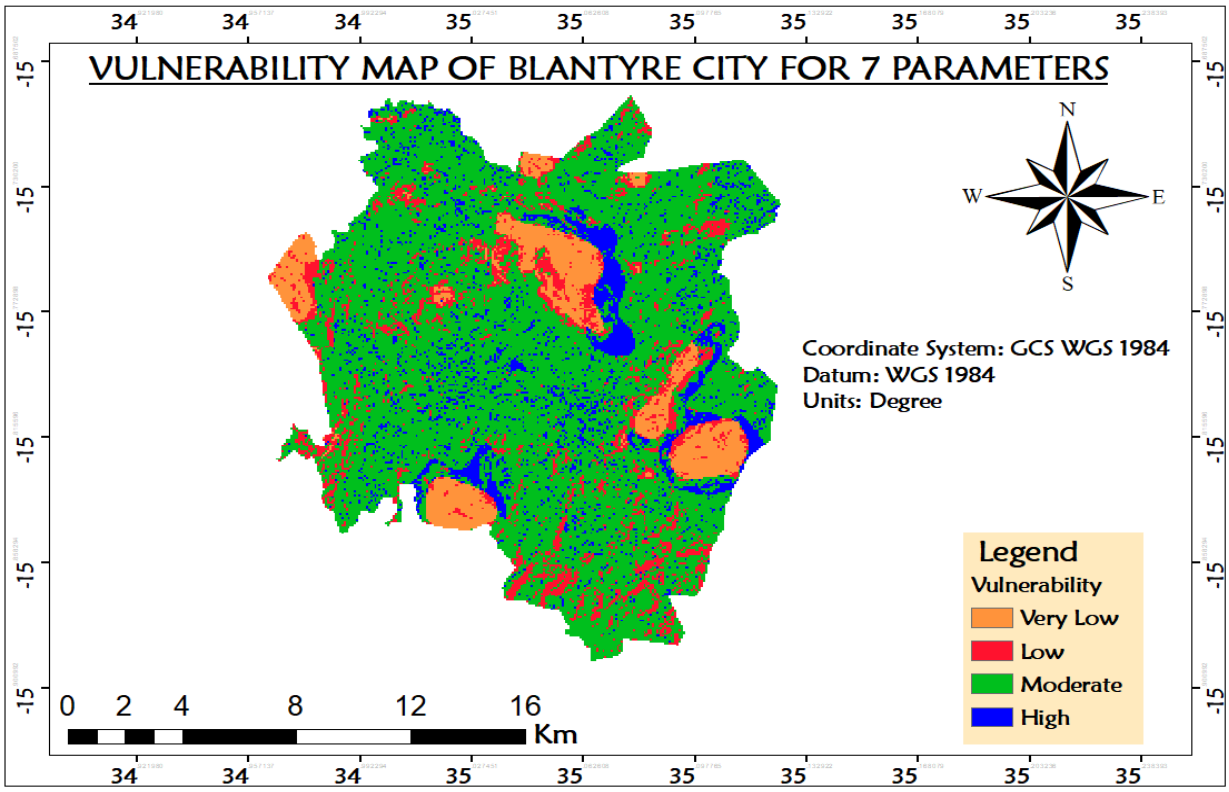


Figure 24: *Vulnerability Map for the seven parameters*

2. The Final Index

This index was made from all the parameters including the 8th parameter (filing station density per km^2). According to Innocent, I., & Massetti, F (2014) in their research found that adding a source of contaminant in their case it was fertilizer used in farms, Sewage waste and other pollutants greatly affected the DRASTIC index. Therefore, in this research Adding the filling station density to the first vulnerability index had a significant effect because this 8th parameter is the main source of contaminants. The final index ranges from 83 to 171 and has been classified into 4 classes using the Natural Break(Jenks) as shown in figure 26. The index is high in the purple zone (146-171) where the filling stations are concentrated while the index range from 124 to 146 cover a large area in Blantyre.

The index for the 7 parameters has 78 as the lowest value and 150 as the highest value while when the filling station density was added the index change with the lowest value increased from 78 to 83 and the maximum value increased from 150 to 171. This justify

the fact that filling stations have a significant effect on the groundwater vulnerability, areas with filling stations are likely to be more vulnerable to contamination. Compared to index for the 7 parameters, the high vulnerable zones in the final index is located at the central and western part of Blantyre city while the first index the high vulnerable zones are located below the hills of Bangwe, Mpingwe, Soche and Ndirande. The final has also a moderate vulnerable zone increased compared to that of the 7 parameters.

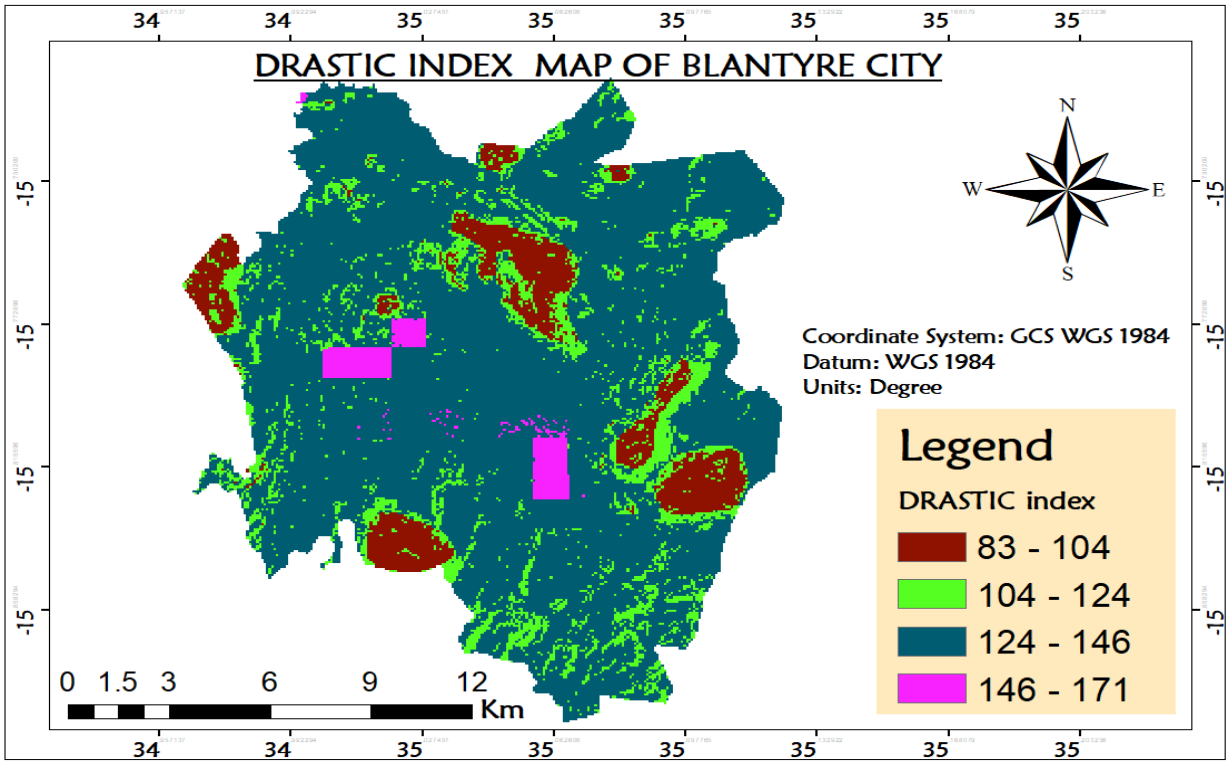


Figure 25: *The Final DRASTIC index Map*

From the vulnerability risk map shown in figure 25, Index ranges 83-104, 104-124, 124-146 and 146-171 have been classified as Very low vulnerable, low, moderate and High vulnerable zones respectively. The study has identified that more filling stations falls within a moderate and high vulnerable zone this can be used to conclude that the filling stations have an effect on the groundwater quality. No filling station is located in a very low vulnerable zone that ranges from 83 to 104 this is so because these locations are hilly with a high steep slope and rocky. In this low vulnerable zones, the net recharge is low because a small amount of water infiltrates as a large amount is a runoff. The groundwater in the

high vulnerable zones needs to be assessed for quality. The figure below shows a final groundwater vulnerability map of Blantyre city and the filling station distribution.

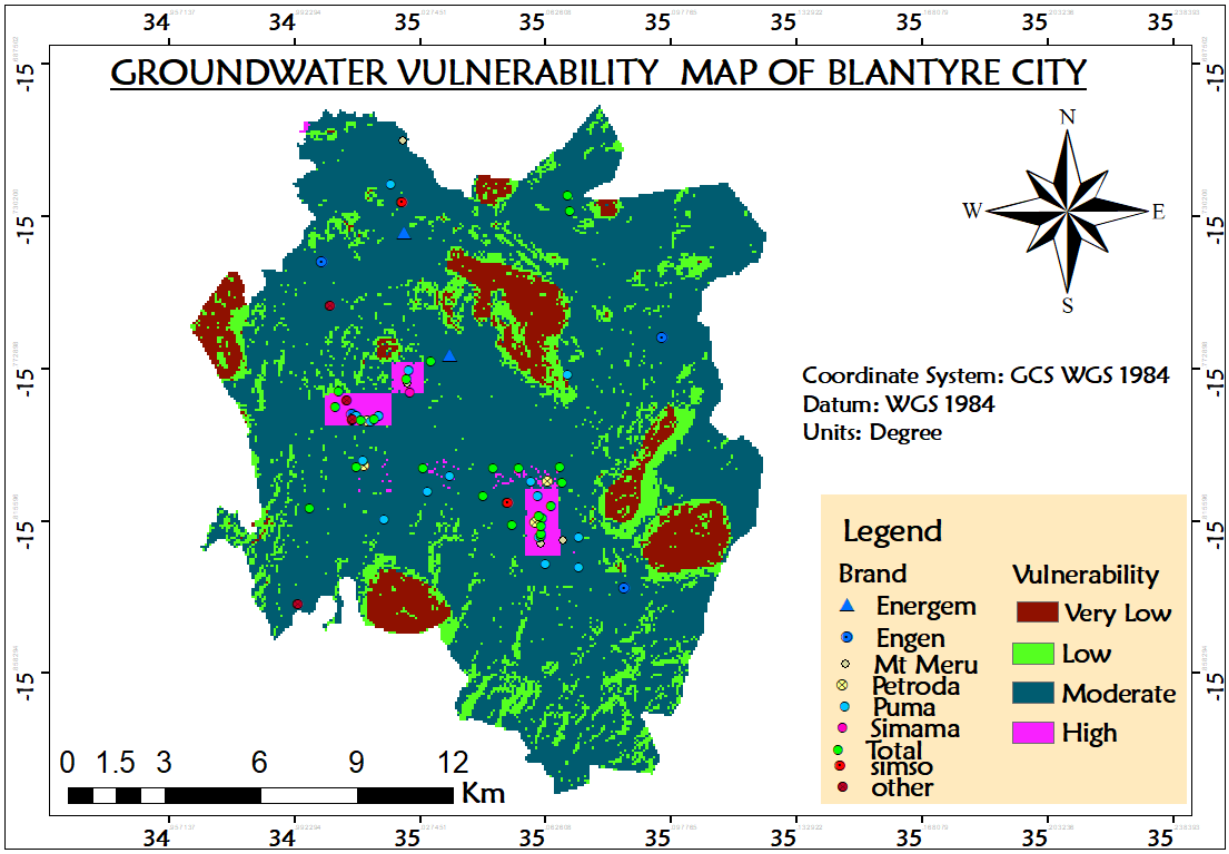


Figure 26: *Vulnerability Map and filling stations*

CHAPTER 5

Conclusion and Recommendations

5.1 Conclusion

This study has evaluated the Blantyre City Aquifer susceptibility to contamination in Malawi using the GIS based DRASTIC model. The Hydrogeology, Soil data, climate data and the Pollution risk were integrated into DRASTIC model to generate the groundwater vulnerability model. From the DRASTIC model the results indicated that large area in Blantyre city is under a very low to low groundwater vulnerability. The DRASTIC index range starts from 83 to 171 which was classified into 4 classes (83-104, 104-124, 124-146 and 146-171) and labeled as very low, low, moderate and high vulnerable zones respectively. The most probable potential sources of contamination from petroleum products are the filling stations. The filling station density were evaluated per square kilometer and combined with the DRASTIC model and it shows that they have a significant effect on the aquifer. The aquifers which are high vulnerable to contamination are located in areas where filling stations are dense populated within a square kilometer. This study clearly shows that the aquifer vulnerability to contaminants depends on depth to water table, Net recharge, Aquifer type, Soil type, Topography of the location, Impact of Vadoze zone, Hydraulic Conductivity and the source of contaminants in this case the filling stations. Different maps were produced for each parameter and all these parameters combined they help to know how vulnerable an aquifer is from contaminants.

5.2 Recommendations

According to this study, Groundwater contamination risk is there in Blantyre city around these filling stations from petroleum products, the study therefore recommends the following based on the results;

1) The underground tanks which stores the petroleum products on the filling stations should be regularly checked to ensure that they are not leaking and are in good condition.

2) MERA should ensure that every newly built filling station should be constructed according to MERA standards and a specified distance should be observed from one filling station to another to minimize the risk to groundwater contamination.
3) The groundwater for these vulnerable zones should be checked for quality assurance. This will help to prevent any carcinogenic effect that can be caused when people uses the water if it has been contaminated.
4) proper measures should be put into place to prevent spillages in filling stations during Loading and offloading trucks and the workers should be sensitized on the importance of keeping the environment free from petroleum products contamination.
5) Future studies should be done to evaluate the net recharge and hydraulic conductivity for every location in Blantyre city and shapefiles should be made so that it can be mapped. This will help to have more accurate DRASTIC model for Blantyre city.

5.3 Limitations

The limitation to this study is the absence of data for a specific location. The data that has not been generated so far, the net recharge data for Blantyre city, the Hydraulic conductivity for Blantyre city and depth to water table for Blantyre city. These parameters estimations were just made using the available data for Malawi, one value was used for the whole location which has limited the accuracy of the model.

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