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USE OF URBAN SURFACE RUNOFF FOR GROUNDWATER RECHARGE IN NAIROBI CITY.

BY

OWEN MICHAEL OMONDI

F56/6686/2017

A thesis submitted in partial fulfilment for the award of Degree of Master of Science in Civil Engineering (Water Resource), in the Department of Civil and Construction Engineering of the University of Nairobi

NOVEMBER 2020

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Name of student:	Owen Michael Omondi
Registration:	F56/6686/2017
College:	College of Architecture and Engineering
Faculty/School/Institute:	School of Engineering
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DEDICATION

This work is dedicated to the residences of Nairobi County, and my loving family- my mother Esther, my father James, my Siblings-Allan, Sophie, Christine, David and my niece Aleinna who their love and support was my source of inspiration. To the Almighty God, for giving me strength and endurance. To God be the glory, Amen.

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ABSTRACT

Surface run-off harvesting systems of collect and store rain-water from rooftops, lawns and street runoffs for later use. While the catchment experiences high run-off in the dry season severe water shortage is experienced. Water crisis keeps looming because of the intense pressure on water resources. Some wells in the upper aquifer within the depth up to 120m below ground level have dried up, indicating depletion.

The objectives of the study were to establish the contribution of groundwater recharge by surface runoff in the mitigation of urban floods in Nairobi. Desk studies were undertaken. Using ArcGIS 10.3 and Boolean Logic function, the parameters of land use cover, slope, geology and vadose zone thickness were analysed, and feasible parameter layer maps were generated. Integration of the feasible parameter layer maps using the Boolean logic function resulted in a feasible area map. The identified feasible areas for groundwater recharge provided for guidelines for planned recharge for the city. To determine urban flood characteristics, Landsat images were used to generate land use cover using ArcGIS. The rate of change in land use was determined. The rational method was used to estimate the run-off potential thus the proportion to be harvested.

Due to non-uniform piezometric level ranging between 30.5m and 120m below ground level, it was evident that the aquifer is multi-layered. 22.57% of the area was found feasible for the planned recharge of the aquifer. For the analysed land use, the available runoff potential proportion was found to be 47.26%. The runoff potential is fundamental as all this water can be channelled to the artificial groundwater recharge. The run-off thus showed the potential of augmenting groundwater in the dry season. The greatest most remarkable outcome will be a reduced rate of aquifer depletion. This is achievable by the implementation of stormwater harvesting to increase groundwater recharge. The study showed a co-benefit of flood mitigation.

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List of Abbreviations

ESRI	Environmental Systems Research Institute
GIS	Geographic Information System
ILRI	International Livestock Research Institute
IWRM	Integrated Water Resource Management
JICA	Japan International Cooperation Agency
KMD	Kenya Meteorological Department
MoTIH&UD	Ministry of Transport, Infrastructure, Housing and Urban Development
MoWI	Ministry of Water and Irrigation
MoWS	Ministry of Water and Sanitation
NAS	Nairobi Aquifer Suite
RWH	Rain Water Harvesting
SCS	Soil Conservation Services
SDG	Sustainable Development Goal
UN	United Nations
UoN	University of Nairobi
USA	United States of America
USGS	United Survey Geological Survey
WHO	World Health Organisation
WRA	Water Resources Authority
WRL	Water Rest Level

WRMA	Water Resources Management Authority
WSL	Water Strike Level

List of units

°	Degree
asl	Above sea level
bgl	Below ground level
Ksh	Kenya Shilling
m	meter
m^3/d	Cubic meter per day
m^3/hr	Cubic meter per hour
MLD	Million Litres per day
Mm^3	Million cubic meter
msl	Mean Sea level

CHAPTER 1: INTRODUCTION

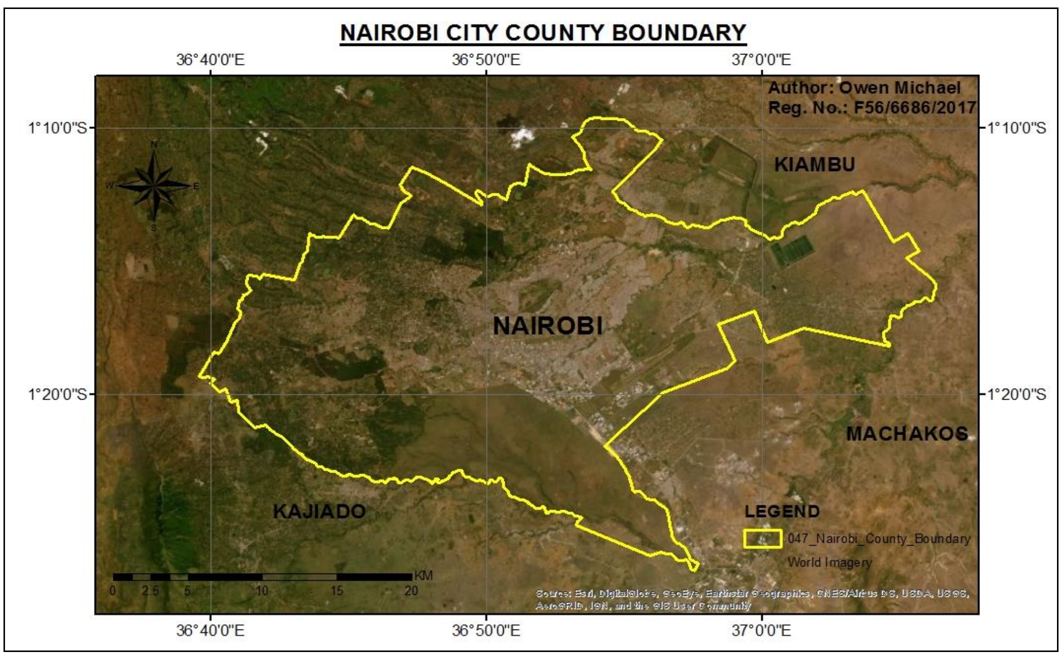
1.1 Background Information

Globally, urbanization continues to exert extreme pressure on water resources (Rokade et al., 2004). In Africa, an unprecedented water demand rate of between 6-9% per annum is being experienced (Lusigi et al., 2017). To meet the growing demand, water must be pumped from locations outside the cities since droughts in these areas cause water shortages in the cities. African cities face droughts and floods alternately. At one time, they are battling excess water in the cities and other times, there are queues of city dwellers seeking water from the few supply points. It is important essential to store water during the rains in the ground, which is the most abundant and cheapest form of storage and use it during droughts. The majority of cities have exhausted the rivers in their neighbourhoods' compounding the problem further leaving groundwater as the only other source of water supply resulting in falling groundwater levels over time due to over-abstraction (Foster et al., 2018; Oiro, 2020; Thomson et al., 2019).

Cities worldwide have adopted different methods that help them deal with run-off (Hammond et al., 2015). Some adopted compulsory rainwater harvesting structures and groundwater recharge structures at an interval of 100m in the drain; sediment control; prevention of solid waste into the drain; planting certain plant tree species like the flame tree, rainwater before it becomes run-off (TNSUDP, 2015). Others used storm drain to channel and discharged in a bay (Seetha, 2012); some adopted green infrastructure, thus slow run-off preventing overflows (CGWB, 2008; Liping et al., 2017). Initially, they used to use the model of combined sewerage and stormwater flows which are ineffective (Ted, 2013). Others implemented channelling stormwater to lakes which are used as recharge points for an underground aquifer.

According to UN Habitat (2006) as cited by Vlahov, Boufford, Pearson and Norris (2010), the city employs about 25% of Kenyans as well as 43% of the nation's urban workforce and contribute 45% of the nation's gross domestic product. Ndakaini, Ruiru, and Sasumua dams supply 75.7% of Nairobi households with piped water (KNBS, 2010). The frequent droughts, climate change, poor infrastructure and inadequate infrastructure management has resulted in regular service disruptions and reduced tap pressures. As a result of this, a significant proportion of Nairobi's population and industries depend on or supplement their water budget with groundwater (CCN, 2007; Jacobsen et al., 2012).

Nairobi City County is the Republic of Kenya’s capital city and economic hub. It lies between 1°17′S 36°49′E and 1.283°S 36.817°E° occupying an area of about 696 km^2 and as shown in Figure 1 and appendix A1 (CBS, 2001). It experiences temperature ranges between 18°C - 28°C. The annual rainfall ranges between 800mm –1,200mm. Nairobi’s altitude varies between 1,600m -1,850m asl (CNN, 2007; Makokha, 2010). The county’s western region is located on high ground ranging approximately 1,700m –1,800m, also having a craggy landscape whereas the eastern region is predominantly low at approximately 1,600m asl and flat (CCN, 2007). The primary water source for the Nairobi City is from the Tana basin being the greatest contributor of surface water (UNEP, 2009).



[Source: Owen, 2019.]

Figure 1: Nairobi City County administrative Boundary Map

Opere (2013) found that floods remain an important concern in Kenya just as it is in other parts of the world. It has turned out to be a risk and even to the degree of a calamity. Nairobi County has over the recent years experienced flash floods, resulting in destruction, loss of life and assets (Doocy et al., 2013); hence, there is need to save excess rainwater for the dry time. Various stakeholders are abstracting groundwater in Nairobi city in increasing capacity towards complementing the Nairobi City County water supply. The rapidly growing number of wells has progressively led to subsiding water-table and increased pumping costs (Koei, 2013; Oiro et al., 2020). Groundwater usage has become more critical in providing substantial amount of water for the briskly increasing city inhabitants besides being a strategic reserve during the drought period.

Borehole exploration began around early 1930 as stated by Thomas et al. (2019). It progressively expanded to a projected 85000 cubic metres per day by 2002, which amounts to about 25% of the total water supply for the larger Nairobi city residents. Several private borehole owners remain connected to the Nairobi City mains water supply system that offers low-priced water while still using the borehole water as a back-up source. The drilled borehole capacity ranging between 300-350MLD is considerably higher than actual abstraction that's estimated at about 150,000 cubic metres per day by 2017 (Foster et al., 2005; Oiro, 2020) against an estimated recharge rate of 5% of precipitation according to Koei (2013).

The primary use of groundwater remains domestic water supply, a complementary source to Nairobi City Council mains. The availability of groundwater as a 'back-up resource' for emergency conditions will contribute significantly to the overall water supply realibility. There are reasons why this function should be conserved and enhanced: - Firstly, the two main reservoirs are where the most significant portion of the surface water supply emanates from and to some extent disruption on any of the supplies usually results in an extensive breakdown of water supply. Secondly, surface reservoirs are vulnerable to drought effects, besides the water supply capacity does significantly reduce, as presented in Appendix A2 of Ndakaini Dam throughout the latest drought.

Some studies found an average recharge within the Nairobi catchment region being 17mm per annum (Mumma et al., 2011) others 15 to 120mm per annum (ISC, 2019; Koei, 2013). The groundwater level has been reported consistently to be in decline. According to Foster and Tuinhof (2005), it is not feasible for long term abstraction of large volumes as the deeper aquifer is increasingly being exploited thus the need to recharge the groundwater artificially.

Foster and Tuinhof (2005) found out that Nairobi aquifer recharge occurs through the infiltration of mains water supply leaks, excess precipitation in addition to wastewater leaks. Total water supply network leakage has been assessed to be about 180 MLD; nevertheless, it is challenging to approximate the quantity reaching groundwater. Localized perched aquifers have been intercepting a portion of the infiltration precipitation and discharging locally to streams as well as springs.

There is an increased surface runoff in the Nairobi city area. Increased roof and impermeable ground cover not matching a drainage capacity have resulted in reduced seepage area, increasing run-off within the city; thus, it's partly why the city experiences flooding as shown in appendix A2.

1.2 Problem Statement

Surface runoff has been a menace within the city, though it remains an un-exploited water resource. Managing it during a rainy period has been a great challenge as it remains under-utilized. The city's major problem is the lack of sustainable water supply (Famiglietti, 2014; Lusigi et al., 2017). According to Oiro (2020), rapid development has led to over-exploitation of groundwater as an average of five borehole permits are made to Water Resource Authority (WRA) daily. This has resulted in adverse effects of declining groundwater level - high drilling and pumping costs; water quality is diminishing due to the higher concentration of salts and minerals of the water due to over-abstraction of groundwater. There is a need to mitigate these two situations affecting the city simultaneously. The lack of guidelines for planned groundwater recharge in the city and the country at large remains a challenge. Poor planning guidelines application and enforcements have affected the city's overall quality of life concerning water supply plus stormwater management systems (CCN, 2007, WaterFUND et al., 2018).

This research addresses the challenges posed by the nexus of natural disasters- flooding and drought in the city that result in health issues, namely the prevalence of infectious diseases resulting from unlimited and unsafe water (Baariu, 2017). This research aims to provide a guideline for identifying feasible areas for planned groundwater recharge points by use of surface run-off in the city, thus mitigating the issue of flooding and drought, negative effects of the decline of groundwater level, and wells exploiting surface run-off in the city. Given the above, the overall impact of floods will be reduced as it can be used to recharge the groundwater, increasing the groundwater level generally, exploitation of stormwater as a water resource.

1.3 STUDY OBJECTIVES

1.3.1 General objective

The overall objective is to estimate the potential of groundwater recharge by surface runoff in the mitigation of urban floods in Nairobi.

1.3.2 Specific objectives

The specific objectives of the study were:-

a) To determine aquifer configuration and exploitation in Nairobi.
b) To identify feasible areas for the groundwater artificial recharge techniques.
c) To characterise urban flood in Nairobi.
d) To establish flood proportion that can be harvested for groundwater recharge in Nairobi.

1.4 Justification for the Study

Nairobi County has and is developing at an exceptional rate. Its sprawling expansion outstrips the public utilities ability to accommodate the skyrocketing demand for water and sanitation amenities. It is becoming a norm for new residential communities to assume total management of their own water and sewerage amenities through residential welfare associations. The majority of them rely on the boreholes and tankers they sooner realise are not a sustainable option- as they are expensive and the source of water unknown. In line with Sustainable Development Goal (SDG) Goal Number 6, the water deficit already experienced and being a water-scarce country, reliance on groundwater is growing to meet this high demand due to unreliability of surface water from the Tana basin. (Mitulla, 2003).

Groundwater recharge can be a great contributor in realizing long-standing water security being one type of rainwater harvesting. Excess water can be channelled from storm drains and used in replenishing shallow aquifers. Through the groundwater recharge, flood intensity decreases while the water table increases. There is a dire need to store excess rainwater sufficiently for the dry time. Stormwater runoff increases proportionally to an impervious surface layer due to land development (Miller, 2006). The drying up of wells within the Nairobi aquifer is a clear indication of reducing groundwater level (WRA, 2020); therefore, the need to store excess water instead of releasing it to the drains for use over the dry season. The sustainability of the aquifer can be improved by planned/artificial recharge. Therefore, groundwater recharge is critical in mitigating floods, which have been a nuisance around the city after a medium to a heavy rainfall event.

1.5 Scope of the Study

The study proposition is centred on Nairobi City County groundwater and the flooding menace it experiences during the rainy seasons and severe water shortages during the dry season. The research focuses within the areas of Ruaraka, Starehe, Dagoretti North, Roysambu, Makadara, Embakasi North, Mathare, Dagoretti South, Langata, Kibra, Embakasi South, Kamkunji, Embakasi Central, Embakasi West, Kibra, Westlands, Kasarani and Embakasi East sub-counties as being the Nairobi County's administrative regions as in Figure 1 and appendix A1. To achieve the research objectives, an extensive literature review regarding the aquifer and quantifying potential run-off proportion while researching the flood characteristic then attempting to find out techniques of utilising the runoff for planned groundwater recharge within the research study area. Lastly, a detailed research report summarizing the results of the exisiting condition was prepared and recommendations given for further research.

CHAPTER 2: LITERATURE REVIEW

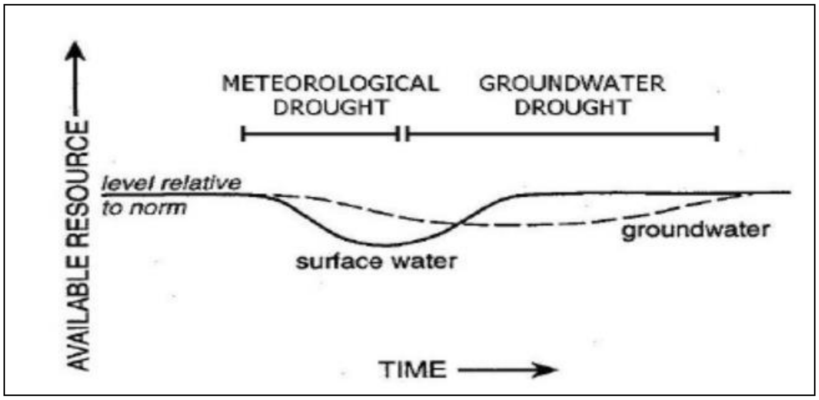
In this chapter, an overview of previous research and literature reviews are undertaken, Background about water, sustainable development goals, climate change, aquifer recharge is introduced, GIS application in mapping explained, and highlights of run-off and stormwater quantification.

2.1 Water

Water is a finite resource. It is the most critical resource in our lifetime and our children's lifetime. Water covers approximately over two-thirds of the surface of the earth. On the international front, freshwater is gradually becoming a scarce resource. It is partly resulting from population increase coupled with changes in climate and consumption/use pattern. According to Guterres (2018), over 1.1 billion persons have inadequate access to clean and safe drinking water worldwide. Climate change causes a change in the frequencies of droughts and floods.

2.2 Climate Change

Climate Change refers to the permanent shift in conventional climatic space-time patterns. For example, change from one climate mode to another climate mode which is outside the normal range of natural climate variability regardless of the causes (Laurini, 2018). It manifests itself by modifying evaporation and rainfall patterns in the river basins and altering the hydrological balance. Changes in mean annual rainfall as well as temporal and spatial distribution influences the water balance as a whole and groundwater recharge. According to Huong and Parthirana (2013), Climate change causes rests with developed countries; however, its implications directly affect all nations. Groundwater responds much slowly slower to changes in the meteorological condition than surface water and due to its resilience, provides a natural buffer against climate variability as in Figure 2 (Calow et al., 1997). Drought as an intermediary to climate fluctuations/variability is the climate deviation from an average long-term meteorological over a given duration. Changing climate induces changing groundwater resources availability and utilization.



[Source: Calow et al., 1997]

Figure 2: Meteorological conditions relating to groundwater response

Climate change scenarios that are likely to occur:- First, the temperatures are presumably going to expand: Throughout the twentieth century, Africa has experienced warming at a rate of about 0.5°C and the warming rate has extended as of late (Taylor et al.,2013). Secondly, the southern and north parts of Africa experienced a reduction of annual precipitation, whereas the eastern part of Africa experiences the inverse and thirdly, rainfall is likely to become increasingly predictable in terms of both intensity and duration with increasing frequency of extreme events. Notwithstanding the world's normal precipitation changes, there could be progressively articulated changes in precipitation qualities because of global warming. Averagely, the precipitation will, in general, be less continuous, however progressively intense, point towards a more prominent occurrence of outrageous droughts and floods, with resulting consequences for water storage.

There are indications that Nairobi City is undergoing climate change, just like many other urban areas globally, and this can be a severe challenge to the accomplishment of the city's sustainability. The current rainfall occurrence in the city is above average compared with previous years. Ongoma, Muthama and Nganga (2010) found that Nairobi receives rainfall for all intents and purposes every month with exceptionally high rainfall amounts being encountered every four to five years. This observation is beneficial for urban planning. The city's minimal temperature is rising at a higher rate than the highest temperature. The modification of the city's climate to factors of urbanization -rapid population growth, expansion of the built-up area, industrial development, increasing vehicular traffic, and reduced vegetation cover have altered the urban energy exchanges, water balance, and prevailing wind speeds and sometimes wind direction in the city.

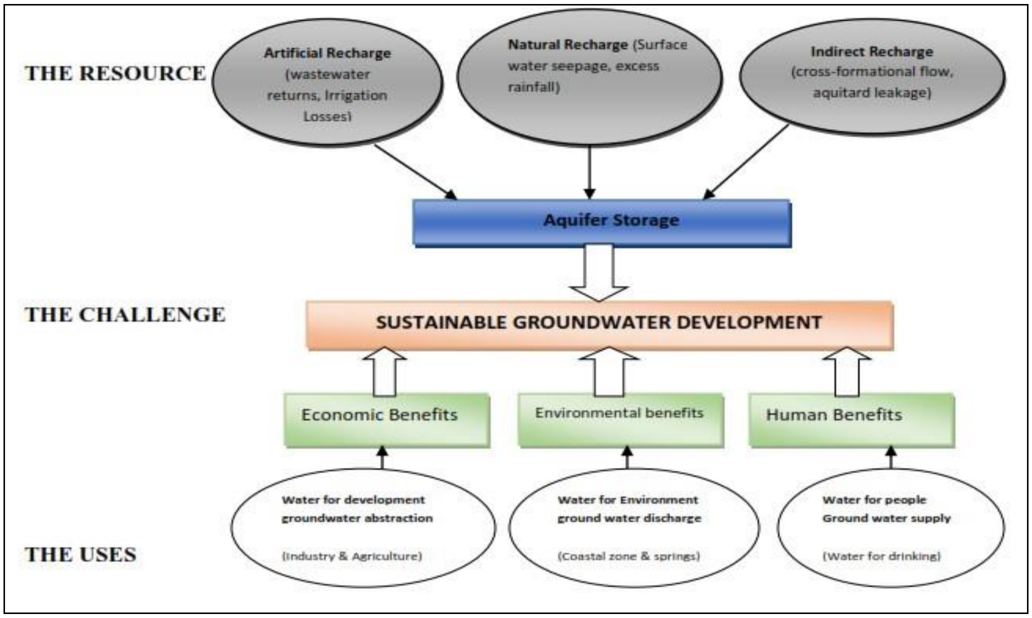
2.3 Sustainable Development Goal (SDG)

Sustainable Development Goals (SDG) was a plan visualised and opted by the United Nations (UN) in the convention in 2015. It envisions seventeen goals to be achieved by the year 2030. Various nations' leaders envisioned towns, cities overwhelmed by poverty, dry spell, war, and floods. They planned for future cities that would be safe from effects of climate change and still get rid of hunger and poverty (United Nations, 2018).

Africa is blessed with abundant groundwater resources. The resource remains the most under-developed in many parts of African. For successful climate change adaptation and SDG achievements, it's vital to undertake sustainable use and utilisation of groundwater. Poor management of wastewater, water scarcity and flooding also hinder economic and social development. In balancing the growing and competing water demands for various uses, it's critical to increase and improve water efficiency and management of water. In over twenty-two nations within northern Africa, central-western and southern Asia regions have about seventy percent water stress levels (Guterres, 2018). An indication of the high possibility of future water scarcity. According to Guterres (2018), sustainable cities can be conceptualised as "place(s) of a greater life quality, in tandem with policies and strategies that effectively moderate the demand for resources drawn from the city's vicinity in this way making manageable city move towards being a progressive self-sufficient economic, environmental and social systems".

Urbanisation being inevitable; thus, rather than slow it down, we must address the main challenge of learning how to deal with the rapid growth. According to University of Nairobi (UoN) (2018), more needs to be done to achieve sustainability. Some of Kenya Vision 2030 goals are first medium-term plan meant to realise increased access to clean in addition safe water, sanitation; adequate housing, better livelihood for slum dwellers as well as integrated regional and urban planning management. The important way of achieving sustainability is through consultations and integrating various urban development aspects, as illustrated in Figure 3. This can be realised through the following provisions in the United Nations (UN) SDG goals, especially goals number

6, 11 and 13 (Guterres, 2018); Kenya Vision 2030 and urban areas and cities Act of 2011. Once these are addressed adequately, Nairobi will be a model city in East and Central Africa as a tourist destination and economic hub.

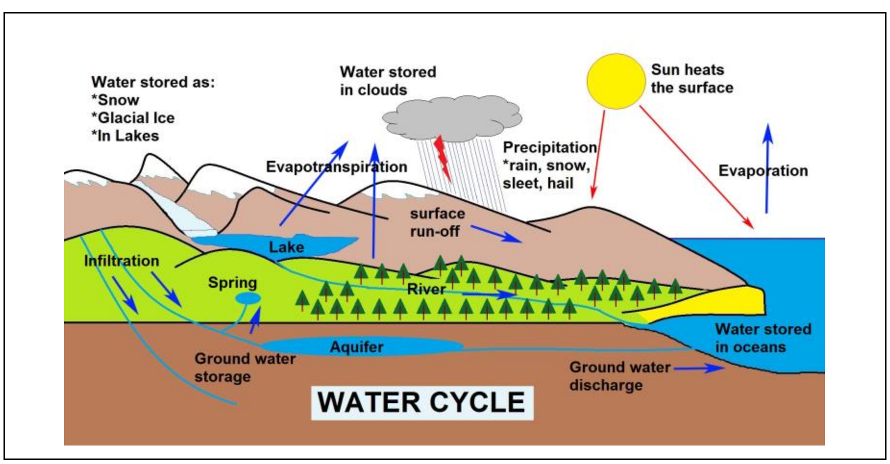


[Source: Hiscock, 2002]

Figure 3: Sustainable Groundwater Development Plan

2.4 Groundwater

The groundwater is a significant feature of the environment and a part of the hydrologic cycle as in Figure 4; therefore, an understanding of its role in this cycle is necessary if integrated analyses are to be used in the study of watershed resources and regional assessment of contamination (Freeze et al., 1979).



[Source: National Groundwater Association ©2007]

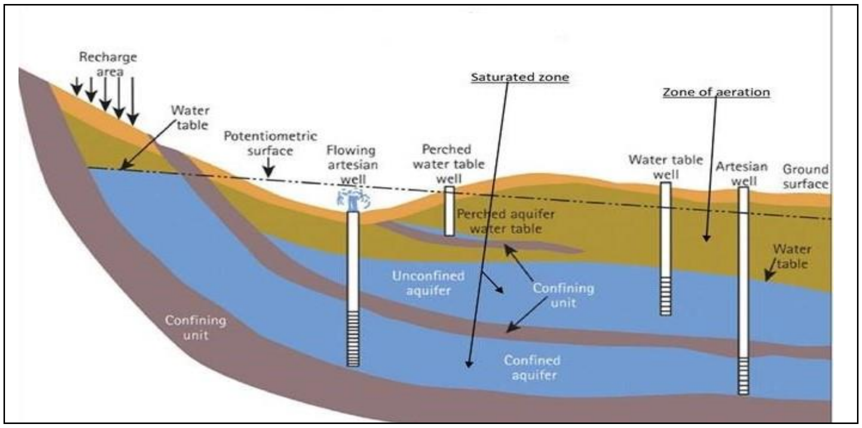
Figure 4: Hydrological cycle

Hydrology involves the study of water of the earth- its precipitation, its movement over and below the earth's surface, its evapotranspiration from the land, water and plants and its subsequent condensation and precipitation (Todd et al., 2005). The only portion of rainfall upon a catchment area will appear in the form of direct runoff. According to McGhee (1991), groundwater is a portion of rain that percolates down the soil until it reaches the rock material that is saturated with water. Water in the ground is stored in the spaces between rock particles. Groundwater moves slowly underground and may finally seep into streams, rivers or lakes.

Vaporization and transpiration is the process through which a portion of sub-surface water returns to the atmosphere. Some surface water infiltrate till it reaches less or totally impermeable formations and others are held through capillary forces. Groundwater refers to water confined by aquiclude and flows to springs, boreholes and other retrieval points (McGhee, 1991). In the world, one main domestic use water source is groundwater. According to Foster et al. (2018), the reliance of groundwater use for the daily water supplies is almost by 50% of Africans. The surface water shortages among the African communities have resulted to adaptation of groundwater to bridge the deficit. Usually, excess groundwater abstraction does lead to polluted water ingression, subsidence of land, the intrusion of saline water, compaction and transmissibility reduction of the aquifer (Adelana et al., 2008).

2.4.1 Aquifer

As per McGhee (1991), an aquifer refers to the groundwater bearing formations that are sufficiently permeable to yield of usable water quantities'. The degree of porosity and permeability in all rocks determines the amount of water it contains. There exist two types of rock classification – non-water bearing or aquiclude or aquifuges and water-bearing or aquifers or aquitards. Water table/ Phreatic surface refers to the highest point of the saturated zone within an aquifer. According to McGhee (1991), the water-bearing formation between less penetrable formations is referred to as a confined aquifer in Figure 5. Water flowing in an unconfined aquifer is akin to one flowing through an open channel, while flow in a confined aquifer corresponds just as in pipes.



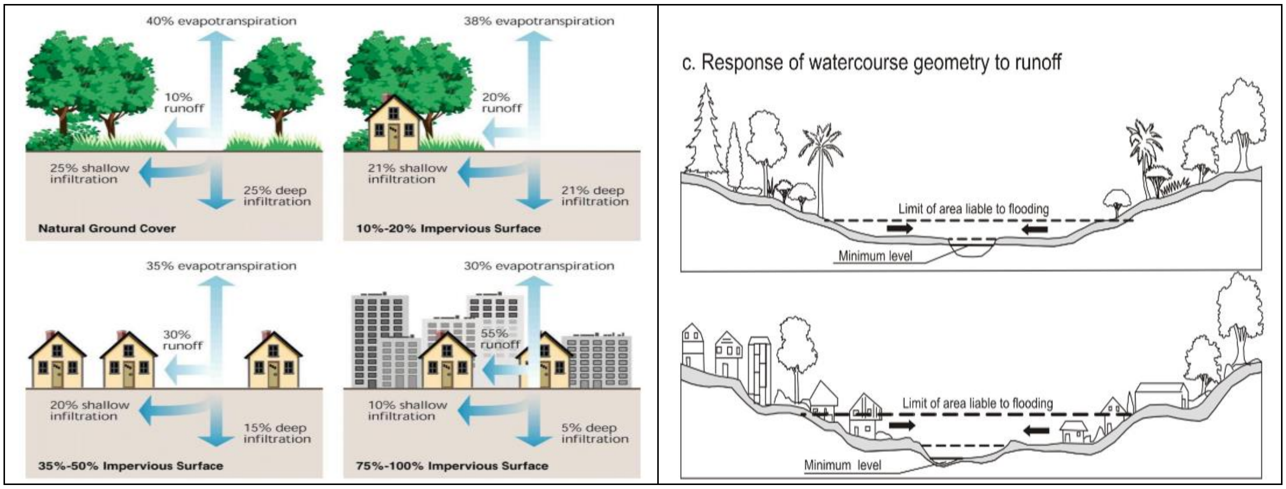
[Source: National Groundwater Association ©2007]

Figure 5: Flows and profile of Underground water.

Piezometric surface refers to water height rise attained in a tube penetrating a confined aquifer (McGhee, 1991). For flow to take place, a hydraulic gradient must exist. Groundwater flows usually from topographic highs to topographic lows. According to Gurcharan and Jagdish (2013), the flow velocity is directly proportional to the hydraulic gradient and inversely proportional to aquifer permeability; The hydraulic gradient range of 0.00125 to 0.0025 results in groundwater flow velocity varying from 0.0001m/s to 0.0002m/s, especially for in gravel aquifer.

2.5 Rainwater and Storm water

Rain remains predominantly the freshwater source globally. Stormwater is generated when the intensity of rainfall is more that is more rainfall takes place in lesser time, rainwater will have very little chance for evaporation and percolation, and more quantity of rainwater becomes available (Gurcharan et al., 2013). Urban areas experience increased occurrences of flooding worldwide, causing repeated damage calling for flood management (Baariu, 2017; Hammond et al., 2015; Simões et al., 2011). Precise run-off estimation is elementary and essential in designing recharge structures with the best possible capacities. Unrealistic assessments of run-off for catchments yield results toward the designing and construction of oversize or else undersized structures, needs to be eluded. Stormwater quality, as well as quantity, is affected by both urbanization and development the increased impervious surface results in decreased infiltration of a substantial amount of water, as illustrated in Figure 6.



[Source: WMO, 2008]

Figure 6: Watercourse geometry response to runoff due to urbanization and Influence of Urbanization on the hydrological cycle

Most Urban cities depend on municipal water for domestic use, which is practically not enough for all households as it is challenging for the government to supply every family (Doughlas, 2008; Huong et al., 2013). As far as water balance, the vast capacity of water gathered from structure tops causes runoff on the impervious concrete and tarmac surfaces, thus increasing the incidence of flooding in the city as in Figure 6 (Maksimovic et al., 2009; Odhiambo, 2015). Based on study by Odhiambo (2015) which reveals the South C area had a 49% impervious layer, this was attributed to an increased run-off. One of the problems to address to achieve sustainability of a city is excessive runoff, which causes the environmental concerns of flooding and the resulting disease outbreaks due to inadequate access to clean and safe drinking water and poor hygiene. Rather than allow this water to kill people, as often happens, we can collect it in dams and use it to enhance the city's vegetation cover, or even purify it for other uses. Continuous urbanisation brings about more rainfall wastage that can be utilized in groundwater replenishment.

Groundwater recharge is an important aspect of rainwater harvesting. In water harvesting, it is the best way to support both the surface and subsoil water sources. Rainwater harvesting is mainly done for two main reasons: First, to store water for future use. Secondly, to recharge the ground. There is a different approach to harvest rainwater; one way may be to divert the rainwater that falls on the terrace into open wells in absence of an open well a percolation or a leaky well might be burrowed next to building to infuse the rainwater for groundwater recharge (Seetha, 2012;

TNSUDP, 2015). A leaky well depth depends on the soil on the site as well as the amount of water it is to receive for recharge during heavy downpour. The rooftop water not only ought to be diverted to the leaky well but also the storm water after passing it through a simple gate trap arrangement to catch all the silt and debris. Once in a year or two, the recharge wells ought to be de-silted (MWR, 2007; TNSUDP, 2015). Leaky wells do not just guarantee that the rainwater falling on your premise is not wasted by mixing with the sewerage or as runoff to the streets. Ahammed, Hewa and Argue (2012) states that in the event that the stormwater channel is directed towards the leaky well, ensure no nonpoint pollution coming in. Precaution measure has to be taken into account inlet of the leaky well or at the point of entry of the stormwater. In case of an accident scenario where there is an oil spill or sewerage, the inlet should allow for closure or capping so the contaminated water can flow downstream without flowing into the leaky well with the hope of being treated at the appropriate point (MWR, 2007).

According to World Water Assessment Programme- WWAP (2017), in developed economies, the storm water is controlled through channelling to the wastewater treatment plants. This is achieved through consolidated sewers as mutually stormwater and wastewater (Ted, 2013). Rainwater Harvesting (RWH) is being implemented in various nations. It is acknowledged as one of the top accomplishments in the Integrated Water Resource Management (IWRM) in this manner RWH is a noteworthy tolerable water resource contributing in bridging the shortfall in water resources particularly in water deficiency countries (Hamdan, 2009).

2.5.1 Run-off and estimation of run-off

Runoff can be identified as an important resource to bridge the gap between water resources demand and supply. It can be used to recharge the groundwater for future use during the dry seasons. The runoff increases due to urbanisation. There are three available techniques of estimating run-off which are rational method, SCS technique and the empirical method. The rational method is the simplest method of three methods. It is used for storm sewer design, it assumes that precipitation intensity remains constant and evenly spread over a region and the effective precipitation falling on the basins far-flung section takes a certain time period or time of concentration (T_c) to reach an outlet of the basin (Chow, 2012). The empirical method created from rational runoff formula. The latter is used in estimating the average annual amount of stormwater (Kiely, 1996), which is given as shown below: -

$$Q = C \times I \times A \quad (2.1)$$

Where: -

Q: Amount of runoff (m^3).

I: Intensity of rain (m/s).

A: Catchment Area (m^2).

Overall surface runoff quantity for zoned area can be computed as summation of the quantities from each zoned area: -

$$Q = \sum \{Q_{Z1} + Q_{Z2} +, \ldots, + Q_{Zi}.\} \quad (2.2)$$

For each region, projected storm water can be computed based on the rational formula: -

$$Q_{Zi} = I_i \times \sum C_{fi} \times A_{fi} \quad (2.3)$$

Where: -

Q_{Zi}: Amount of storm water in zone number i (m^3/s),

I_i: mean yearly precipitation in rain station representing zone number i (m/s).

C_{fi}: runoff coefficient of land surface type of land use category (f) in zone i;

A_{fi}: area of land use category (f) in zones i (m^2).

Table 1: Runoff coefficient for various surfaces

SURFACE TYPE	RUN-OFF COEFFICIENT, *f*
Roof tiles, corrugated sheets,concreted bitumen, plastic sheets	0.8
Brick pavement	0.6
Compacted Soil	0.5
Uncovered Surface, flat terrain	0.3
Uncovered Surface, slope >0-5%	0.4
Uncovered Surface, slope >5-10%	0.5
Uncovered Surface, slope >10%	> 0.5

[Source: MoWI 2005 Design Manual for water]

Realistic storm water can be projected for existing as well as future planned land use, thus runoff coefficient (*C*) varies for various land use types in the two scenarios (Hamdan et al, 2007). An effective runoff coefficient for a composite drainage area can be obtained by estimating the percentage of the total which is covered by roofs, paving, lawns etc., multiplying each fraction by the appropriate coefficient as provided for in Table 1 and then summing products as detailed in equations 2.2 and 2.3. The rational method may still be useful for designing drainage improvement for the restricted area (McGhee, 1991).

2.6 Recharge of Aquifers

The region within which water enters an aquifer is referred to as recharge area. The faults, sinkholes, fractures or soil infiltrations is where the water infiltrates into the aquifer and this practise and process is what is termed as recharge (Rokade et al, 2004). As per American Society of Civil Engineers - ASCE (2001), the deliberate modification of natural recharge pattern with an aim of increasing recharge is referred to as planned recharge. Planned recharge is the process by which the surface water is transferred to the aquifer through human interference (MWR, 2007).

An aquifer recharge afforded by natural hydrologic processes is sometimes deliberately augmented either to create barriers to other flow or to restore water to the aquifer for other use. Groundwater recharge through land disposal of treated sewage is an alternative which is routinely considered in wastewater facility planning (Reed, 1972). The recharge of aquifers is undertaken to maintain or augment natural groundwater as an economic resource, to combat progressive depletion of groundwater levels, to conserve surplus surface water underground, and also to combat un-favourable salt balance and salt-water intrusion. Groundwater supplies and individual wells can be soiled by surface water for the duration of torrents and through waste material percolation through the soil. Wells are protected against contamination from flooding by careful construction techniques that require the casing be grouted down to the first impermeable stratum, that the casing extends above the surface of the ground and that a concrete apron protects the surrounding the casing. It is impractical to guard against contamination which enters the aquifer at points remote from the well (McGhee, 1991; MWR, 2007).

The main advantages of planned groundwater recharge are sub-surface storage space is available at no fee and flood stays circumvented, negligible evaporation losses, high organic purity, improved quality by infiltration through penetrable media. It has no adversarial societal effects for example population displacements, it is an environmentally friendly, loss of already scarce agrarian land, flood and soil erosion controls, minimal temperature variants, provides sufficient moisture in the soil even during warmest season, water kept underground is somewhat invulnerable towards artificial and natural catastrophes, offers a natural distribution system between discharge and recharge points. It consequently saves energy owing to delivery and suction heads decrease by means of shallow water levels (MWR, 2007).

According to Parghane, Kulkami and Dhawale, (2006), high hydraulic conductivity results to high recharge rate however ability to clean recharge water is low. Recharge process needs to be done using clean water. A large aquifer grain size tends to result in very hydraulic conductivity values. Fracture spacing, inter-connectedness, and size openings controls the hydraulic conductivity. The recharge is significant in regulation of the groundwater volume. It is influenced by land use changes, the rainfall intensity, magnitude, seasonality and frequency. Reduced recharge will result in reduced renewable groundwater volume. The effects of climate change has made people to over-abstract renewable aquifers and hence depletion of storage.

2.6.1 Fundamental elements playing a vital purpose in groundwater recharge naturally or artificially

The selection of appropriate technique necessary for enactment in a specific region is rather challenging based on the factors that influence locally and involved parameters. The fundamental elements that influence artificial groundwater recharge techniques is elaborated in subsequent subsections.

2.6.1.1 Vadose thickness

It refers to the region between the water table and land surface. It has an inverse proportionality to recharge. Greater vadose thickness results in less recharge rate. The marshy area usually indicates that vadose thickness is too small. Usually the first three meters are not considered to recharge aquifer because of logging and salinization effects (MWR, 2007).

2.6.1.2 Slope

The fall and rise of landscape refers to the slope. Slope generally governs run-off, erosion as well as alluvial transport, infiltration rate. For a minimum slope, maximum infiltration occurs and thus flat areas facilitate higher infiltration rates thus becomes suitable areas unlike areas with great slopes. It is usually one of the key deciding factors in the choice of planned recharge technique (McGhee,1991).

2.6.1.3 Land use cover

It is an extremely vital parameter in the identification of the potentially feasible area for planned aquifer recharge. Vegetation usually draws their water needs from the saturation zone, others from absorbing soil moisture in the aeration zone. Presences of xerophytes indicate a scarcity of groundwater at shallow depths.

2.6.1.4 Soil texture

Permeability of soil greatly controls groundwater recharge depends mostly on areas geology. When there is large soil permeability, surface planned recharge techniques can be chosen. When the permeability is small then sub-surface recharge techniques are chosen. Geology influences infiltration and percolation rates plus the water flow preferential paths (Raghunath, 2014). Broad alluvial fan and glacio-fluvial deposits, formations of sand, gravel or vastly fractured rocks either underground or exposed over a large surface area or in stream channels play key roles in recharge.

2.6.1.5 The nature of aquifer

The type of aquifer plays a key role as there should not be any barrier for horizontal or vertical movements of groundwater. Porosity and specific yield are the key properties of an aquifer related to its storage function which forms one of the important purposes for implementation of planned recharge systems (MWR, 2007; Raghunath, 2014).

2.6.2 Techniques and procedures for artificial groundwater recharge

The various kinds of procedure and techniques for artificial groundwater recharge have been recognized and well-articulated in the various scientific research publications reviewed (CGWB, 2011; IGRAC, 2007; MWR, 2007). Appendix A3 presents the strategy and techniques collectively with the scenarios worldwide in area and regions it has been undertaken.

2.7 Geographical Information System (GIS)

According to Okoth (2018), Geographical Information System (GIS) is a computer-based software empowers user/operator to understand required data, collect, store, manage, scrutinize, analyse and present it as a spatially referenced information for candid decision making in a more user-friendly format. Saving water, saves time results to saving money. According to ESRI (2019), the basis of intelligent water management is GIS. GIS plays a key role in spatial decision making through the Boolean application and the approaches of weighted intersection to the problem of spatial decision making. It can be used to determine the suitability of areas for a particular use. GIS can be used to produce the areas of the polygon of land use. Suitability of an area for a particular use was one of the focal motivation for development of the GIS. Suitability analysis is used to depict combinations of specific characteristics for various described regions. Its output is thematic or suitability map. Decision making is used planning process thus in simple suitability analysis, the logical combination of false/true information often leads to a more or less straightforward solution.

2.7.1 Boolean Algebra

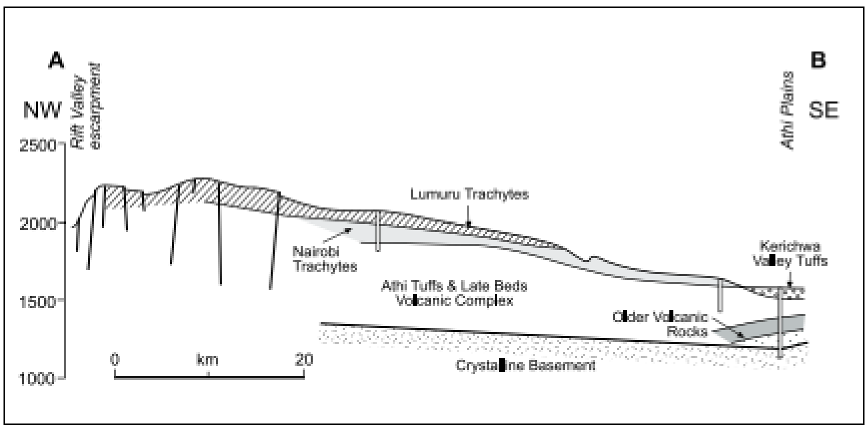
The binary logic operations essentials facilitated the establishment of Boolean algebra. It was found on the basics of binary logical operations, forming a mathematical structure based upon two values one and zero. It is mathematical-type dealing with truth conditions but not with numbers. It handles operations that link two truth conditions as input values together and results in another condition of truth. The most simplest way explaining Boolean operators is through Venn diagrams (Edwards, 2004).

2.7.1.1 Boolean Overlay

Boolean overlay a spatial query method common in analysis function in GIS. It was found on the assumptions that different combinations can be either “false “or “true” but under no circumstances both. It is an intersection of binary coded data layer that uses the Boolean operators intersect, union, exclusive union, and erase/ negation usually containing data layers with areas that are false and other true in many GIS software (Zaidi et al, 2015). New informational layer results from the spatial intersection.

2.8 Geological morphology

The Nairobi City County is widely covered by Tertiary volcanic rocks according to Schackleton (1945) as cited by Saggerson (1991a). The County geological morphology has a stratigraphic order beginning with Limuru Trachytes, Kerichwa Valley Tuffs, Nairobi Trachytes, Athi Series, Kapiti Phonolites forming the stratigraphic order of the local morphology of the geology as Figure 7. Limuru Trachyte is the thickest lava layer going to a depth of about 152m, with intercalated with trachytic and agglomeratic tuffs as in Figure 7. It is a soft, rarely fissile member, highly porphyritic with truncated feldspar laths in a pale groundmass. Kerichwa Valley Tuffs consist of the pyroclastic ash and pumice flows, trachytic tuffs and agglomerates, it largely covers the Nairobi area (Saggerson, 1991a; 1991b). The tuffs are distinguished into three members: - lower, middle and upper members. They occur such that the lower and Middle tuffs are mostly found in valleys whereas the upper tuffs being more pervasive.



[Source: Saggerson, 1991b]

Figure 7: Nairobi cross-sectional formation of the geology

The Nairobi Trachytes have sections of it being intercalated with pyroclastic pumice and ash flows. Banding is common and correlates to flattening and pressure release within the lava flow on the trachyte. Nairobi Phonolites consist of numerous lava flows and the greater part of Nairobi is covered by it as in Figure 7. It also covers a large part of the county. Nairobi trachytes generally stretches from northern part to the southern part though overlay Athi Series in a type of unconformity known as disconformity (Saggerson, 1991a).

The Athi Series Formation is a composite of tuffs and 'Lake Beds' as in Figure 7. Lake beds are mainly lacustrine sediments consisting of reworked volcanic material. Athi tuffs have also been identified as a highly productive aquifer zone. It is intercalated with tuff bands, pumice bands and welded tuff deposits. The material includes obsidian sands, conglomerates and siliceous agglomerates. Kunkar nodules occur. It is sub-divided into three units:- First, the Upper Athi Series: often consists of sandy sediments, tuffs and lake beds in a wide lateral variation of bedding; it is generally clay-free, hence is one of the most targeted aquifers in the Nairobi area. Secondly, the Middle Athi Series is made up of basaltic lava, basaltic sands and agglomerates. The lavas show abundant insets of feldspar in the groundmass, whereby the sands often have a clayey matrix. Again, its maximum known thickness is 150m. Thirdly, the Lower Athi Series comprises primarily clay deposits and lies on the Kapiti Phonolite. It has a maximum known thickness of 150m (Saggerson, 1991a).

2.8.1 Groundwater occurrence, quality and hydro-geological conditions

According to Water Resource Management Authority- WRMA (2005); as a consequence of water quantity abstracted in relation to the population it serves, Nairobi Aquifer Suites stands as an unique important aquifer. Based on the study to Stephen et al (2005), the abstraction rate is estimated to about 85MLD. The perennial rivers drain within Kikuyu highlands. There exists a good aquifer located between underlying phonolite and the Kerichwa valley tuffs. The quality of groundwater from this aquifer largely meets the World Health Organisation (WHO) drinking water standards except for fluorides with $17mgL^{-1}$ with rare cases of excess iron of about $10mgL^{-1}$ as found by Saggerson (1991b) and cited by Marleen, Kilonzo and Walraevens (2008). The multi-layered aquifer system of Nairobi Aquifer Suite (NAS) is quite complex. Generally, the natural recharging happens along the rift valley edge. The groundwater flows eastwards along the Athi plains. The main aquifer layer, the Upper Athi Series underlies the phonolites, is confined and found at depths of 120 to 300 m bgl (Owuor, 2019). Other aquifers belonging to the NAS, commonly encountered, is a medium depth aquifer found at the base of the Nairobi Trachytes. There are largely intervolcanic sediments with discontinuous occurrences (Gevaerts, 1970; Saggerson, 1991a, 1991b).

The research studies that have been previously undertaken regarding the Nairobi perrential flooding mainly focused on the impact of the floods with great focus in informal settlement (Doughlas et al, 2008), the physical infrastructure and engineering aspects (Odhiambo, 2015), the legal and institutional framework (WRMA, 2015; Baariu, 2017). However, there exist a research gap concerning the utilisation of the storm water/floods as a water resource and as a way of mitigating its negative impact and also a way of sustaining the groundwater.

CHAPTER 3: MATERIALS AND METHODS

This chapter deals with the study procedure involved ranging from desk study, the data and their sources, softwares and their analytical uses, the conceptual methodology- application of Boolean logic to various thematic maps and its influence on suitability analysis.

3.1 MATERIALS

3.1.1 Data type and sources

The data utilised in achieving the objectives were secondary data from the government departments and agencies- Ministry of Water and Sanitation (MoWS), WRA, Kenya Meteorological Department (KMD), Kenya Survey, Ministry of Trnasport, Infrasturcture, Housing and Urban Development (MoTIH&UD) and international organisations both governmental and non-governmental- Japan International Cooperation Agency (JICA), International Livestoock Research Institute (ILRI) and United Survey Geological Survey (USGS) portal databases. Table 2 shows the numerous types of data, various sources the data was obtained from and their purpose in the research study.

Table 2: Study Data type, their sources, formats and purpose

	TYPE OF DATA	SOURCES	DATA FORMATS	PURPOSE IN RESEARCH
a)	Land use and cover	USGS/JICA	Landsat / shape file	Generate land use thematic map
b)	Background Image	Google Earth	Image	Truthing data
c)	Precipitation data	KMD	MS excel Workbook	Calculation of run-off
d)	Borehole	WRA	MS excel Workbook	Generate the Vadose thickness thematic map
e)	Geology	Kenya Survey	Shape file	Generate geological thematic map
f)	Rivers, Lakes	ILRI / WRA	Shape file	Generate the river thematic map
g)	Soils	Kenya Survey	Shape file	Generate the soil thematic map
h)	Literature	WRA, MoWS	Pdf, MS word, books	Literature research
i)	Contours	Global Mapper	Shape file	Generate DEM then slope map
j)	Road infrastructure	MoTIH&UD	shape file	Generate the road thematic map
k)	Boundary	ILRI	shape file	Definition of the research area

3.1.2 Software and Hardware

Several softwares were used to undertake this research work: Environmental Systems Research Institute (ESRI) ArcGIS 10.3 used in extract and analyse the data, the Global Mapper v18.2 used in generate data, Microsoft office 2016 used to prepare the reports and adobe PDF reader was used to open literature documents in pdf format, e-books and scanned works etc. The key hardware used is a laptop for running the softwares.

3.2 METHODOLOGY

3.2.1 Literature studies of Nairobi Aquifer Suite

3.2.1.1 Desk/ Literature reports studies

A research study on the area of interest and a comprehensive literature review on the hydro-geological of the research area was undertaken.The borehole data obtained from the WRA data management system, others like - hydro-geophysical and hydrogeological reports of various drilled boreholes (Odero, 2017), geological reports, meteorological reports and groundwater reports and drilling guidelines from the government departments enabling the deeper understanding of the NAS. The borehole data helped in the analysis and understanding of the aquifer. The previous hydro-geological reports on NAS and geological report and logs (Odero, 2017; Saggerson, 1991) are key in the understanding of NAS configuration and exploitation. Data from various departments of the Government - like MoWI, MoTIH&UD provided insights of the aquifer as well as sub-surface information of most permeable zones within the catchment.

3.2.2 Feasible zone identification

Based on the flow process of the methodology guiding the analysis for identification of feasible areas for planned recharge as illustrated in Appendix A4. This research study considers the key factors influencing planned recharge for groundwater that is land use, slope, the thickness of vadose zone and geology being the available data used to develop applicability maps. The maps were developed using Boolean logic functions within ArcGIS 10.3, each layer of each factor was created and reclassified in binary coding system with “1” being the applicable feasible areas whereas “0” being the not applicable feasible areas. Figure 8 shows the intended flow process.

Boolean operators namely intersect (AND), erase/ negation (NOT), exclusive union (XOR), and union (OR) are used to combine binary logic maps obtaining the integrated results (Edwards, 2004). Each factor map was combined using Boolean logic function and final map of the feasible area for applicability of recharge.

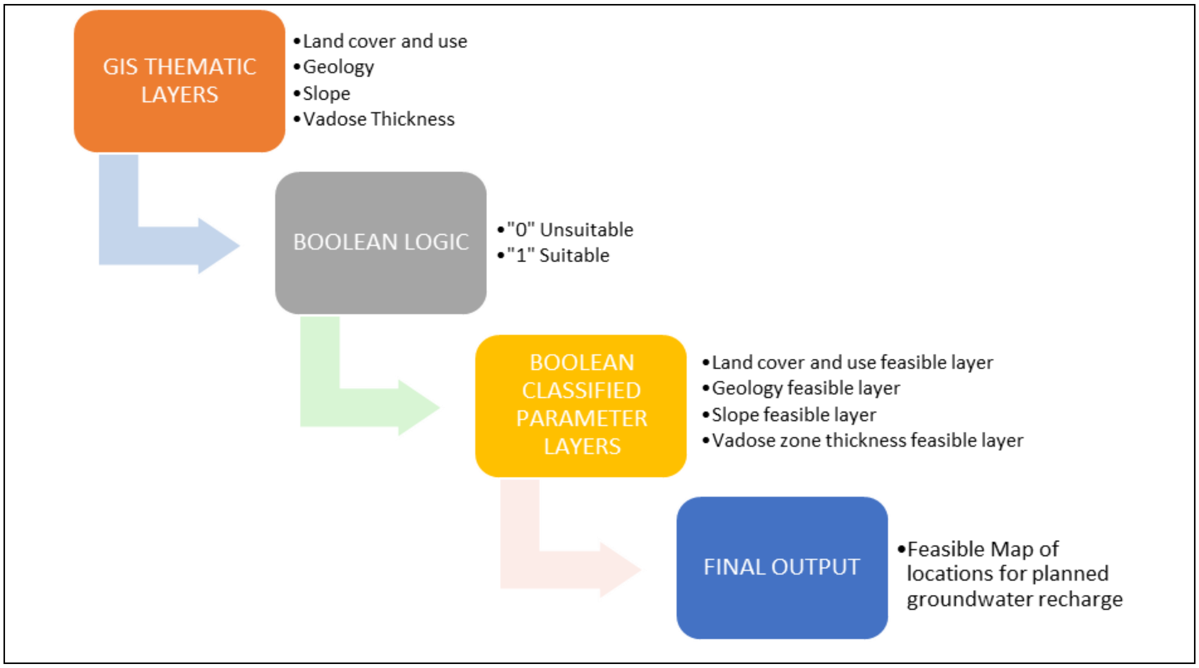
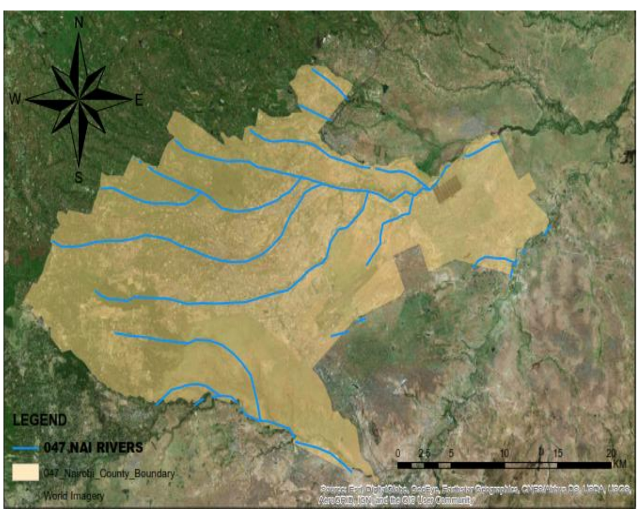


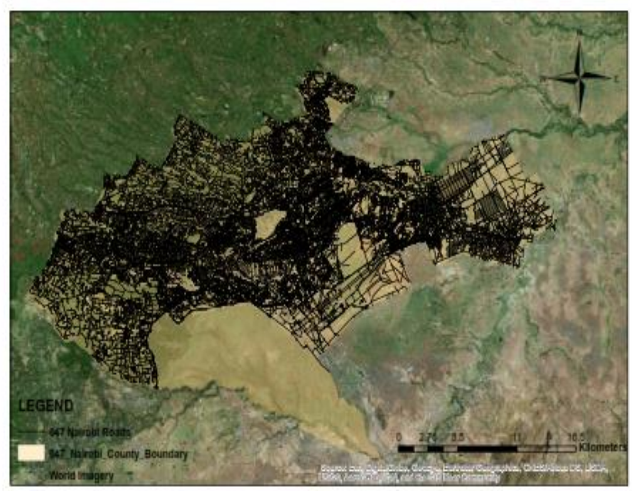
Figure 8: Flow process of the GIS input and output expectation

3.2.2.1 Land use/cover

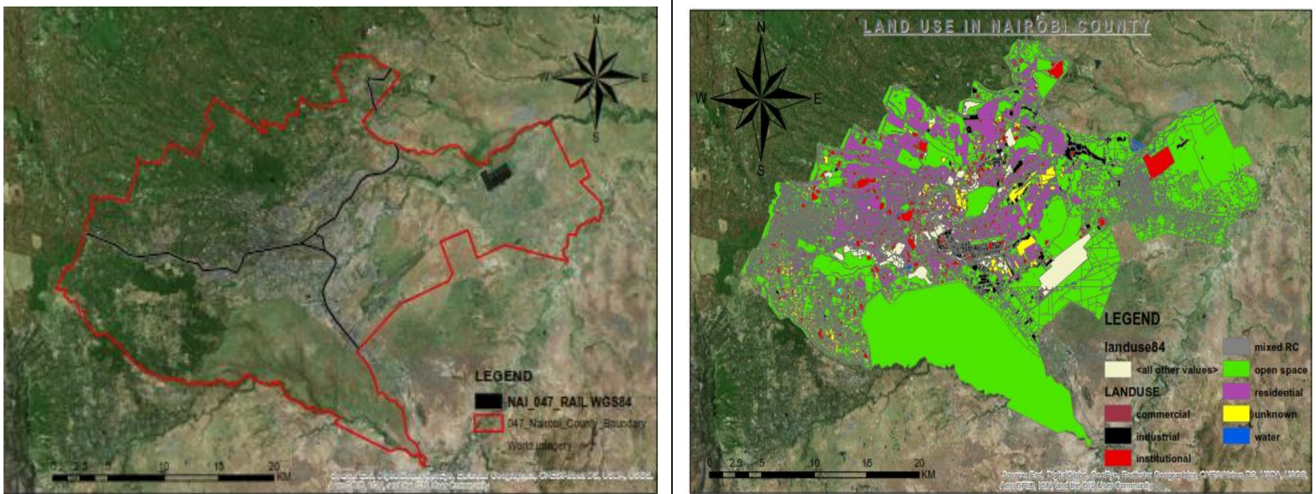
The spatial identification and demarcation of road networks, river drainage, railway network and structures within the location were used in the preparation of the shape files used for developing ArcGIS feasibility map. ArcGIS 10.3 was loaded with each structured data in shapefile formats, the outputs overlaid on world imagery referenced to WGS84 is shown in Figure 9.



Rivers within the research study area



All types of Roads within the research area



Rail network within the research area | Structures/ built –up within the research area

Figure 9: Spatial identification of various structures and utilities in research areas

3.2.2.2 Slope

The elevation/contours of the terrain within the location was used in the preparation of the shapefile used in ArcGIS 10.3 creating slope layer is shown in Figure 10.

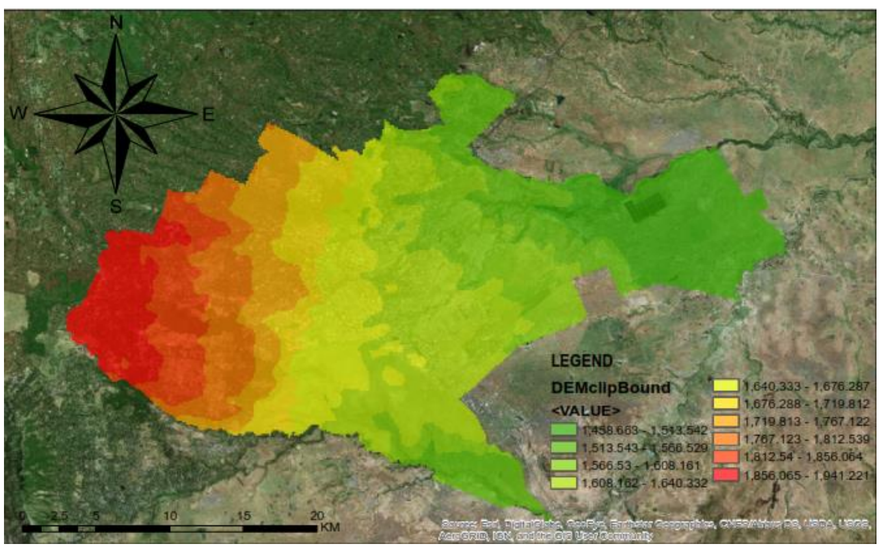


Figure 10: Slope map of the research area

3.2.2.3 Vadose thickness

In obtaining the thickness of vadose zone, the map of the groundwater elevation and surface elevation were obtained and the difference became the vadose thickness obtaining map in Figure 11.

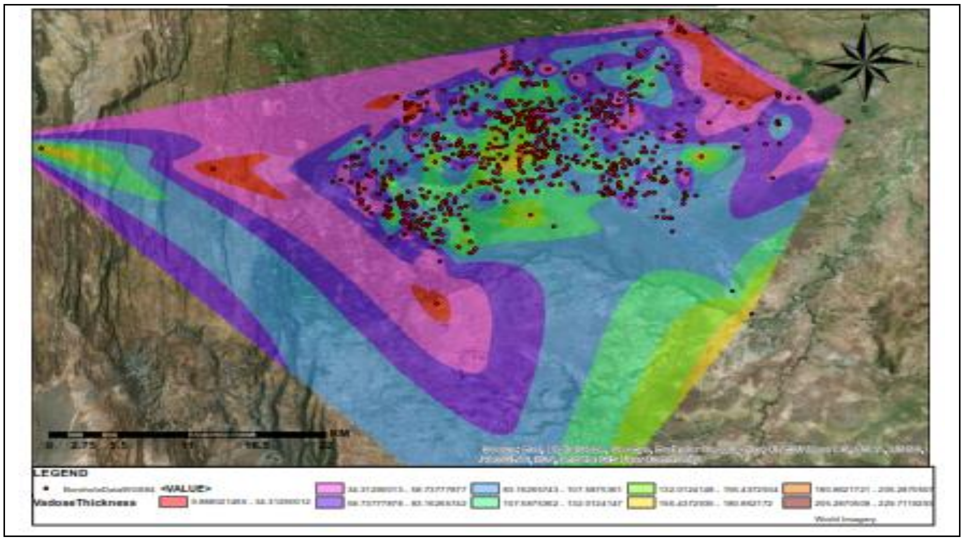


Figure 11: Vadose thickness of the research area

3.2.2.4 Geology

The type of geological deposits within the research area was used in the preparation of the shapefile used in ArcGIS creating slope layer: The realized layer for the research area is shown in Figure 12.

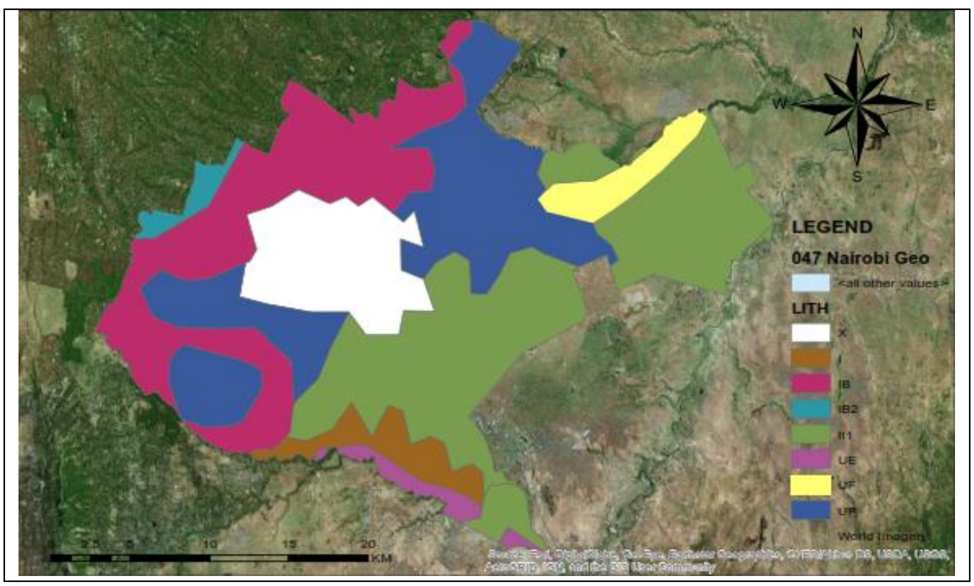
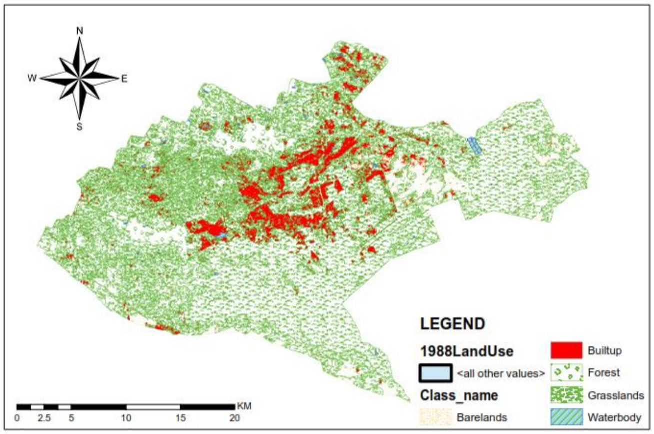


Figure 12: Geology of the research area

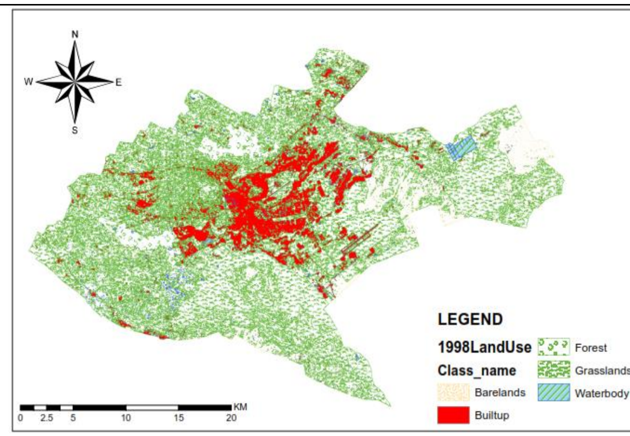
Using graphical illustrative methodology as in Appendix A4 and input data presented from the key factors above. The step of elaborating feasibility maps for planned recharge is presented in chapter 4 on results and discussion.

3.2.3 Urban flood characteristics

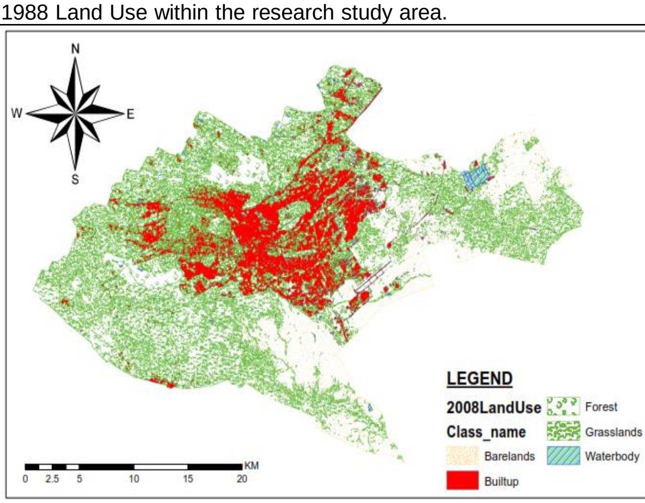
In determining the urban flood characteristics of the area, this objective was achieved by using generated land use shape files for the years 1988, 1998, 2008 and 2018 (USGS,2018). It involved the use of ArcGIS 10.3 in analysis of data.



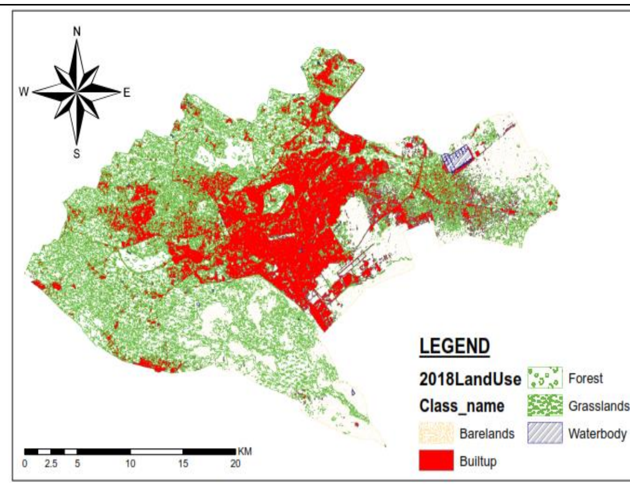
1988 Land Use within the research study area.



1998 Land Use within the research area



2008 Land Use within the research area



2018 Land Use within the research area

Figure 13: Land Use of the research area over various years 1988, 1998, 2008 & 2018

The shapes file were used to calculate the diminishing rate for the land-use using previous areas being a 10-year interval. The Land-use map derived for the years 1988, 1998, 2008 and 2018 is shown in Figure 13. They were analysed on the geometry area of each land use class thus obtaining the area as shown in the results Table 11, Table 12 and Appendix A5. This will help in identifying the structural adjustment and management to reduce diminishing groundwater recharge points resulting from this diminishing rate.

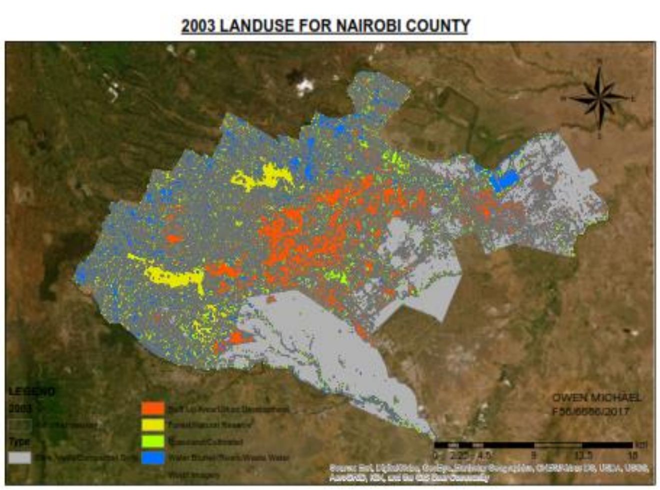
3.2.4 Amount of Runoff

The potential runoff quantities are based on the land use of the study area- Nairobi County. As a result of available meteorological rainfall data for the years 2000 and 2018 in the monthly basis and missing data. Land use map was therefore derived from Landsat satellite images of 30m spatial resolution acquired from database of USGS (2018) for the 5-years interval of 2003, 2008, 2013 and 2018 generated is shown in Figure 14.

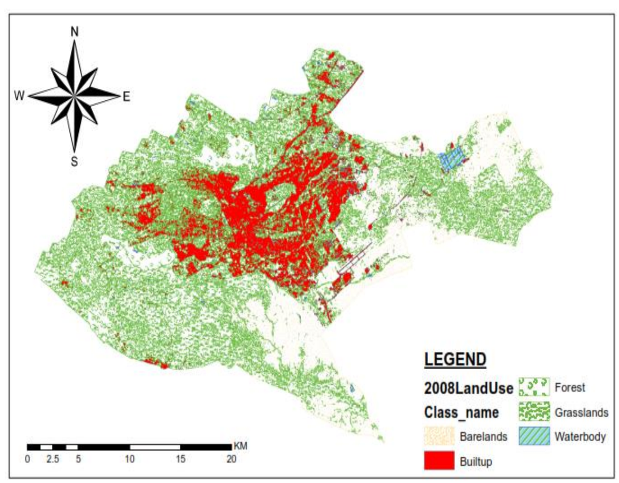
The data were captured by Landsat 8 and Landsat 7 with cloud covers less than 10% is shown in Table 3 and underwent pre-processing and analysis through ArcGIS 10.3 with the right band combination being signed for further analysis. For Landsat 8 in order to get the true colour of the image the bands 4, 3, 2 were assigned to the image giving capacity to understand the land scape in terms of the land use and cover in the research area. Landsat toolbox was used to remove the scan line errors.

Table 3: USGS Landsat cloud cover percentage with acquisition dates

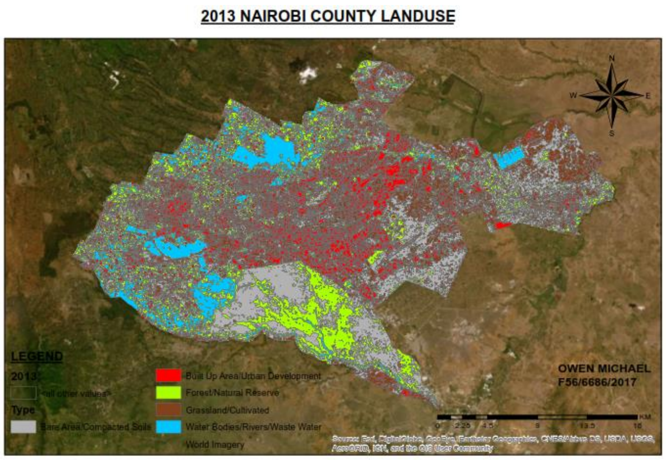
No.	Year	Acquisition date	Cloud cover %	Type
1.	2003	14TH December 2003	10	LANDSAT 7 image
2.	2008	06TH September 2008	10	LANDSAT 7 image
3.	2013	15TH November 2013	3.59	LANDSAT 8 image
4.	2018	29TH January 2018	0.02	LANDSAT 8 image



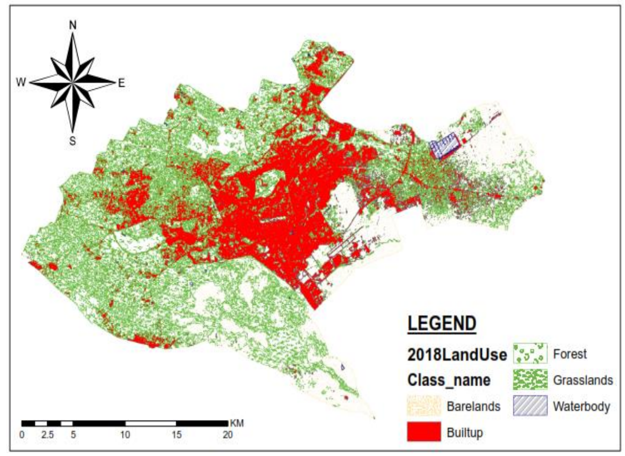
2003 Land Use within the research study area.



2008 Land Use within the research area



2013 Land Use within the research area



2018 Land Use within the research area

Figure 14: Land Use of the research area over various years 2003, 2008, 2013 & 2018

The Image processing included the ground truthing where the sample points collected in the field is used as sample signatures classification purpose thus creating accurate supervised classification signature which will finally create the land use land cover analysis. This was the analyst controlled classification where the training samples for classification are generated under the guidance of the ground truthing points to create land use land cover visualization, which can further be used for better decision making and understanding the land use.

The research area has five meteorological stations distributed in Nairobi County area with station numbers is shown in Table 4. The ArcGIS 10.3 was used to generate the Thiessen polygon zone based on meteorological stations. The co-efficient of runoff values shown in the Table 1 were used to calculate the runoff potential using rational method (Chow, 2012; McGhee, 1991; MoWI, 2005). The planned land use could not be obtained due to the dynamics of the city currently under review, thus previous years run-off was calculated to estimate the projected run-off in the future years due to the rate of increasing change of land use in the study area.

Table 4: Five meteorological Stations in the Research area

No.	Meteorological Station No.	No.	Meteorological Station No.
1.	9136130	2.	9136168
3.	9136208	4.	9136164
5.	9136087		

CHAPTER 4: RESULTS AND DISCUSSION

In this chapter, the results and findings deduced from the methodology are discussed. The deliverables include the thematic maps used to determine the feasible area for planned recharge, the hydrogeological cross-section graph to enable understand the configuration and nature of aquifer, land use change rate for over three decades and quantification of run-off for over 15-year period.

4.1 Analysis of monitoring wells and configuration of the aquifer

The multi-layered aquifer system extensions are fairly well identified from the drilled boreholes to depths of 100 up to 350 m bgl. The important aquifer recharge sources are the upstream section of the catchment. Over-abstraction of groundwater, declining groundwater levels and greater demand for water resources are highlighted as key issues (Schaeffer et al, 2013; WRMA, 2015). The monitoring wells data indicate a ceclining groundwater levels that vary from 2m to over 35m in some wells over the decade is illustrated in Figure 15. This is justifying the reports of consistent decline and dwindling groundwater levels at a rate of 1.2m yearly (WRMA, 2005).

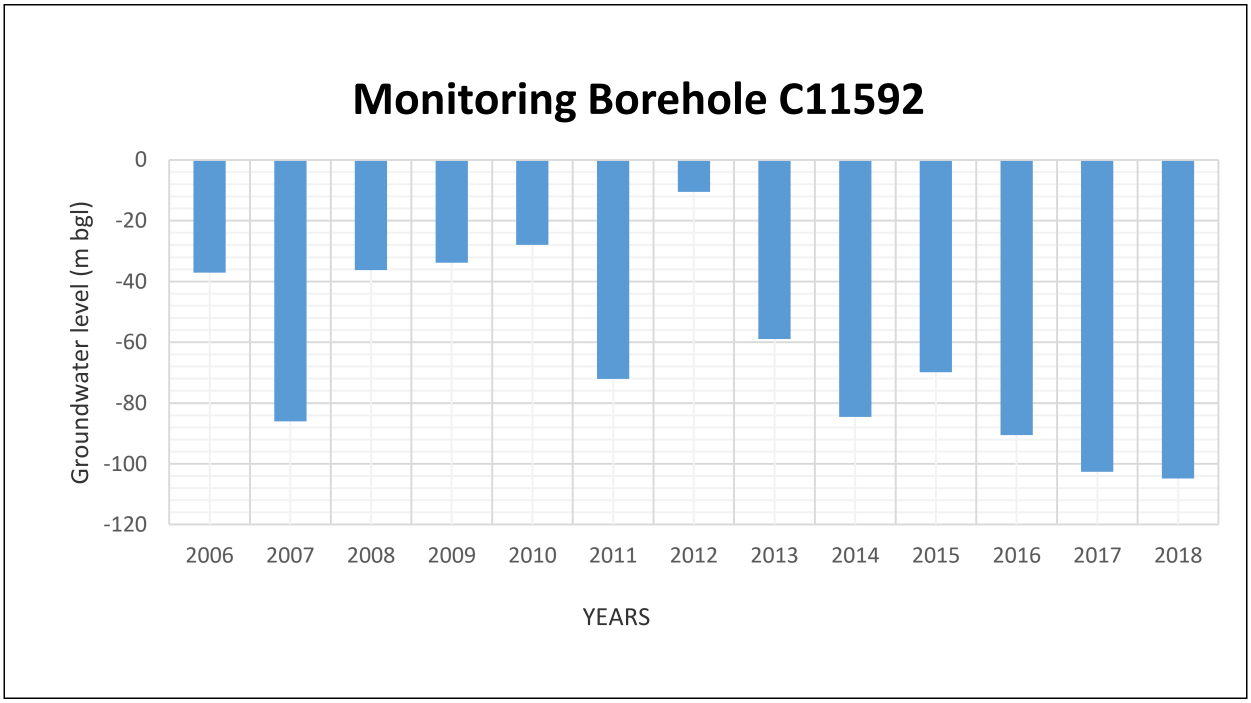


Figure 15: Sample monitoring well groundwater level hydrograph

The limited monitoring, poor coordination and unmanaged abstraction of the groundwater resources based on the number of boreholes drilled are not quite known by the monitoring agency- WRA. From the borehole data information from WRA, it is quite evident that groundwater yield is heterogeneous in NAS even within a very small distance, this is qualified by the evolution of areas and neighbouring areas geology. The borehole data confirms that the boreholes exploit the existing multi-layered aquifer within ranges of 6-48m depth, 57-127m, 133-181m and above 200m respectively. When correlated with the geologic logs of the boreholes, the aquifers located between 54-76m and 179m depth correspond to fractured aquifers located within fractured and weathered volcanic rocks while those struck at 128-178m deep occurs in coarse sediments and red gravel which forms the main aquifer. Saggerson (1991a) found that good aquifer formed by fractured volcanic as observed in the research area and notably reflected by the borehole data. The transmissivity and flow of groundwater increases based on the fractures in this type of rock formations. Water Strike Level (WSL) lies within the gravel and coarse sediments and that forms the research areas main aquifer as observed in several boreholes like borehole ID No. C9734 and C1017. The prevailing non-eruptive stages, depositions of the formations occurred resulting from volcanic and sedimentary. The formation portrays erosion stages as resulting from lava flows and the volcanic eruptions thus possible aquifer. It usually comprises weathered rocks, soils and water-lain eroded volcanic material having a variable thickness (Gavaerts 1970).

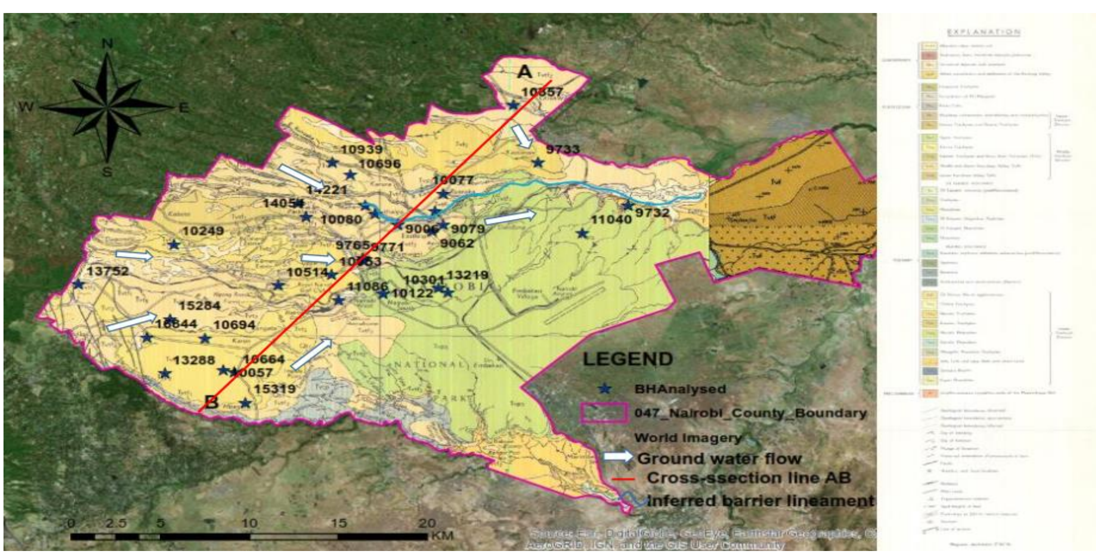


Figure 16: Analysed boreholes along hydrogeological cross-section AB

Hydro-geological cross-section line was drawn as shown in Figure 16 for groundwater level analysis. The hydro-geological cross-section shows existence hydraulic gradients deviating groundwater flow resulting in varied yields and also flow direction of groundwater within the research area as depicted in Figure . Groundwater flows from high raised regions to low raised region that is flowing from North East towards South East as well as from the South West to North East directions as shown in Figure 16 and as in the hydro-geological cross-sectional in Figure 17. The non-uniform piezometric levels indicate the majority of the boreholes does not share the same aquifer thus NAS is a multi-layered aquifer.

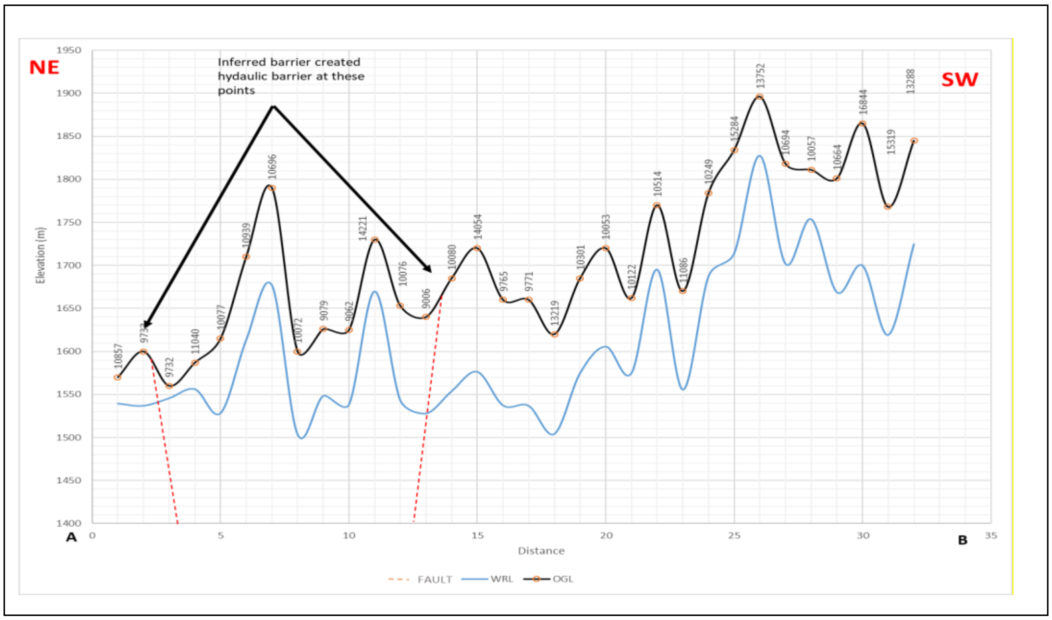


Figure 17: Hydro-geological cross-section through section A-B

Faulting is quite an exceptional occurrence within the research area resulting in flow occurring horizontally. Faults act as canals facilitating the flow of groundwater. From Table 5, Boreholes along and closer to the fault line have a considerable worth yield of more than $8m^3hr^{-1}$- C10076, C10072, C14221 and C9732. However, the boreholes C10077, C14221, C9771 having depths more than 200m bgl have water struck at rather shallow depths indication of faults being key in aquifer existence. The various borehole locations on the overlaid Nairobi geological map is as shown in Figure 18. Boreholes - C13752, C15284, C10857, C10514, C14221 and C11040 have yields greater than $10m^3hr^{-1}$. This indicates they are either recharged directly by natural rainwater infiltration or through fault lines (Odero, 2017). Some boreholes C13288, C10696, C16844 have high total depth but low yield. This can be attributed to their locations near a discharge area with an overexploited groundwater resource as observed in Karen area.

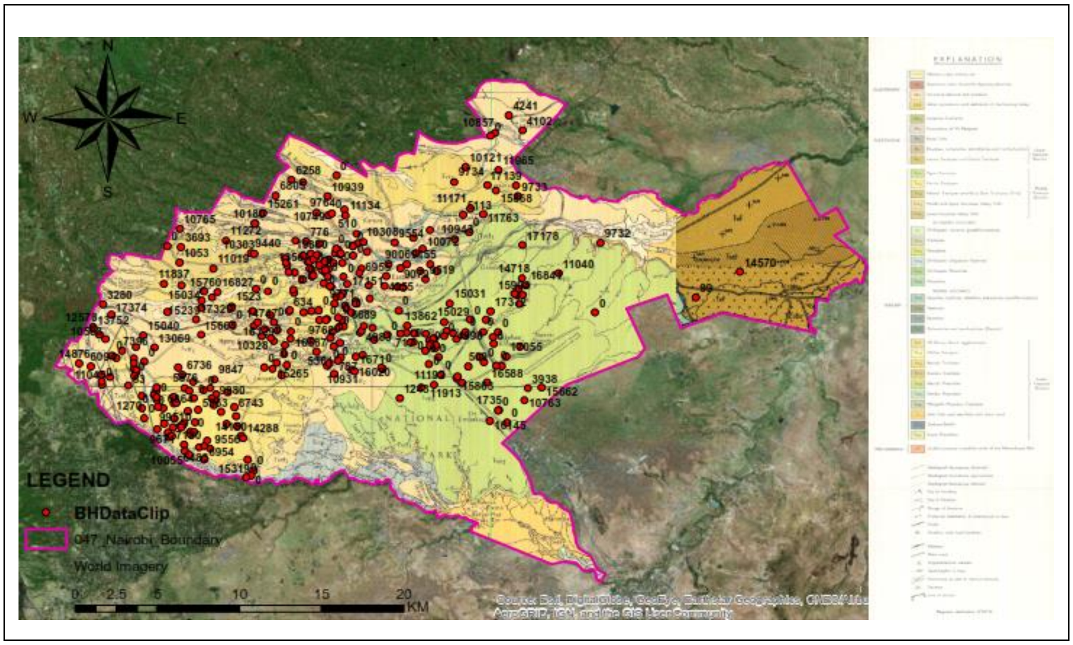


Figure 18: Borehole Locations as shown on Nairobi's geological map

Table 5: Analyzed boreholes for Aquifer characteristics in the research area

BH - ID	OGL (m)	Total Depth (m bgl)	WSL (m bgl)	WRL (m bgl)	YIELD (m^3hr^{-1})	SPECIFIC CAPACITY (m^3/day)
C9006	1640	181	125, 175	112	5.87	8.004
C9062	1625	177	109, 120, 150	86.5	0.84	2.3712
C9079	1626	162	128	77.5	7.92	10.272
C9732	1560	121	22, 98	14.2	8.82	4.4231
C9733	1600	120	76	63	6.6	11.82
C9765	1660	200	132, 168	122.6	9	17.28
C9771	1660	200	32, 167	123.1	12	21.12
C10053	1720	252	135, 165, 228	114.2	4.2	2.755
C10057	1811	200	86, 120	57	4.38	
C10072	1600	218	100, 158	96.4	11.6	2.928
C10076	1653	180	108, 156	109.6	8.4	11.39
C10077	1615	200	15, 154	86.5	6.06	8.218
C10080	1685	162	25, 101, 131	131	5.82	8.342
C10122	1662	170	4, 164	87	5.64	4.8
C10249	1784	250	110, 160, 212	96.5	5.46	
C10301	1685	204	40, 144	110	16	9.048
C10514	1770	250	2, 192	74.6	17.6	
C10664	1801	137	84, 104	132	3	
C10694	1818	192	86, 148, 156	116	3.42	
C10696	1790	315	90, 94, 108	113	6	1.706
C10857	1570	139	46, 130	30.5	30	64.296

C10939	1710	150	35, 82	96.4	7.68	3.888
C11040	1587	111	104, 134	30.7	13.8	24.353
C11086	1670	233	146, 178, 204	114.3	5.04	11.4
C13219	1620	235	40, 144	115.7	18	9.048
C13288	1845	330	160, 257, 320	120	1.44	
C13752	1896	250	102, 148, 208	68.2	20	
C14054	1720	235	208, 232	143.5	6	4.296
C14221	1730	250	13, 82	60.02	14.4	5.616
C15284	1834	340	156, 316	119.8	12	
C15319	1768	330	226, 258, 276, 284	148.63	7.2	
C16844	1865	300	38, 210, 244	165	6	

(Source WRA, 2019)

Based on the borehole data, majority of NAS aquifers can be considered confined. This is as a result of the WSL lying below the WRL for the majority of the boreholes. Varying tested yields for the boreholes range from 0.66 m^3/hr up to 36 m^3/hr accounted due to the varying geological conditions. The WSL range within varying depths from 4.0m–270m bgl. The perched aquifer is encountered at depths ranging between 4m– 54m bgl, the second perched aquifer lies around 76m– 124m bgl whereas a third perched aquifer lies between 126m– 280m bgl. In most areas, the perched aquifer can be observed in depths between 25m- 109m bgl within which the Kerichwa valley tuffs and underlying lava flows – water-bearing zone.

It's observed that for increased depths there’s increased yield in the 120m to 250m aquifer due to an increased degree of weathering and fractures on the Nairobi trachytes and Kandizi Phonolites. However, the boreholes have specific capacities being heterogeneous in nature. High specific capacities observed for boreholes in recharge regions, for example, C10857, C14221 and C11040. These area forms good potential sites for borehole citing. Unconsolidated gravel regions have high transmissivity ranging upto $160m^2$/day hence yields less than $9m^3hr^{-1}$ unlike for sediments regions having high yields greater than $9m^3hr^{-1}$ with low transmissivity ranging as low as $0.1m^2$/day.

4.2 Assessment of feasible recharge area

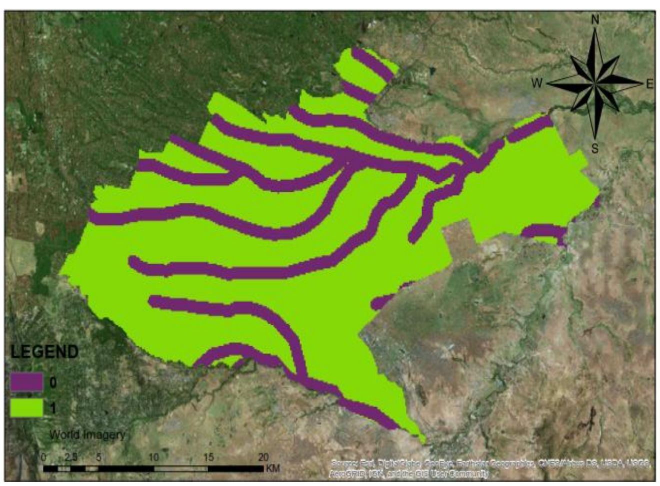
4.2.1 Land cover and use

In obtaining maps for feasible recharge areas in relation to land cover and use, Binary values were assigned using Boolean function as shown Table 6.

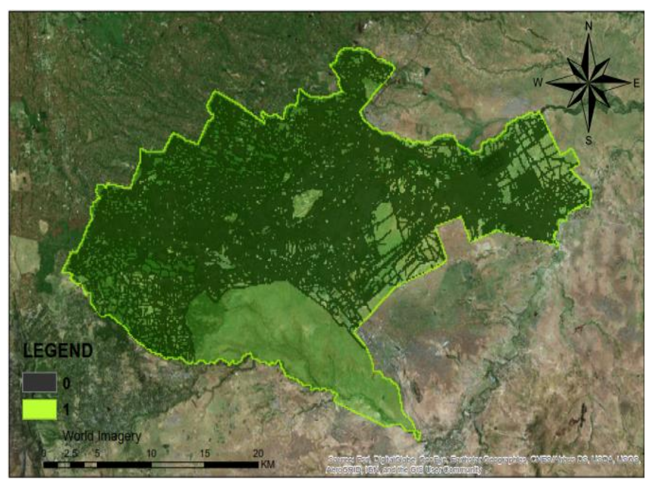
Table 6: Land cover and use assigned Boolean values

No.	Factors	Description	Boolean value	Applicability	Observation
1.	Rail	Present	0	Not Applicable	-
		Absent	1	Applicable	
2.	Roads	Present	0	Not Applicable	-
		Absent	1	Applicable	
3.	Rivers	Present	0	Not Applicable	It was considered a buffer zone of 500m
		Absent	1	Applicable	
4.	Built-up area	Present	0	Not Applicable	-
		Absent	1	Applicable	

Figure 19 and Figure 20 present results of each factor.



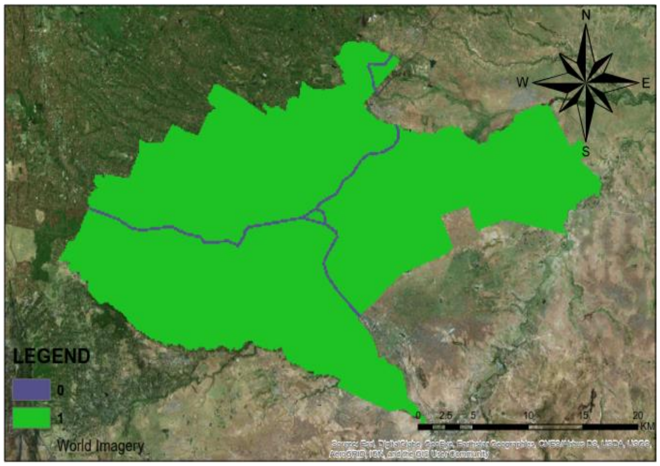
A. Feasible area map in terms of Rivers within the research area



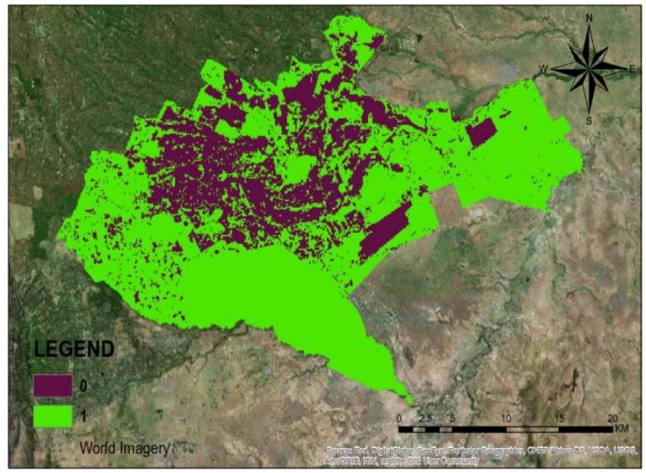
B. Feasible area map in terms of Roads within the research area

Figure 19: Feasible area map for planned recharge in relation to rivers and road networks

- The feasible area mapped in terms of the river network, only **73.42%** of the study area is feasible for planned recharge application as depicted in Figure 19A.
- The feasible area mapped in terms of the road network, only **35.39%** of the study area is feasible for planned recharge application as depicted in Figure 19B.



A. Feasible area map for planned recharge in terms of rail network within the research area



B. Feasible area map in terms of Structures/ built –up within the research area

Figure 20: Feasible area map for planned recharge in relation to rail and built-up networks

- The feasible area mapped in terms of the rail network, only **98.34%** of the study area is feasible for planned recharge application as depicted in Figure 20A.
- The feasible area mapped in terms of built-up/Structures network, only **64.78%** of the study area is feasible for planned recharge application as depicted in Figure 20B.

Overlaying the four maps in Figure 19 and Figure 20, a feasible area map was obtained for applying recharge techniques shown in Figure 21. After overlaying the Boolean logic maps, only **64.68%** of the research study area is feasible in terms of land cover and use for planned recharge application.

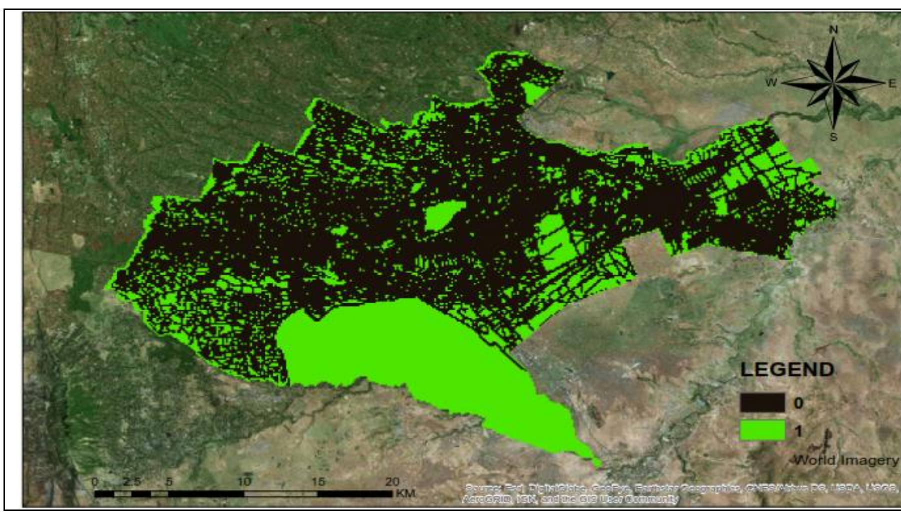


Figure 21: Feasible area map in terms of land cover and use within the research area

4.2.2 Slope / Terrain

In obtaining maps for feasible areas in relation to the slope, the binary values were assigned using the Boolean function shown in Table 7.

Table 7: Slope assigned Boolean values

No.	Factor	Description	Boolean value	Applicability
1	Slope	>5%	0	Not applicable
		<5%	1	Applicable

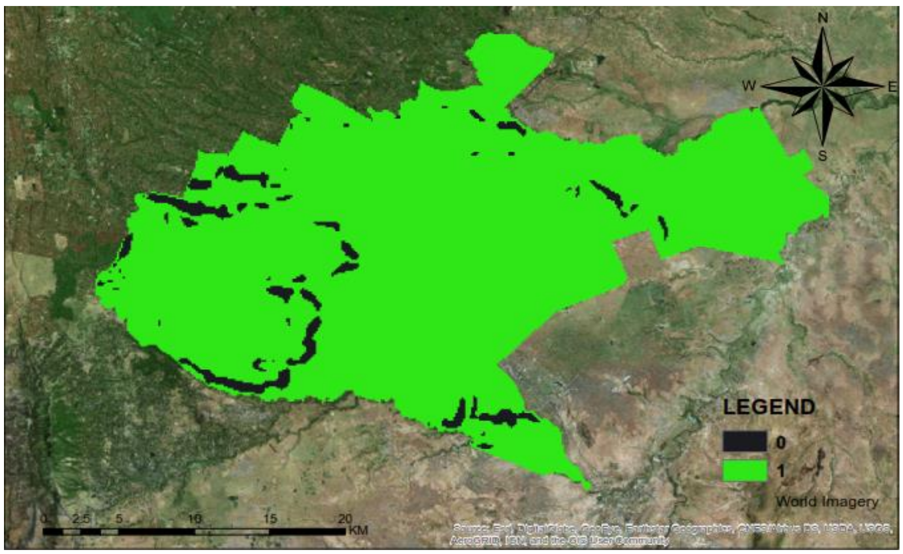


Figure 22: Feasible area map in the relation to Slope

Upon overlaying the Boolean logic maps, the feasible area within the research area in relation to slope for planned recharge application techniques is found to be only 95.59% as illustrated in Figure 22.

4.2.3 Vadose thickness

In obtaining maps for feasible areas in relation to vadose thickness, Binary values were assigned using Boolean function shown in Table 8.

Table 8: Vadose Thickness assigned Boolean values

No.	**Factor**	**Description**	**Boolean value**	**Applicability**
1	Vadose thickness	<15m	0	Not applicable
		>15m	1	Applicable

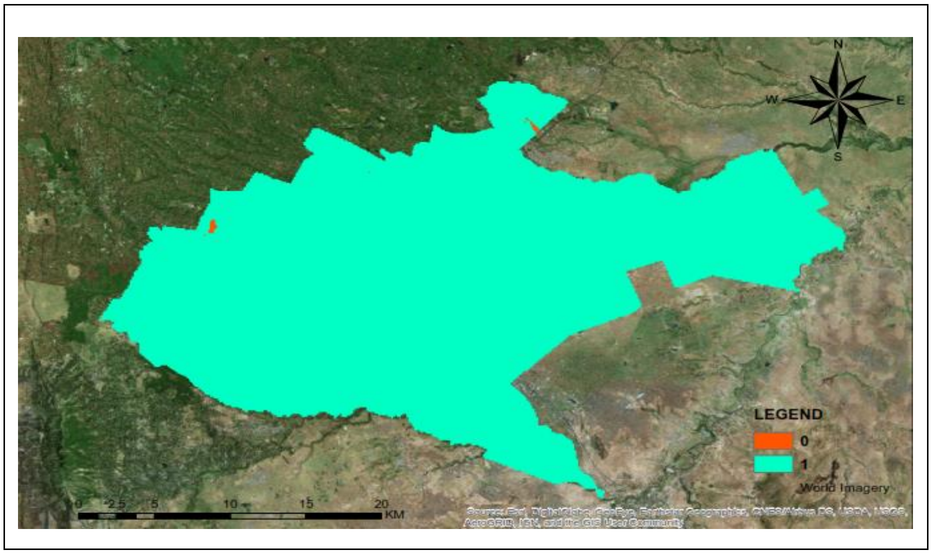


Figure 23: Feasible area map in terms of vadose thickness within the research area

The result is shown in Figure 23. After overlaying the Boolean logic maps, only 98.91% of the research study area is feasible in terms of vadose thickness for planned recharge application techniques.

4.2.4 Geology

In obtaining maps for feasible areas in relation to geology, Binary values were assigned using Boolean function shown in Table 9.

Table 9: Boolean values assigned for geology

No.	Factor	Description	Boolean value	Applicability
1	Geology	Hydrography / Deposits Swamp	0	Not applicable
		Colluvial deposits	1	Applicable

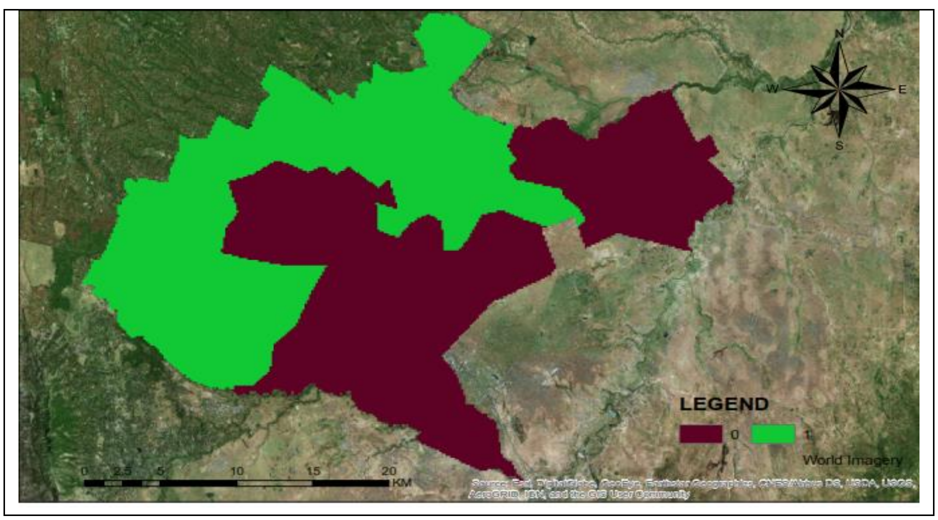


Figure 24: Feasible area map in terms of geology within the research area

The result is shown in Figure 24. Upon overlaying the Boolean logic maps, only **47.92%** of the research study area is feasible in terms of geology for planned recharge application techniques.

4.2.5 Final feasible areas of applicability

Combining the results obtained from the four factors analysed, a map on the applicability of planned recharge technique was obtained as shown in Figure 25. Final map from the Boolean logic overlay shows only **22.57%** of research study areas to be feasible for planned recharge techniques.

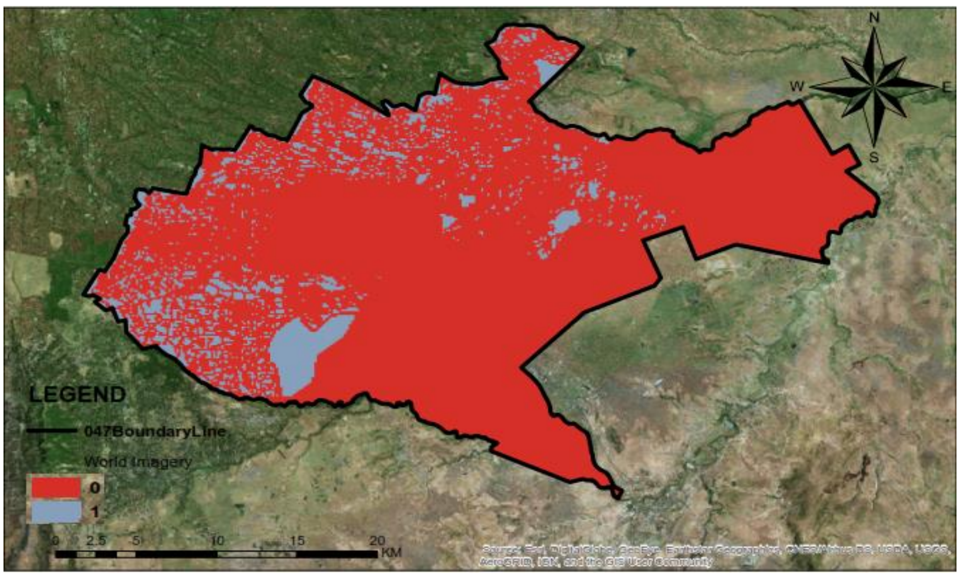


Figure 25: Final feasible area map within the research area

4.3 Characterisation of urban floods

Table 10: Area coverage for each land use in the years 1988, 1998, 2008 and 2018

Area (Km²)coverage for every land use in Nairobi (Year 1988-1998-2008-2018)									
No.	**Land Use**	**1988**		**1998**		**2008**		**2018**	
		Area (km^2)	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**
1	Grasslands	453.6424	61.5	395.3680	53.6	279.1998	37.9	243.8619	33.1
2	Forest	121.1297	16.4	96.0795	13.0	96.4677	13.1	64.9812	8.8
3	Builtup	91.9349	12.5	104.9107	14.2	133.4347	18.1	227.5435	30.9
4	Barelands	68.4709	9.3	136.1296	18.5	224.7349	30.5	196.9519	26.7
5	Waterbody	1.9619	0.3	4.6638	0.6	3.2995	0.4	3.8128	0.5
6	**TOTAL**	737	100	737	100	737	100	737	100

Table 10 illustrates the results as obtained in analysis in obtaining area of each class for each analysed area using ArcGIS 10.3. Further detailed class result per the analysed years are attached in Appendix A5. From the Table 11, the results show substantial increase in built-up area from 1988 to 1998 it is 1.8%; further rising by 3.9% from 1998 to 2008; then rapidly increasing to 12.8% from year 2008 to 2018. Built up areas increased by 18.5% between 1988 and 2018 due to high population influx in the research area. The negative values of area in km^2 illustrates the reduction in area and vice versa in Table 12. There was reduction of forest from the year 1988 to 1998 by 3.4 %; remain bit steady increasing by 0.1% over 1998 to 2008 period because of the high environmental campaigns with main aim of preserving and increasing the forest cover and then drastically reductions during the 2008 to 2018 by 4.3%. The forest cover decreased by 7.6% from 1988 till 2018 due to increased access to more open space for building is illustrated in Table 12.

Table 11: 10-year Interval various land use change rates

10 YEAR INTERVAL						
Land Use	1988-1998		1998-2008		2008-2018	
	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
Grasslands	-58.3	-7.9	-116.2	-15.8	-35.3	-4.8
Forest	-25.1	-3.4	0.4	0.1	-31.5	-4.3
Builtup	13.0	1.8	28.5	3.9	94.1	12.8
Barelands	67.7	9.2	88.6	12.0	-27.8	-3.8
Waterbody	2.7	0.4	-1.4	-0.2	0.5	0.1

Similarly, the grasslands or light vegetation decreased during 1988-1998 period by 7.9%; decreased further from 1998-2008 by 15.8 %; decrease is observed during the period 2008-2018 by 4.8%. The light vegetation/ grassland areas decrease from 1988-2018 is 28.5% and mainly attributed to expansion of built-up areas replacing grassland. Bare lands area rose between the year 1988-1998 by 9.2% and abruptly increased from 1998-2008 by 12.0 % as a result of the high deforestation rate; decreasing by 3.8% in the last decade. Henceforth, an increase in bare land from the year 1988-2018 which is 17.4%. The area of water body increased by 0.4% between 1988 and 1998 and decreased by 0.2% from 1998-2008. It increased by 0.1% over last decade generally due to increase in waste produced and overflow of treatment works, swimming pools and increased animal water points in the National park in this decade. The overall increase of water body area between the years 1988-2018 is 0.3% in Table 12.

Table 12: Land Use change over the period of 1988 to 2018

CHANGE OVER THE THREE DECADE PERIOD		
LAND USE TYPE	**1988 - 2018**	
	AREA (KM^2)	**%**
Grasslands	-209.8	-28.5
Forest	-56.1	-7.6
Built up	135.6	18.4
Bare lands	128.5	17.4
Water body	1.9	0.3

The various techniques and methods of planned recharge groundwater can be used varying from one site location to another as captured in the literature review. It is important the identified recharge points be analysed independently or in clustered group based on the key parameters already captured to ascertain the most suitable technique.

Based on the 22.57% feasible area for planned recharge and an increase land use rate over time, various structural adjustment and management needs to be put in place to reduce diminishing groundwater recharge points as emphasised by Odhiambo (2015) on increase in impervious layer in part of city. Based on the results obtained in Table 12, the rapid reduction of grassland and forest cover which provides a great area for infiltration for the partial recharge of the shallow aquifers being the Nairobi Aquifer System is multi-layered in nature, then government departments and ministries needs to secure the unutilised areas identified as recharge points and gazette them as reserves, whereas located in private land then repossession of such land by the constitution and acts of parliament.

4.4 Quantity of Run-off

The estimated total runoff amount for the study area considering the current land use was found to be 365.87 Mm^3 for the year 2018. Zone 2 had missing data thus more run-off would have been estimated besides the results in the Table 13. Detailed computations of runoff quantities in all Thiessen polygon zones that is the five zones (Z-0 to Z-4) are shown in Appendix A6. From the results in Table 13, there is run-off of 365.87Mm^3 as at 2018 compared to 261.61Mm^3 at 2003 being an increase of 39.85% increase, a clear indication of increase of run-off as the years go by based on the increased change in land use. There is need to implement flood mitigation measures with incorporation of planned recharge of groundwater to supplement the limited resource in the study area and beyond

Table 13: Total Run-off

AVAILABLE STORMWATER RUNOFF IN EXISTING AND PREVIOUS YEARS BASED ON LAND USE					
No.	ZONE NUMBERS	STORM WATER OF EXISTING LANDUSE FOR PREVIOUS 5 YEAR INTERVAL			
		2003	*2008*	*2013*	*2018*
1	ZONE 0 (Z-0)	55987083.36	56232157.84	55506333.26	71516346.03
2	ZONE 1 (Z-1)	98447616.07	72597806.94	93139714.05	115261870.12
3	ZONE 2 (Z-2)	10429891.24	32018494.30	19747473.96	0.00
4	ZONE 3 (Z-3)	72415320.26	48070213.81	67175460.35	77700428.26
5	ZONE 4 (Z-4)	24330956.74	60058196.38	35813228.93	101390316.19
6	***TOTALS (m^3)***	***261610867.67***	***268976869.27***	***271382210.55***	***365868960.60***
7	***TOTAL (Mm^3)***	***261.61***	***268.98***	***271.38***	***365.87***

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Inadequate implementation of 1927, 1948 and revised in 1978 master plans for the city makes it difficult to project exact run-off due to unplanned settlement and development patterns as pointed out by Vogel (2008) and emphasised by Baariu (2017). Zone 1 and 3 being greatly under the Industrial zone and residential zones, the quality of water may be compromised due to poor sanitation and waste handling thus may not be key in the harvesting as per research findings by Lusigi et al (2017). According to Kithiia (2007), degradation of water quality over time in the downstream as observed in data over 1998-2003 for example mercury concentration being 0.02-0.03mgL^{-1} than WHO recommended 0.001mgL^{-1}. This justification of increased pollution intensity in the drains as Zone 1 and 3 are concerned as highlighted (NRBP IUCN-UNEP, 2005; CNN, 2007). Runoff water harvesting may be key in water re-use than in groundwater recharge. In general, resulting run-off of Zone 1 and 3 confirmed occurance of high volume thus agreeing with research work by Odhiambo (2015) that found out South C area being 49% impervious layer. The Zones 0, 2 and 4 are a great runoff harvesting for groundwater. In 2018, it is estimated that about 172.91Mm^3 being potential for recharge.

An increase of 63.43% between 2003 and 2008 where 90.75Mm^3 and 148.30Mm^3 could be harvested respectively. 25.11% decrease is observed in 2013 from 2008 and 55.68% increase noted in 2018. An indication of great potential role that storm water run-off can be in terms of water resource management.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusions

- Runoff harvesting is key in supplementing the limited water resource in Nairobi County. The current potential of 172.91 Mm^3 based on the existing land use, this can help in bridging the gap of existing water deficit within water budget.

- Upon application of the methodology in determination of feasible planned recharge is found to be 22.57% of the total area based on the available data and information for the study area. It can be concluded that such methodologies play a real support and contribute significantly in obtaining feasible aquifer planned recharge thus optimal choice of potential sites. The potential feasible recharge points identified need to be investigated further as each recharge technique has varied suitability of the ground aspects. Suitability of each planned recharge technique in relation to identified recharge points needs to be checked before implementation.

- The utilization and management of runoff as water resource is critical with rapid radical land use changes over time, with run-off potential increasing from 90.75Mm^3 in year 2003 up to 172.91Mm^3 in the year 2018, an increase of about 90.54% over a 15 year period. The most effective way to utilise runoff is through the planned groundwater recharge but beyond this is urgently protect the city from frequent flooding during raining seasons and sustaining it during the dry season.

5.2 Recommendations

In regard to possible further research – I can recommend the following: -

- Data Investment should be prioritised and made accessible with use of modern storage to avoid loss of data: - Missing rainfall data from KMD which had gaps in certain period from certain weather stations example Station ID 9136164 lack 11 months of precipitation for the year 2006; Station ID 9136168 lacked data for the last 4 months before the end of year 2005; Station ID 9136208 had missing data from the October 2016 till December 2018.

- Owing to the existing deficit in water budget, groundwater quality deteriorates thus proper action should be done to ensure resource management by the government. Acquisition of the identified feasible planned recharge areas should be protected while those that has been encroached the government needs to develop policies to revert and preserve such areas to enable create a sustainable city.

- Water quality of the run-off needs to be needs to be carried out and monitored frequently as the quality keep changing.
- Developing ways of bulk re-use of waste water in bridging the gaps of water shortages and effects of climate change.

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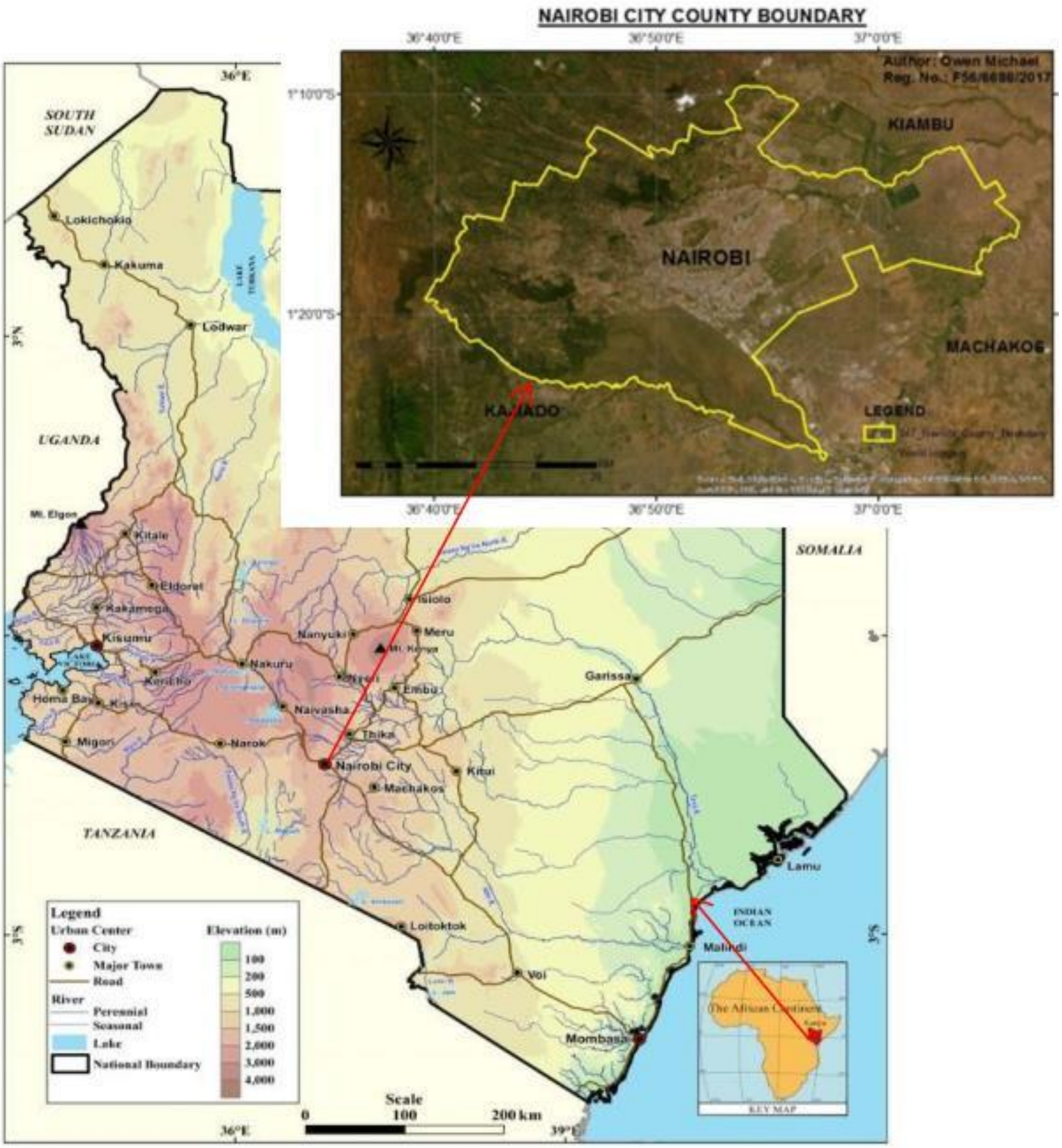
APPENDICES

Appendix A1: Map of Kenya and location of Nairobi City



(Source: Author, 2020)

Appendix A2: Situation of Nairobi City when it rains

1. Ndakaini Dam at near deplection state.

2. Ndakaini Dam at near full capacity

3. Section of Eastlands along Jogoo Road

4. Section of the Nairobi CBD along Moi Avenue

5. Section of Uhuru Highway

6. The situation of Kirinyaga Road

Sources: Picture 1, 2 : Standard digital newspaper, 4, 5&6 Daily Nation & Star newspaper Picture 3 Author

Appendix A3: Planned/Artificial Ground water techniques and methods

A3.1: Analysis of methods and techniques for planned recharge

	Type of Method	Type of Techniques	Techniques	Role of Application
a.	Direct Method	Spreading Methods	Flooding	Infiltration of the recharge water in underground
			Irrigation	
			Ditch and furrow	
			Reverse drainage	
			Recharge basin	
b.	Direct Method	Recharge techniques through runoff harvesting	Percolation ponds	Interception, storage and subsequent infiltration of water in the underground
			Check dams and gully plugs	
			Contour trenches and bunds	
			Bench terracing	
c.	Direct Method	Sub-surface techniques	Recharge well and shafts	Infiltration of water in the underground
			Gravity head recharge wells	
			Recharge borehole /Injection well	
d.	Indirect method	Modification of natural water flow	Subsurface dams	Preserving and increasing the quantity of water stored in the aquifer
			Aquifer modification	
			Channel spreading techniques	
			Groundwater recharge dams	
			Sand storage dams	
e.	Indirect method	Induced Recharge	Induced Recharge	Preserving and increasing the quantity of water stored in the aquifer

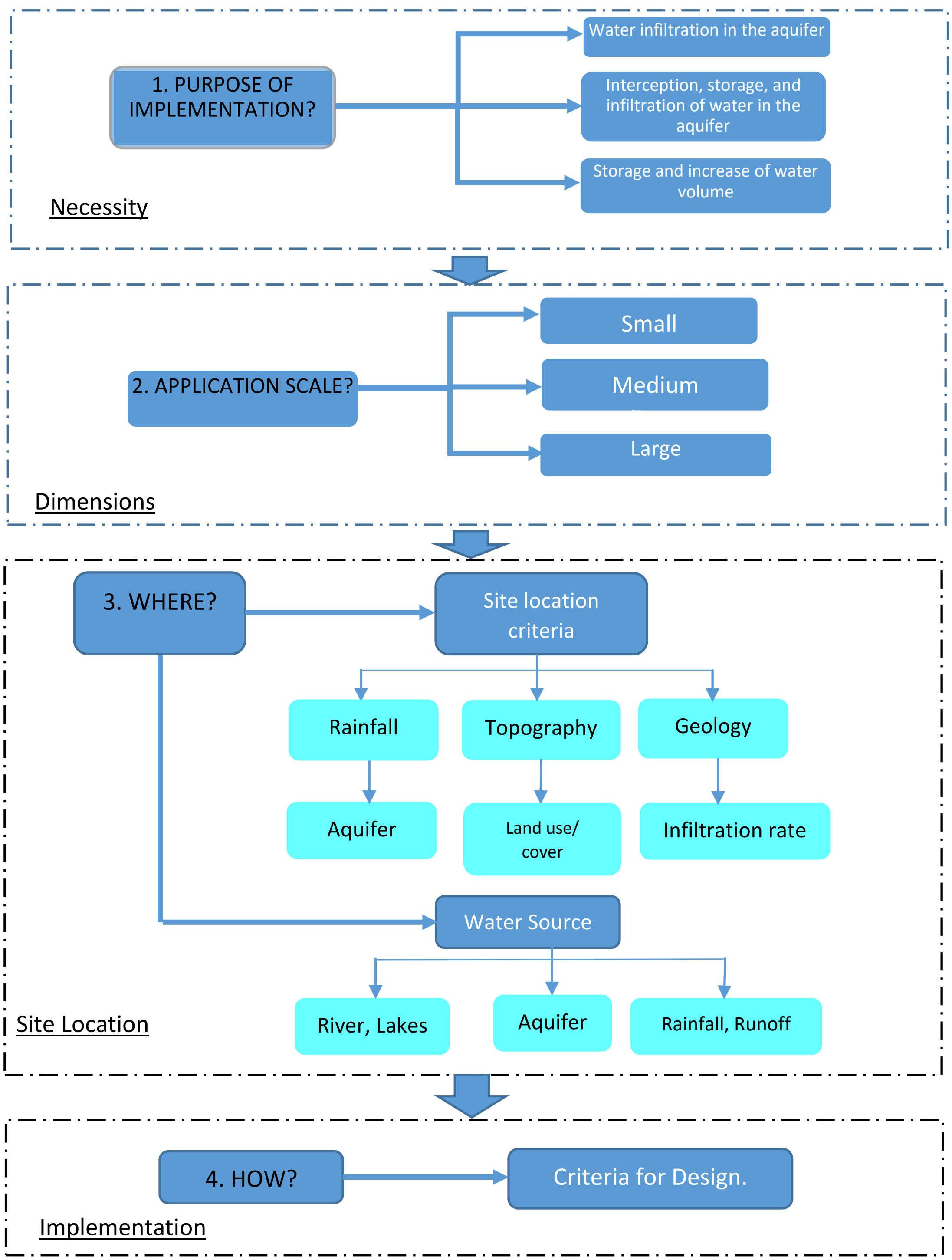
(Source: CGWB, 2011; IGRAC, 2007; MWR, 2007)

A3.2: Examples of locations where various planned aquifer recharge technique applied

	Techniques	Area Applied	Location
1.	Flooding	Flooding of Dorz Sayban Plain from Kaftari ephemeral river	Iran
2.	Irrigation	Irrigation applied in South area of Sierra Nevada	Spain
3.	Ditch and furrow		
4.	Recharge Basin	Atlantis recharge basin	South Africa
		Ruhr Valley	Germany
5.	Reverse drainage		
6.	Bench terracing	Konso terraces	Ethiopia
7.	Contour trenches and bunds	Amadongri village contour bunds and trenches in Bastar district	India
8.	Check dams and gully plugs	Arani River Check dam in Chennai	India
		Rohrer Island, Dayton in Ohio	USA
9.	Percolation ponds	Warud taluka Percolation ponds, Amravati District	India
10.	Recharge pits and shaft	Dewas District recharge pits and shafts	India
		Peoria pits at Illinois	USA
11.	Gravity head recharge well	Gravity head recharge wells in Orlando recharges Florida aquifer.	USA
12.	Injection wells/Leaky well	The water factory 21 project California, Orange District	USA
		Aquifer Storage and Recovery wetlands in Salisbury city	Australia
13.	Recharge dams	Palcacocha recharge dam in Ocona Basin	Peru
14.	Subsurface dams	Barwa Kalan subsurface dam in Rajgarh District	India
15.	Sand storage dams	Kiindu River sand dams, Kitui District	Kenya
16.	Watercourse modification	Gumjir Village diversion channels in Kanker District	India
		Pusaghat Village diversion channels in Kanker District	India
17.	Aquifer structure modification		
18.	Induced Recharge technique	Csepel Island Induced Recharge scheme in Budapest	Hungary

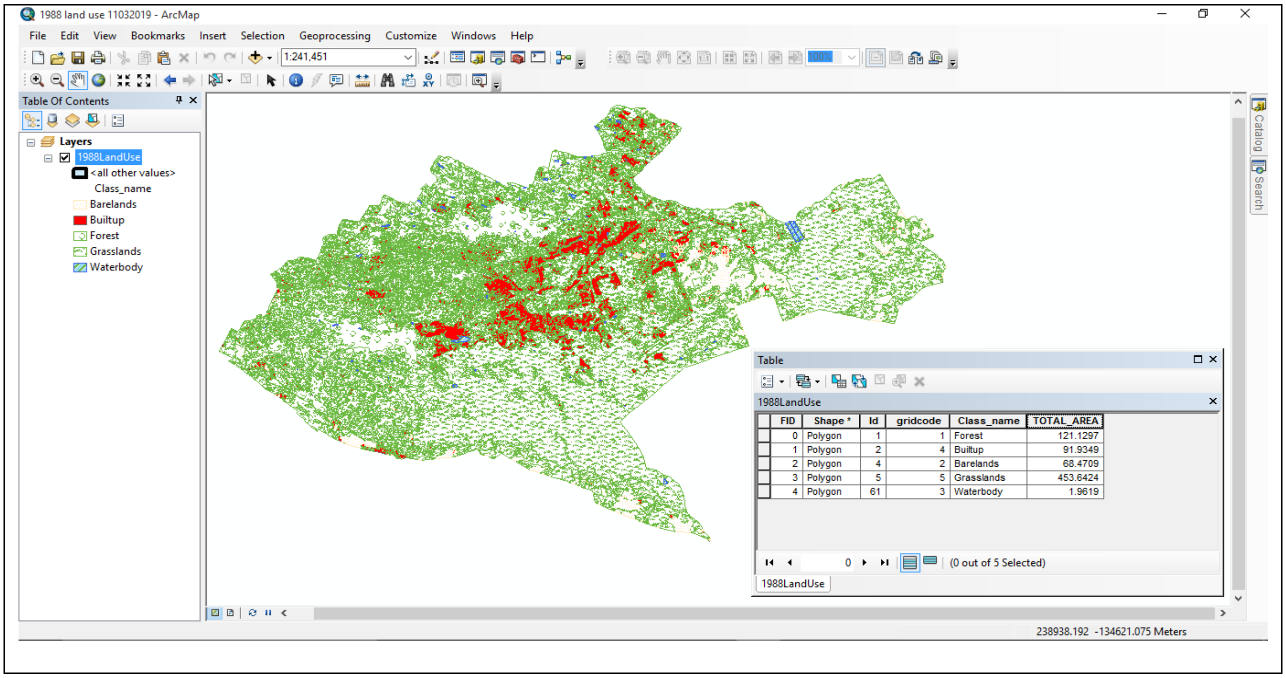
(Source: CGWB, 2008; IWP; *whc.unesco.org/en/list/1333; Raghunath, 2014; IGRAC, 2007)*

Appendix A4: Guideline analysis for applicability of groundwater planned recharge techniques.

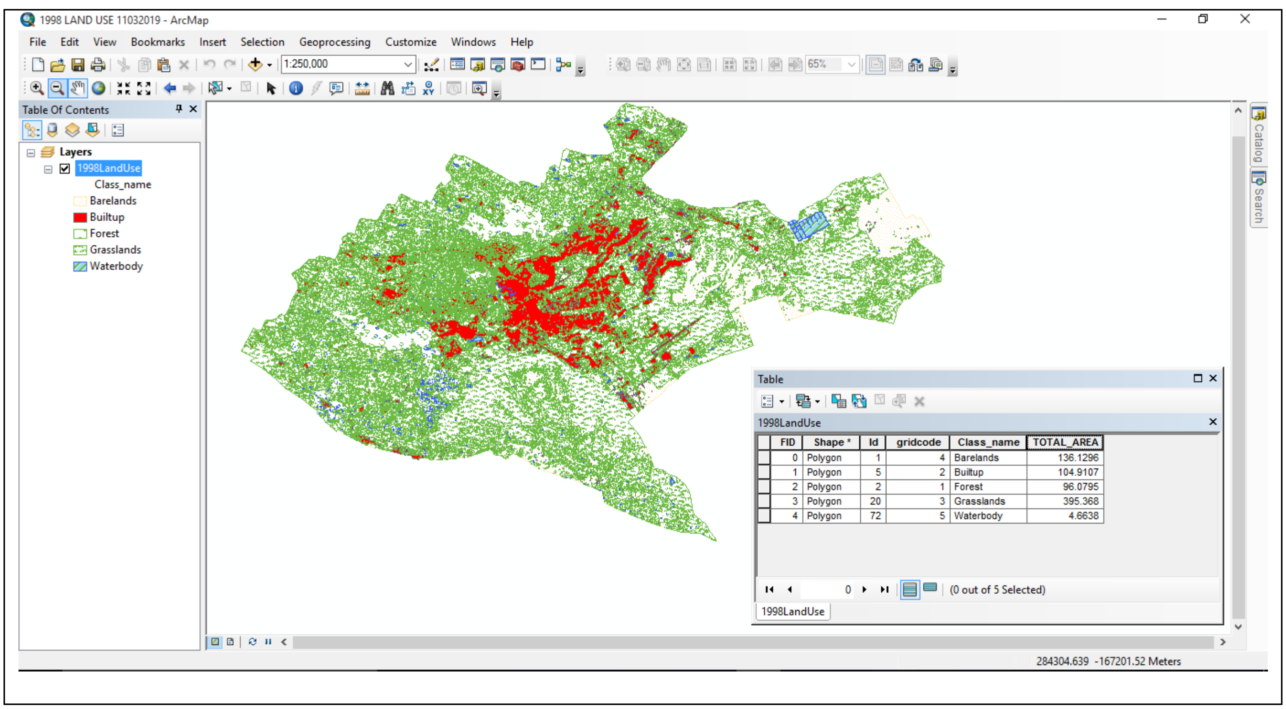


Appendix A5: Land Use Analysis for Analysed Years

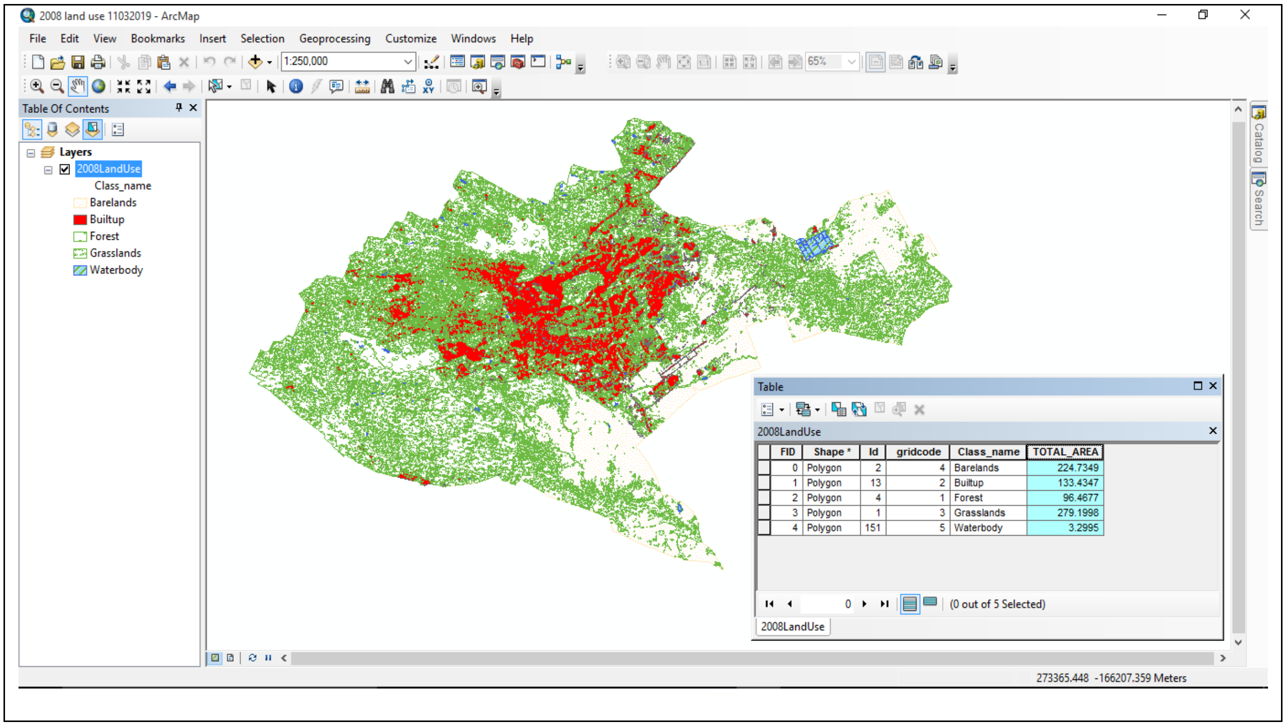
A5.1: 1988 Land use Results for Nairobi County



A5.2: 1998 Land use Results for Nairobi County

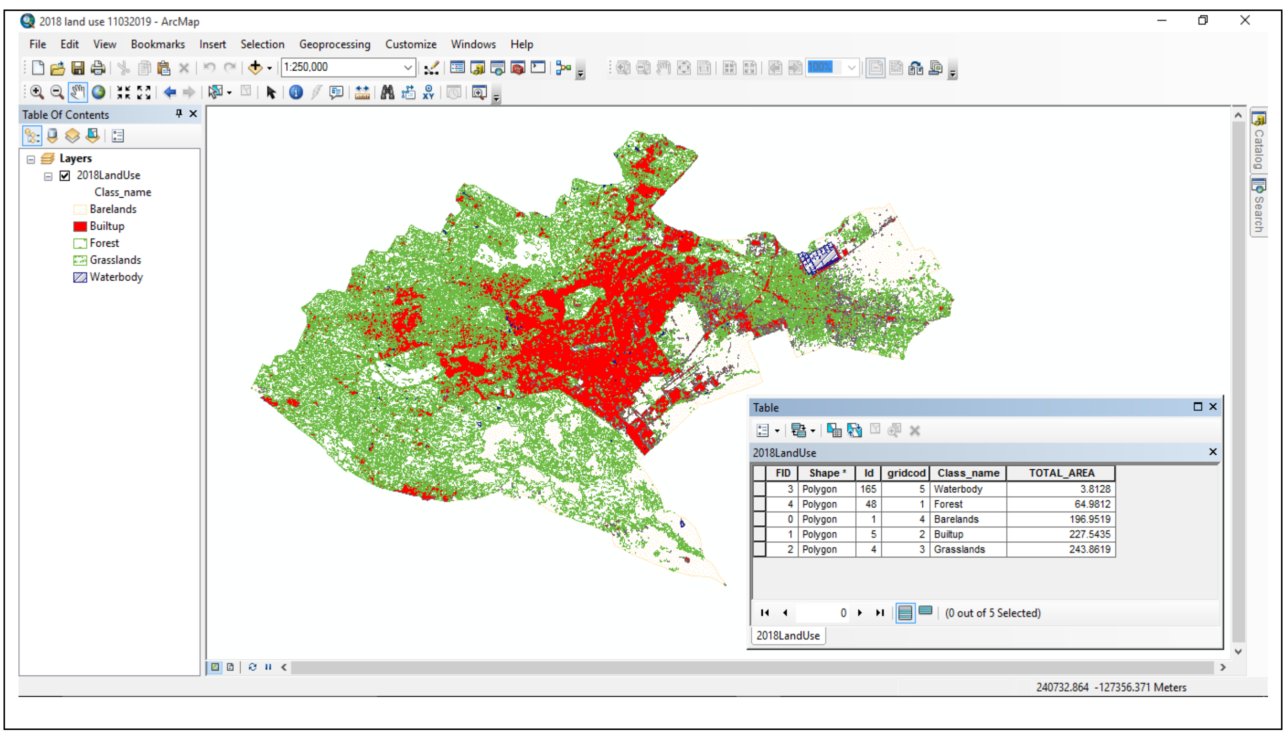


A5.3: 2008 Land use Results for Nairobi County



FID	Shape *	Id	gridcode	Class_name	TOTAL_AREA
0	Polygon	2	4	Barelands	224.7349
1	Polygon	13	2	Builtup	133.4347
2	Polygon	4	1	Forest	96.4677
3	Polygon	1	3	Grasslands	279.1998
4	Polygon	151	5	Waterbody	3.2995

A5.4: 2018 Land use Results for Nairobi County



FID	Shape *	Id	gridcod	Class_name	TOTAL_AREA
3	Polygon	165	5	Waterbody	3.8128
4	Polygon	48	1	Forest	64.9812
0	Polygon	1	4	Barelands	196.9519
1	Polygon	5	2	Builtup	227.5435
2	Polygon	4	3	Grasslands	243.8619

Appendix A6: Detailed Storm water Run-off in Zones Z-0 to Z-4

A6.1: Storm water Run-off in Zone Z-0

STORMWATER RUNOFF IN ZONE 0 (Z-0)

No.	LANDUSE IN Z-0	AREA, A_0 (KM^2)				C OF EXISTING LAND SURFACE	RAINFALL (I) mm/year				STORM WATER OF EXISTING LANDUSE FOR PREVIOUS 5 YEAR INTERVAL			
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11 = (2×6×7)*	*12 = (2×6×8)*	*13 = (2×6×9)*	*14 = (2×6×10)*
		2003	*2008*	*2013*	*2018*		*2003*	*2008*	*2013*	*2018*	*2003*	*2008*	*2013*	*2018*
1	BUILT UP / URBAN DEVELOPMENT / INDUSTRIAL AREA /AIRPORT	28.8327	22.0722	39.5139	29.8377	0.8	936	857	888.8	1030.7	21589925.76	15132700.32	28095963.46	24602973.91
2	WATER BODY / SWAMPY AREA	11.7723	0.0757	11.6153	0.1039	0.0	936	857	888.8	1030.7	0.00	0.00	0.00	0.00
3	FOREST / TREE COVER	4.9662	9.6365	14.0112	2.9361	0.4	936	857	888.8	1030.7	1859345.28	3303392.20	4981261.82	1210495.31
4	GRASSLAND / UNCOVERED SURFACE	9.5213	58.5329	6.6413	50.8446	0.4	936	857	888.8	1030.7	3564774.72	20065078.12	2361114.98	20962211.69
5	BARELAND / NATURAL RESERVES	61.9082	41.3792	45.1575	48.0075	0.5	936	857	888.8	1030.7	28973037.60	17730987.20	20067993.00	24740665.13
6	***TOTALS (m^3)***										***55987083.36***	***56232157.84***	***55506333.26***	***71516346.03***

A6.2: Storm water Run-off in Zone Z-1

STORMWATER RUNOFF IN ZONE 1 (Z-1)

No.	LANDUSE IN Z-1	AREA, A_1 (KM^2)				C OF EXISTING LAND SURFACE	RAINFALL (I) mm/year				STORM WATER OF EXISTING LANDUSE FOR PREVIOUS 5 YEAR INTERVAL			
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11 = (2×6×7)*	*12 = (2×6×8)*	*13 = (2×6×9)*	*14 = (2×6×10)*
		2003	*2008*	*2013*	*2018*		*2003*	*2008*	*2013*	*2018*	*2003*	*2008*	*2013*	*2018*
1	BUILT UP / URBAN DEVELOPMENT / INDUSTRIAL AREA / AIRPORT / FREE TRADE ZONE	61.4797	16.5479	16.8039	62.4271	0.8	727.2	605.2	819.2	848.1	35766430.27	8011831.26	11012603.90	42355538.81
2	WASTE WATER TREATMENT WORKS / MARSHY AREAS	11.5006	20.7805	6.7597	3.2079	0.0	727.2	605.2	819.2	848.1	0.00	0.00	0.00	0.00
3	FOREST / TREE COVER	0.0245	0.7882	42.7595	0.2935	0.4	727.2	605.2	819.2	848.1	7126.56	190807.46	14011432.96	99566.94
4	GRASSLAND / UNCOVERED SURFACE	10.327	65.2413	72.4133	42.3924	0.4	727.2	605.2	819.2	848.1	3003917.76	15793613.90	23728390.14	14381197.78
5	BARELAND / NATURAL RESERVES	164.1093	160.6132	108.3674	137.7799	0.5	727.2	605.2	819.2	848.1	59670141.48	48601554.32	44387287.04	58425566.60
6	***TOTALS (m^3)***										***98447616.07***	***72597806.94***	***93139714.05***	***115261870.12***

A6.3: Storm water Run-off in Zone Z-2

STORMWATER RUNOFF IN ZONE 2 (Z-2)

No.	LANDUSE IN Z-2	AREA, A_2 (KM^2)				C OF EXISTING LAND SURFACE	RAINFALL (I) mm/year				STORM WATER OF EXISTING LANDUSE FOR PREVIOUS 5 YEAR INTERVAL			
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11 = (2×6×7)*	*12 = (2×6×8)*	*13 = (2×6×9)*	*14 = (2×6×10)*
		2003	*2008*	*2013*	*2018*		*2003*	*2008*	*2013*	*2018*	*2003*	*2008*	*2013*	*2018*
1	BUILT UP / URBAN DEVELOPMENT	7.2346	8.5303	2.0588	12.724	0.8	640.9	1093.2	886.1		3709324.11	7460259.17	1459442.14	0.00
2	WATER BODY / MARSHY AREAS	29.9	0.1556	13.3505	0.1498	0.0	640.9	1093.2	886.1		0.00	0.00	0.00	0.00
3	FOREST / TREE COVER / NATURAL RESERVE	6.8118	22.8008	23.8668	17.3288	0.4	640.9	1093.2	886.1		1746273.05	9970333.82	8459348.59	0.00
4	GRASSLAND / CULTIVATED LAND	19.2193	31.7693	8.8098	33.9104	0.4	640.9	1093.2	886.1		4927059.75	13892079.50	3122545.51	0.00
5	BARELAND / COMPACTED SOIL	0.1474	1.273	15.1363	0.4738	0.5	640.9	1093.2	886.1		47234.33	695821.80	6706137.72	0.00
6	***TOTALS (m^3)***										***10429891.24***	***32018494.30***	***19747473.96***	***0.00***

A6.4: Storm water Run-off in Zone Z-3

STORMWATER RUNOFF IN ZONE 3 (Z-3)

No.	LANDUSE IN Z-3	AREA, A_3 (KM^2)				C OF EXISTING LAND SURFACE	RAINFALL (I) mm/year				STORM WATER OF EXISTING LANDUSE FOR PREVIOUS 5 YEAR INTERVAL			
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11 = (2×6×7)*	*12 = (2×6×8)*	*13 = (2×6×9)*	*14 = (2×6×10)*
		2003	*2008*	*2013*	*2018*		*2003*	*2008*	*2013*	*2018*	*2003*	*2008*	*2013*	*2018*
1	BUILT UP / URBAN DEVELOPMENT / INDUSTRIAL AREA	69.663	17.8466	28.0923	30.4354	0.8	927.9	775.1	915.2	1156.8	51712238.16	11066319.73	20568058.37	28166136.58
2	DUMP SITE/ WATER BODY / RETENTION PONDS	39.72	0.1137	17.9602	0.1524	0.0	927.9	775.1	915.2	1156.8	0.00	0.00	0.00	0.00
3	TREE COVER / NATURAL RESERVE	8.9252	45.1743	30.3199	30.5578	0.4	927.9	775.1	915.2	1156.8	3312677.23	14005839.97	11099508.99	14139705.22
4	GRASSLAND / RECREATION / TOURISM DEVELOPMENT	39.8027	70.5262	48.1934	71.4232	0.4	927.9	775.1	915.2	1156.8	14773170.13	21865943.05	17642639.87	33048943.10
5	BARELAND / UNCOVERED SURFACE	5.6412	2.9212	39.0412	4.0554	0.5	927.9	775.1	915.2	1156.8	2617234.74	1132111.06	17865253.12	2345643.36
6	***TOTALS (m^3)***										***72415320.26***	***48070213.81***	***67175460.35***	***77700428.26***

A6.5: Storm water Run-off in Zone Z-4

STORMWATER RUNOFF IN ZONE 4 (Z-4)														
No.	LANDUSE IN Z-4	AREA, A_4 (KM^2)				C OF EXISTING LAND SURFACE	RAINFALL (I) mm/year				STORM WATER OF EXISTING LANDUSE FOR PREVIOUS 5 YEAR INTERVAL			
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11 = (2 × 6 × 7)*	*12 = (2 × 6 × 8)*	*13 = (2 × 6 × 9)*	*14 = (2 × 6 × 10)*
		2003	*2008*	*2013*	*2018*		*2003*	*2008*	*2013*	*2018*	*2003*	*2008*	*2013*	*2018*
1	BUILT UP / URBAN DEVELOPMENT / INDUSTRIAL AREA	17.8203	68.4117	7.6252	92.1193	0.8	685.6	650.3	899.6	1007.1	9774078.14	35590502.81	5487703.94	74218677.62
2	WATER BODY / SWAMPY AREA	45.9312	0.1737	30.0824	0.1988	0.0	685.6	650.3	899.6	1007.1	0.00	0.00	0.00	0.00
3	FOREST / TREE COVER	20.9481	18.0374	31.9756	13.865	0.4	685.6	650.3	899.6	1007.1	5744806.94	4691888.49	11506099.90	5585376.60
4	GRASSLAND / RECREATION/ NATURAL RESERVE	25.3197	52.9767	19.3548	45.2912	0.4	685.6	650.3	899.6	1007.1	6943674.53	13780299.20	6964631.23	18245107.01
5	BARELAND / NATURAL RESERVES	5.4504	18.4392	26.3557	6.6352	0.5	685.6	650.3	899.6	1007.1	1868397.12	5995505.88	11854793.86	3341154.96
6	***TOTALS (m^3)***										***24330956.74***	***60058196.38***	***35813228.93***	***101390316.19***