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Groundwater Management Practice in Nairobi County

Researcher: Mr Nato Simiyu

Registration Number: F56/81512/2012

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university.

____________________ Date: 07 July 2015

Mr Nato Linus Simiyu
Registration Number: F56/81512/2012
Department of Civil and Construction Engineering
University of Nairobi

APPROVAL

This thesis has been submitted for examination with my/our approval as university supervisor(s).

____________________ Date: 07 July 2015

Dr Simeon Otieno Dulo
Senior Lecturer, Department of Civil Engineering,
Associate, Institute for Climate Change and Adaptation, University of Nairobi
PhD, FHSK, GERB, GIEK, MKSAE, Member NBCBN-RE,
Member Nile-IWRM, Member Water Cap

Dedicated to Kukhu Helena Namai Lusweti and Baby Wachiye Simiyu

‘while you are both happy in heaven your memories will keep us warm until we meet again’

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NOMENCLATURE

ACRONYMS

2D	Two Dimensional
37S	37 South (UTM Zone)
3D	Three Dimensional
ANN	Average Nearest Neighbour
BH	Borehole
BIS	Borehole Inventory Study (WRMA 2011)
CBD	Central Business District
CCN	City County of Nairobi
CIA	Central Intelligence Agency
DD	Decimal Degrees
DMS	Degrees Minutes Seconds
EC	Electrical Conductivity
EMCA	Environmental Management and Coordination Act
EPA	Environmental Protection Agency
ESRI	Environmental Systems Research Institute
GADM	Global Administration
GCA	Groundwater Conservation Area
GDP	Gross Domestic Product
GIS	Geographic Information System
ICRC	International Commission for the Red Cross
IUWM	Integrated Urban Water Management
KES	Kenya Shillings
LR No	Land Registration Number
MoPHS	Ministry of Public Health and Sanitation
MoPNDV2030	Ministry of Planning, National Development and Vision 2030
MS	Microsoft
NAS	Nairobi Aquifer Suite
NASWAP	Nairobi Aquifer Suite Water Allocation Plan
NWMP	Nairobi Water Master Plan
OOP	Object Oriented Programming
pH	Potential Hydrogen

PCS	Project Coordinate System
RDBMS	Relational Database Management System
TIN	Triangular Irregular Network
UAR	Utilization Factor
UN	United Nations
UN HABITAT	United Nations Human Settlements Programme
UNEP	United Nations Environmental Programme
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WGS	World Geodetic System
WHO	World Health Organization
WRI	World Resource Institute
WRMA	Water Resources Management Authority
WRRA	Water Resource Regulatory Authority
WSB	Water Service Board

UNITS

asl	Above Sea Level
BCM	Billion Cubic Meters
d	Day
Km	Kilometre
lpm	Litres per minute
m	Meters
m^3/d	Cubic Meters per day
MCM or Mm^3	Million Cubic Meters
mg	Milligram
mg/l	Milligram per litre
º	Degrees
p or pers	Persons
yr	Year

ABSTRACT

Nairobi County falls in the greater Athi River Catchment. Its groundwater resources lie in the Nairobi Aquifer Suite (NAS) which is a group of multi-layered aquifers in the volcanic flows rising from the southern Aberdares, the Kikuyu Escarpment and Ngong Hills and dipping gently eastward into the pre-Tertiary Athi Lake Basin, terminating at the Mozambican Basement System (CCN, 2007; WRMA, n.d (a)). The county is Kenya's economic hub employing about 25% of Kenya's employed population and contributing to 45% of Kenya's GDP. However in as much Nairobi is best served with infrastructure and utilities it faces challenges in providing adequate good quality water for its 3.1 million residents in 2009 who thus supplement the piped surface based supply with groundwater (UN Habitat 2006, Jacobsen et al, 2012). Groundwater was estimated to supply about 12.5% of the total daily demand, it's sustainable management faces challenges of haphazard drilling, over-abstraction, pollution, weak legislative framework and enforcement of regulations (CCN, 2007; World Bank, 2011; Jacobsen et al, 2012; UN HABITAT, 2006; Caroline O. et al, 2012; Stephen F. and Albert T., 2005). This study documented management practices, trends and recommend the best way forward to manage groundwater in the county. It mapped 2,632 licensed boreholes and developed spatial discrimination maps; assessed trends in practices such as borehole locations, drilling depths and interviewed WRMA staff on compliance and challenges faced. A hotspots analysis was performed to elucidate statistically significant borehole density and water abstraction hotspots. Proximity analyses also showed a 6% increase in the number of boreholes that lie within 100 m from each other from 2011 to 2013 whereas analyses on drilling depths indicated that an average increase of 170 m from 1930 to 2013 and this was attributed to pollution of the upper aquifer and potentially competition for groundwater. This study also elucidated that the low level of compliance is mainly driven by the county's population increase which drives other exigent contributing factors that include: increased water demand; intermittent piped supply; unclear legal framework; poor enforcement of supportive regulations; lack of a publicly available groundwater database for decision making; low capacity of the regulator; apparent groundwater availability that allows errant drillers to forego due processes, and low level of awareness of residents and borehole owners.

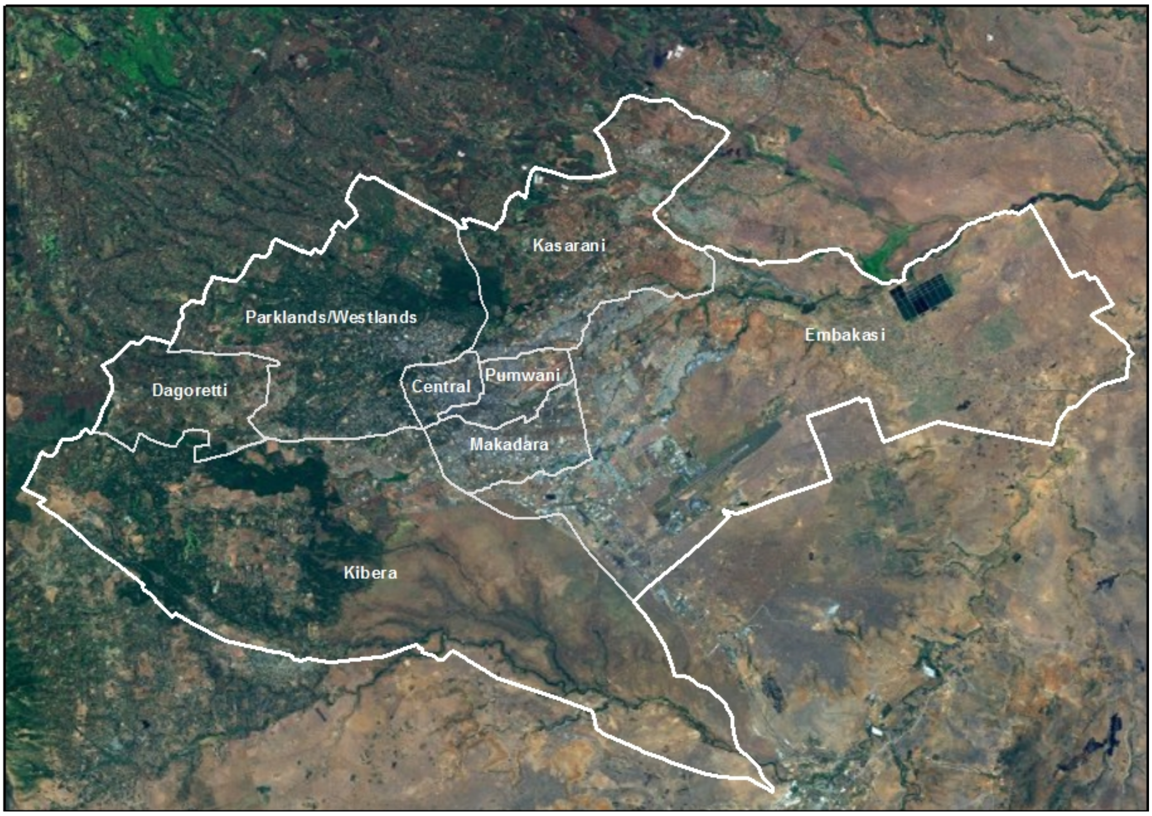
Keywords: Nairobi, Groundwater, GIS, Spatial Analysis, Management Practice, Compliance, Boreholes

INTRODUCTION

1.1 BACKGROUND

Nairobi County lies between longitude 37.106805° and 36.650011°; latitude -1.164925° and -1.456459° occupying an area of about 696 km^2 and is shown in Plate 0-1. Nairobi's altitude varies between 1,600 and 1,850 m asl. The county's western region is located on high ground (approximately 1700–1800 m asl) with a rugged topography. On the contrary the eastern region is generally low (approximately 1600 m asl) and flat.

Hydraulically the county falls in the greater Athi River Catchment, with its main drainage following the regional slope of the volcanic rocks towards the east, while subsidiary internal drainage into the Rift region is confined to the western part. The lava plains east of the line Ruiru-Nairobi-Ngong are underlain by a succession of lava flows alternating with lakebeds, streams deposits, tuffs and volcanic ash. These plains, comprising mainly the Athi plains and the northern section of the Kapiti plain, extend westwards, rising from 4900 feet (1493 m) at the Athi River to 6000 feet (1829 m) in the faulted region near Ngong (CCN, 2007; WRMA, n.d (a)).



Source: Google Earth, 2013.
Plate 0-1: Nairobi County

Administratively the county is divided into 8 divisions namely: Westlands, Kasarani, Dagoretti, Kibera, Makadara, Nairobi Central (Central Business District), Pumwani and Embakasi. In these divisions sub-divisions are generally named after neighbourhoods and they are over 50 sub-divisions in Nairobi, (CCN, 2007). The county falls under the jurisdiction of the Nairobi County government which is headed by an elected governor in accordance to the Constitution of Kenya of 2010. Similar to all other counties in the country, the functions of the central government and its parastatals are devolved into county offices.

Nairobi is Kenya’s capital city and economic centre employing about 25% of Kenyans and 43% of the country’s urban workers whilst generating over 45% of the country’s GDP, (UN Habitat, 2006). In 2009 the county’s population was enumerated to be approx.3.1 million during the night and 5 million during the day, however it is also estimated that 60% of this night population lives in Nairobi’s slums, (MoPNDV2030, 2009; UN Habitat 2006, Jacobsen et al, 2012).

In Kenya, Nairobi’s population has the highest access to infrastructure and services which include electricity, water, transport and sewerage. In the water sector it is estimated that 63% of Nairobi’s population has utility coverage whereas from the 2009 Housing and Population Census it was observed that 7.2% of households access water through boreholes whilst over 3,600 boreholes have been drilled in the county, (MoPNDV2030, 2009; WRMA, 2010, Jacobsen et al, 2012). From the 2009 Census, which focussed on households, the major access mode to water in Nairobi was piped water (75.7%) and this was mainly from Ndakaini, Ruiru, and Susumua dams thus the county imports its piped water primarily from the Tana basin, (UNEP, 2009; Jacobsen et al, 2012). However frequent droughts, climate change, poor infrastructure and improper management of the infrastructure has resulted in frequent service disruptions and reduced tap pressure. As a result of this a significant proportion of the population and industries of Nairobi depend on or supplement their water budget with groundwater, (CCN, 2007).

In the Athi Catchment it was found in 2009 that the available groundwater was $87x10^6$ m^3/yr which was approx. 7% of the total water available and this plays an important role in the sustenance of life and other economic activities in Nairobi County. This is because groundwater is widely exploited in urban areas as observed in 2009 the abstraction rate in the metropolitan area was approximately $58x10^6$ m^3/yr, (World Bank, 2011).

Despite the importance and availability of groundwater in Kenya, there are various challenges that are faced in sustaining and managing its supply and these include: poor water quality, over exploitation and saline intrusion. These factors lead to only 0.18 BCM of the 1.04 BCM available annually to be used, (World Bank, 2011). Other factors that affect its utility also include regulatory institutions' management capacities, weak policy and regulatory frameworks and implementation as well as climate change.

In Nairobi, although groundwater is an important substitute and supplement to the piped network, its utility and sustainability still faces similar challenges as the rest of the country. Whereas the county specific challenges and pressures in Nairobi include land use change, and population growth which is the major driver of all pressures and stresses, and increases water demand. It has also been reported that Nairobi presents a classic case of how the imbalance of supply and demand might grow over time since the population of Nairobi grew from 1.2 million to 3.2 million between 1989 and 2010 while water demand rose from 203,000 m^3/d to 579,000 m^3/d in the same period. The pressure on water resources together with poor enforcement of regulations has been reported to lead to non-compliance with regulations and industry guidelines, (World Bank, 2011; Jacobsen et al, 2012; UN HABITAT, 2006; CCN, 2007).

In view of this, attempts at sustaining and ensuring better management of Nairobi's groundwater are timely since water is fundamental to life and more so Kenya's economic centre and goals, (Caroline O. et al, 2012; Stephen F. and Albert T., 2005). This research is one such attempt since it will review abstraction principles and well locating practice based on regulatory stipulations in Nairobi. It will also map licensed boreholes in Nairobi and collect information management practices to elucidate analyse current trends and draw comparisons to legislative and industry guidelines or good practice. This will enable this study to inform policy and decision makers on the measures to take based on the review of current practices in addition to having a decision support system for groundwater management in Nairobi.

1.2 RESEARCH PROBLEM

Kenya is defined as a water scarce country with an annual water supply of 647 m^3/capita, and in this respect access to good quality water is not guaranteed in the required quantities, (Hilda M. et al, 2012). This situation is exacerbated by an increasing population which not only drives the water demand, negative environmental changes but also increases the costs of supplying this scarce supply to an increasing number of consumers. The impacts of this lack of access to good quality water is frequently observed with water-borne diseases being amongst the top ten causes of morbidity, (MoPHS, 2011). The importance of water to Kenya's goals is also embedded in the country's Vision 2030 which seeks to conserve water whilst also enhancing ways to harvest rain and groundwater, (MoPNDV2030, 2007). However this has not been the case with studies pointing to over exploitation of groundwater and only 54% of Kenya having access to safe drinking water and this is weighs on the achievement of MDGs 1, 4, 5, 6 and 7 (World Bank, 2011; MoPHS, 2011; WRMA, 2011).

Whilst Kenya has enacted several legislations and policies to manage its water resources, the management of groundwater remains a challenge due to low capacities of regulators in enforcing regulations, lack of streamlined mandates, and low awareness amongst the public on the regulations, (World Bank, 2011; Stephen F. and Albert T., 2005; Hilda M. et al, 2012).

In Nairobi groundwater supplements and in some cases substitutes the stressed piped water supply, however the lack of adequate management and enforcement of regulations has led to over exploitation and pollution reducing its availability and utility, (World Bank, 2011). Additionally it is also reported that as result of the pressure caused by 1999/2000 drought, the regulation of siting boreholes at least 0.8 km from one another was ignored and this thought to have put various regions at risk of developing of depression cones, (CCN, 2007). Thus there is an urgent need to manage Nairobi's groundwater sustainably and assessing trends in abstraction to inform policy and decision making.

Although sectoral reforms guided by the Vision 2030 are being undertaken in the form of the Kenya Water Master Plan and Water Bill of 2012, the importance of groundwater can't be overlooked, and few studies have been attempted at its mapping and modelling extraction in Nairobi. The Nairobi Borehole Study observed that the county's aquifer(s) are under threat from over-abstraction whilst the Nairobi Water Allocation Plan proposes that the distances between boreholes be determined from the area of well influence established from drawdowns, (WRMA, 2010). Other studies also observed that the rapid increase in number of boreholes has gradually led to a falling water-table and increased the cost of pumping, (Stephen F. and Albert T., 2005). These studies make it imperative to investigate ongoing trends in groundwater management in Nairobi as well as identifying any areas where regulations may have been overlooked. Thus this research will be one such study that will use engineering and scientific principles and methods, to contribute to solving the challenges faced whilst enabling informed decision making on groundwater management as partly required by Caroline O. et al, (2012), whilst also providing additional baselines.

1.3 RESEARCH OBJECTIVES

The main objective of this study was to assess groundwater exploitation practices in Nairobi and make recommendations for best practices to be adopted in the future. This objective was broken down into the following sub-objectives which are to:

- Assess the current trends in borehole location and siting,
- Assess the current trends of groundwater abstraction practices;
- Review prevailing groundwater abstraction practices against legislations and industry guidelines; and
- Make recommendations for best practices in the future based on study findings.

2 LITERATURE REVIEW

2.1 WATER SUPPLY AND DEMAND IN NAIROBI

In Nairobi County both ground and surface water supply residents, and the latter is mainly pumped from distances of up to 50 km from Ndakaini, Ruiru, and Susumua dams in the Tana basin. This surface supply is the main source of water and it supplied about 75.7% of households in the county in 2009. Groundwater on the other hand supplied about 7.2% of the households in 2009 and is also used by industries and other commercial developments in the county. In as much as there are three rivers (Nairobi, Mathare and Ngong) flowing through the county their quality often reduces their utility as a freshwater source, (CCN, 2007; Stephen F. and Albert T., 2005, MoPNDV2030, 2009).

Nairobi's population grew from approximately 1.2 million in 1985 to 3.2 million in 2010 and during the same period, water demand grew slightly faster, from 203,000 m^3/d per day to 579,000 m^3/d, (Jacobsen et al, 2012). The per capita water demand in Nairobi varies with the socioeconomic conditions of the different groups in the county and the national standard is set at 50 l/d. It had been estimated that the supply was capable of reaching an optimum of 592,000 m^3/d and thus supplying water comfortably up to the year 2010, (CCN, 2007). However future scenarios point that more water supply schemes, recycling and demand management measures would be required to ensure supply meets demand since studies have pointed that the water demand could rise to between 1 and 1.2 Mm^3/d by the year 2035. This is in view of the fact that the demand in Nairobi and its satellite towns in 2013 stood at an estimate of 750,000 m^3/d whereas supply stood at a deficit at 580,000 m^3/d, (Transworld Publishers, 2013; Jacobsen et al, 2012).

Under normal conditions in the county, the piped supply meets demands however this bulk water-supply is not reliable during periods of drought, and is also endangered by reservoir siltation associated with catchment deforestation. The supply problem is further aggravated by the poor state of the distribution system, which results in about a 50% supply loss due to leakage and illegal connections. Another factor affecting water supply is the inefficient and wasteful use of water by some consumers, even under rationing regimes, (Stephen F. and Albert T., 2005).

In view of these factors groundwater plays an important role in supplementing or substituting the surface supply. It was estimated that groundwater supplied 85,000 m^3/d in 2002 and after deducting main losses this amounted to 25% of the overall supply of Nairobi. This amount was estimated to have grown to 157,700 m^3/d in the entire NAS in 2009 and 133,300 m^3/d within the boundaries of the County in 2011, (WRMA, 2011). Most wells in Nairobi are operated by large private consumers (industrial enterprises and hotel complexes) or by individual residential owners in parts of the city that receive only intermittent supply. In these areas of individual residential owners wells are often shared with neighbours or water is sold for distribution by tankers at prices of about KES 4,000/m^3, (Stephen F. and Albert T., 2005). In addition to this most residential establishments such as apartment complexes in the middle and high income areas of the county also use groundwater to provide a consistent supply to their residents.

2.2 GROUNDWATER OCCURRENCE

Groundwater is an important source of portable water and excluding ice in the polar caps it is estimated to account for 97% of the freshwater in the world, (World Bank, 2011). Groundwater occurs from the infiltration, percolation or seepage of precipitation into the ground. It occurs in two zones with one immediately below the surface called the unsaturated zone and another which underlays this unsaturated zone, known as the saturated zone. The saturated zone is the one which mainly supplies wells and springs and is thus mostly commonly referred to as groundwater, (Ralph C., 1983).

Aquifers are rock units which yield water whereas those with low hydraulic conductivity are known as confining beds. Aquifers which are partly filled with water up to the upper saturated zone are known as unconfined aquifers whilst those that are fully filled with water and overlain by a confining bed are known as confined aquifers, (Ralph C., 1983).

There are various properties of aquifers which are important in studying groundwater as well as in its extraction and these are:

- **Porosity:** The ratio of openings (voids) to the total volume of a soil or rock, (Ralph C., 1983).

- **Specific yield:** The amount of water in storage that will drain freely under the influence of gravity, (Ralph C., 1983).
- **Specific storage:** The amount of water that is retained as a film on rock surfaces and in very small openings, (Ralph C., 1983).
- **Hydraulic Conductivity:** The rate of flow under a unit hydraulic gradient through a unit cross-sectional area of aquifer, (Ferris J.G. et al, 1962)**.**
- **Storativity:** The volume of water released from storage per unit surface area of a confined aquifer (or aquitard) per unit decline in hydraulic head, (Ferris J.G. et al, 1962)
- **Transmissitivity:** The rate of flow under a unit hydraulic gradient through a unit width of aquifer of thickness, (Ferris J.G. et al, 1962).

Groundwater is normally extracted through boreholes and wells which are drilled to the depth of the aquifers. In the case of boreholes the aforementioned parameters are measured during drilling and borehole testing.

2.2.1 Borehole Drilling, Construction and Development

The location of groundwater and subsequently a borehole is often determined by a hydrogeological survey and a development plan which specifies how the groundwater will be used is prepared therein. Hydrogeological surveys typically use magnetic resistivity methods to identify aquifers and carry out investigations on proposed borehole locations. Once a borehole's location is identified it is usually drilled through hand auger drilling, jetting, sludging, percussion drilling or rotary drilling. Rotary drilling is the most commonly used method of drilling and apart from hand auger drilling all the other methods are carried out through a drilling rig, (ICRC, 2010).

Boreholes are usually drilled to a target depth either in one constant diameter or through a set of reducing diameters through a process known as telescoping. Drilling is typically stopped when ideally an aquifer with a required yield is encountered within the drilling reach of a rig. The drilling process is also lubricated through the use of bentonite muds or organic polymers which also trap cuttings that are pumped to the surface. In the same respect drilling can also be done through the use of air whilst the chosen method often depends upon the geology encountered. This geology also determines the borehole's design and drilling logs developed from rock samples collected at regular intervals during drilling as used to identify this geology, (ICRC, 2010).

Boreholes construction is typically done to maintain a borehole's structural integrity and allow for water abstraction. Construction is done through casings mainly made of steel, galvanized iron or PVC. A gravel pack or screen is also installed in a borehole to filter out colloids from the water and a submersible pump is installed to lift water from the aquifer to the ground. A sanitary seal is normally installed at the top of the borehole and it can also be installed at the bottom to seal the borehole. Borehole development is carried out with two broad objectives, the first is to repair any damages done to the formation by the drilling operation so that the natural hydraulic properties are restored. Secondly it alters the basic physical characteristics of the aquifer near the borehole so that water can flow more freely to a well. Development can be carried out through mud dispersants, acid treatment, surging, blowing yield, air-lift pumping, jet washing and mechanical cleaning, (ICRC, 2010; Driscoll F.G, 1986 as cited in ICRC, 2010).

Test pumping is also carried out on a borehole to determine its yield and this information is also used in pump selection as well as determination of a pumping regime. Test pumping mainly determines the performance of the borehole, its efficiency, or variation of its performance under different rates of discharge, and quantifies aquifer characteristics, such as transmissivity, hydraulic conductivity, and storativity. Several test are usually carried out on a borehole and they curtail: test pumping, step tests, constant discharge tests and checking verticality. Geophysical logging and disinfection are then carried after testing, (ICRC, 2010).

2.2.2 Challenges Associated with Groundwater and Boreholes

Amongst the typical challenges associated with boreholes which cause its production and water quality to deteriorate include: water drawdown caused by pumping, incrustation, corrosion and mechanical failure. Therefore, consistent monitoring is important to any borehole and aspects that are usually monitored include water quality as well as the borehole's structural integrity, (ICRC, 2010).

Amongst the several challenges associated with groundwater subsidence caused by over-abstraction and anthropogenic pollution are the most key and these are reviewed in the following subsections.

2.2.2.1 Draw-down and Subsidence

The abstraction of water through pumping in an unconfined aquifer causes drawdown of the water table and a cone of depression occurs. The size and shape of this cone is dependent on: the rate and duration of pumping; the coefficients of transmissivity; the increase in recharge; the reduction in natural discharge, and the boundaries of the groundwater basin, (Fred K., 1960). Returning the water table to its initial level requires recharge of the aquifer and therefore over abstraction in the context of a borehole can be considered to be pumping until the water table drops to the pumping depth. In this respect a borehole eventually becomes dry if its aquifer's recharge rate doesn't meet the abstraction rate in the long run or if it lies in a confined aquifer with no recharge. This phenomenon of drawdown is theorized to occur as per the Theis equation given Equation 2-1 and illustrated by Figure 2-1.

Equation 2-1: Theis Drawdown Equation

$$s = \frac{Q}{4\pi T} W(u)$$

And

$$u = \frac{r^2 S}{4Tt}$$

Where:

s = Drawdown, m

T = Transmissivity, m^2/s

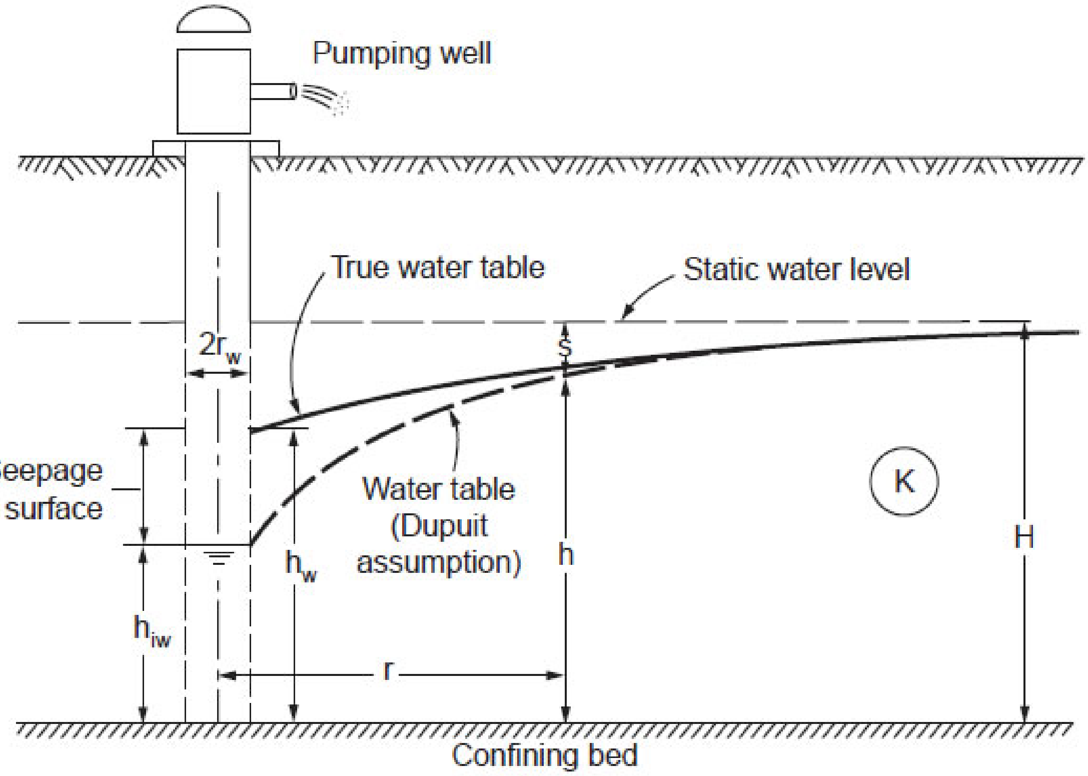
r = Distance to observation point, m

S = Storativity, dimensionless

t = Pumping Time, sec

$W(u)$ = Well function

(Source: Theis, 1935 as cited in Fred K., 1960)



Source: Chen F. and Liew Y., 2003 as cited in Ralph C. 1983.

Figure 2-1: Well Drawdown

Typically the pumping regime of a borehole allows for recharge through percolation into cone of depression of the aquifer based on its conductivity and transmissivity as per the relation given by the Theis equation.

Linked to the phenomenon of drawdown is the area of influence of a borehole which can be taken to be the direct area covered by the cone of depression. It is this area that the primary effects of pumping will be felt and when two or more areas of influence converge the overall drawdown will be the sum of the individual drawdowns, (Ralph C., 1983). Therefore, the case for over-abstraction in such a case and in the context of the aquifer would be pumping water from the boreholes at such rates as to increase the size of the zone(s) of convergence or the overall drawdown of the water table beyond the recharge rate's capacity to replenish the aquifer. This can cause land subsidence if an aquifer has beds of clay and silt within or next to it when water is pumped from the pore spaces between grains of sand and gravel. This is because the pumping will result in a lowering of hydrostatic pressure in the sand and gravel causing slow drainage of water from the clay and silt beds. The reduction in water pressure will result in a loss of support for the clay and silt beds which are compressible and thus compact resulting in the observable effect of the lowering of the land surface, (Leake S., 2013; Chen F. and Liew Y., 2003).

Subsidence is associated with further problems such as: changes in elevation and slope of streams, canals, and drains; damage to bridges, roads, railroads, storm drains, sanitary sewers, canals, and levees; damage to private and public buildings, and failure of well casings from forces generated by compaction of fine-grained materials in aquifer systems, (Leake S., 2013). It is also thought that over-abstraction practices in Nairobi County can cause subsidence as observed in Mexico City, (CCN, 2007).

Over abstraction can have several effects on the borehole and aquifer scales and these are presented in Table 2-1 according to their reversibility.

Table 2-1: Possible Effects of Over-Abstraction

Effect is:	Consequence	Indicator
Reversible	Pumping lift and cost increase.	Aquifer diffusivity characteristic.[1]
	Borehole yield reduction.	Depth to productive horizon and pumped drawdown.
	Spring and / or river baseflow reduction.	Aquifer storage characteristic. [2]
Reversible or irreversible [3]	Vegetation stress (natural and agricultural).	Depth to groundwater table.
	Aquifer compaction and transmissivity reduction.	Aquifer compressibility.
Irreversible [4]	Saline water intrusion.	Proximity of saline or polluted water.
	Intrusion / migration of polluted water.	
	Land subsidence.	Vertical compressibility of confining and / or intercalated aquitards – declining transmissivity.

NOTES

1 Transmissivity (*T*) divided by storage coefficient (*S*).

2 Storage coefficient (*S*) divided by mean annual recharge (*R*).

3 Short term response controlled by *T*/*S* (hydraulic diffusivity), long term response by *S*/*R*.

4 May be reversible in the long term (decades to centuries).

Source: Morris et al, 2003 as cited by WRMA, 2011.

2.2.2.2 Groundwater Pollution

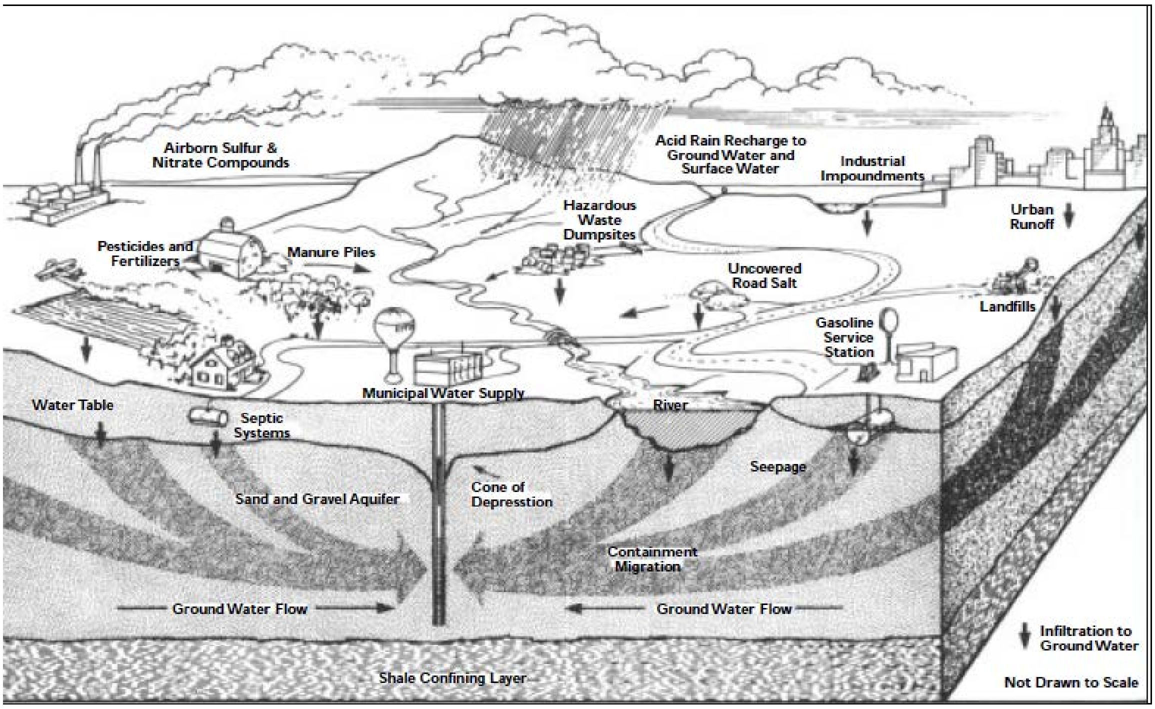
Groundwater can be polluted by the seepage of contaminants from human activities into aquifers. These contaminants are transported below the surface through either advection, diffusion, or dispersion, and their nature and composition varies with their source and the chemical, physical and biological processes that may occur on them. Table 2-2 outlines the potential sources of pollutants according to land use categories and the human activities which can mainly act as sources of groundwater contamination include: pesticide and fertilizer use; sewers and other pipelines; surface impoundments; septic systems; improper disposal of hazardous waste; mining activities; poorly constructed irrigation wells; poorly constructed active drinking water supply wells; improperly abandoned wells; improperly constructed wells; releases and spills from stored chemicals and petroleum products; landfills; injection wells; floor drains, and drainage wells, (Chen F. and Liew Y., 2003; EPA, 2013). Plate 2-1 illustrates some of these sources of contaminants and their transportation.

Table 2-2: Potential Sources of Groundwater Contaminant by Land Use

Category	Contaminant Source	
Agriculture	Animal burial areas Animal feedlots Fertilizer storage/use	Irrigation sites Manure spreading areas/pits Pesticide storage/use
Commercial	Airports Auto repair shops Boat yards Construction areas Car washes Cemeteries Dry cleaners Gas stations Golf courses	Jewellery/metal plating Laundromats Medical institutions Paint shops Photography establishments Railroad tracks and yards Research laboratories Scrap and junkyards Storage tanks
Industrial	Asphalt plants Chemical manufacture/storage Electronics manufacture Electroplaters Foundries/metal fabricators Machine/metalworking shops Mining and mine drainage	Petroleum production/storage Pipelines Septage lagoons and sludge sites Storage tanks Toxic and hazardous spills Wells (operating/abandoned) Wood preserving facilities
Residential	Fuel oil Furniture stripping/refinishing Household hazardous products Household lawns	Septic systems, cesspools Sewer lines Swimming pools (chemical storage)

Category	Contaminant Source	
Other	Hazardous waste landfills Municipal incinerators Municipal landfills Municipal sewer lines Open burning sites	Recycling/reduction facilities Road de-icing operations Road maintenance depots Storm water drains/basins Transfer stations

Source: EPA, 1991a as cited in EPA, 2013



Source: Paly, Melissa and Lee Steppacher, n.d as cited in EPA, 2013.

Plate 2-1: Groundwater Contamination Processes

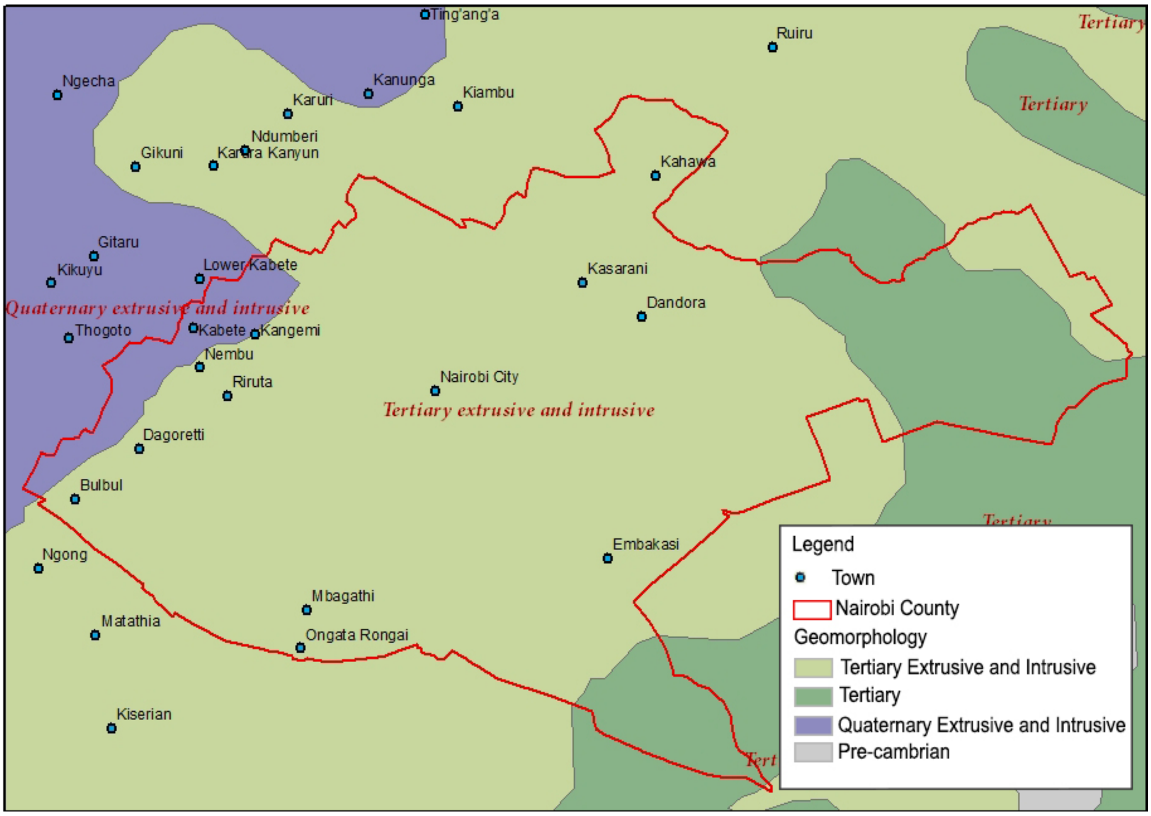
Natural processes such as dissolution or deposition of soluble rocks and minerals by run-off can also transport mineral contaminants into groundwater and this has been attributed to the high fluoride content in Nairobi's groundwater, (Gaciri S. and Davies T., 1993 as cited in Marleen C. et al, 2008). However regardless of the source of pollution of groundwater, the pollution of groundwater reduces its utilitarian value by lowering the water quality whilst the clean up or treatment of groundwater is often expensive. The slow movement of groundwater also results in the contaminants having a long residence time in the groundwater. Additionally groundwater contaminants can also be transported into surface water such as streams and rivers through seepage and in the case of springs they will be transported directly in the water, (EPA, 2013).

2.3 GROUNDWATER IN NAIROBI COUNTY

2.3.1 Hydrogeology of Nairobi

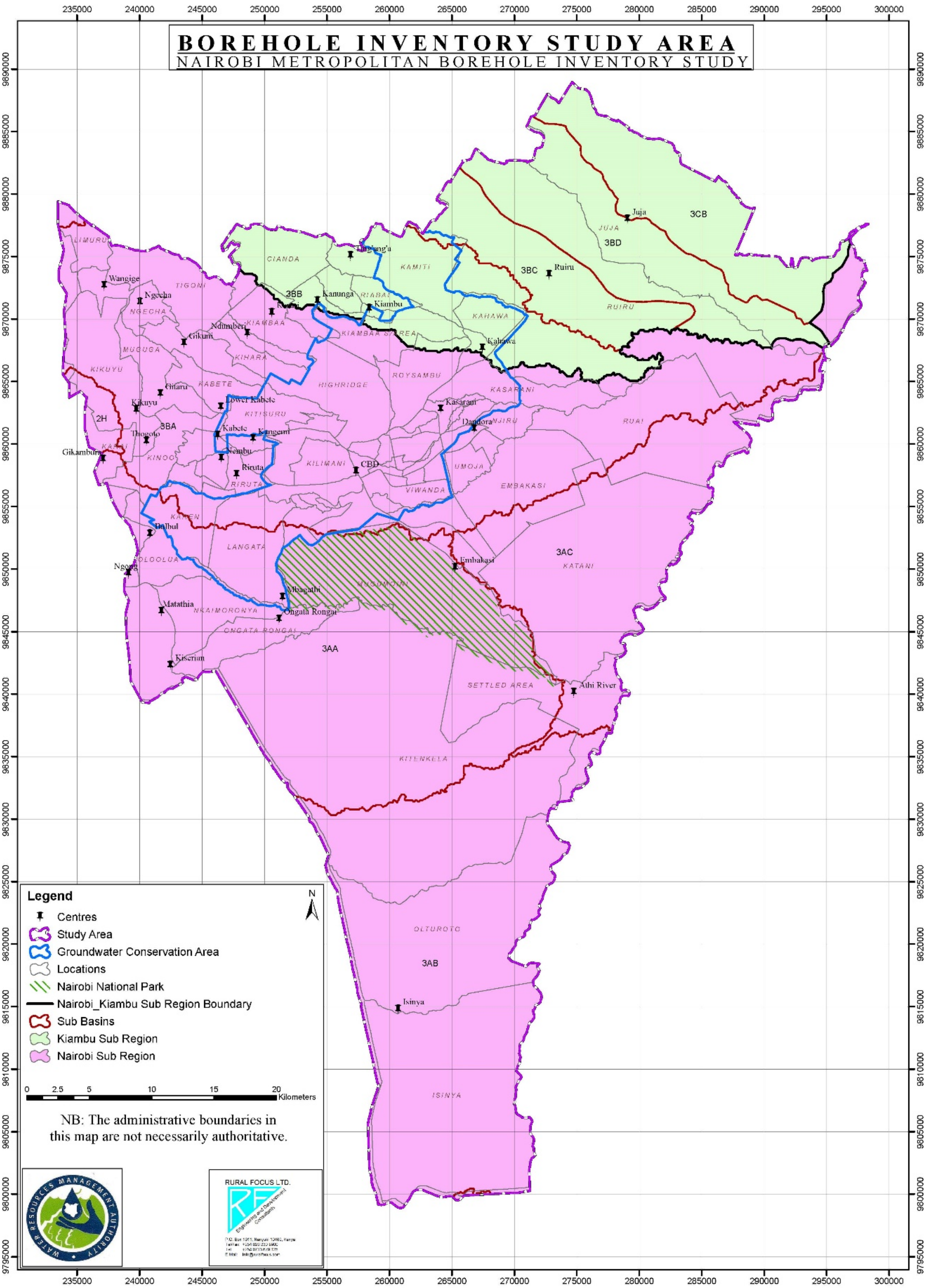
The Nairobi Aquifer Suite (NAS) is a group of multi-layered aquifers in the volcanic flows rising from the southern Aberdares, the Kikuyu Escarpment and Ngong Hills and dipping gently eastward into the pre-Tertiary Athi Lake Basin, terminating at the Mozambican Basement System (See Figure 2-2). The groundwater basin extends from the zone of north-south rift faulting west of the city (with an elevation of about 2400 m asl) towards the Athi river floodplain (with an elevation of 1500 m asl) east of the city centre. Volcanic activity has controlled the geomorphologic evolution – the rocks of the Nairobi basin mainly comprising a succession of volcanic lavas and ashes (tuffs), whose thickness reaches some 400 m underneath the city itself and which eastward gradually merge into to the Tertiary deposits of the Athi floodplain, (Gulf Power Ltd., 2010; Stephen F. and Albert T., 2005; WRMA, 2010).

The volcanic rocks show a wide range of porosity and permeability and have developed aquifer units separated by lower permeability strata. The aquifers consist of the Kerisha Valley Series and Upper Athi Series (transmissivity of 5-50 m^2/d and low storativity). The extension of this multi-layered aquifer system is fairly well known from the many boreholes that have been drilled to depths of 100-350 m. The Upper Athi Series is reported to be the main aquifer for boreholes in Nairobi, (Stephen F. and Albert T., 2005).



Source: WRI, 2009.
Figure 2-2: Geomorphology of Nairobi County

Recharge of groundwater in the NAS occurs from natural recharge and infiltration of wastewater, water mains leakage and excess rainfall. Most of the natural recharge occurs on the slopes of the rift zone, west of the city in the Ngong area, where the volcanic rocks are incised by numerous streams related to fault lines and weathered zones of the previous land surfaces. The upstream portions of these streams form an important source of aquifer recharge. The higher rainfall (1200 mm/a), dense vegetation, permeable soils and drainage pattern along the upper parts of these streams provide good recharge conditions – and although there is a lack of reliable recharge estimates some 25 Mm^3/a has been estimated to occur on average in this area, (Mulwa J. et al, 2005; Stephen F. and Albert T., 2005). Figure 2-3 shows the extent of the NAS and the groundwater sub-basins surrounding Nairobi County from Borehole Inventory Study (BIS) of 2011.



Source: WRMA, 2011.

Figure 2-3: Nairobi Aquifer Suite and Sub-Basins

2.3.2 Groundwater Legislative and Policy Framework

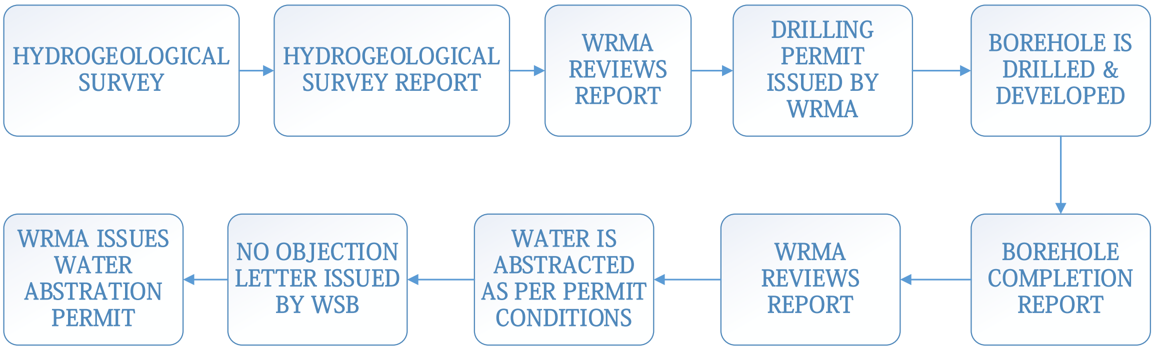
Groundwater is managed by various legislations enacted in Kenya and the key ones include: The Kenya Water Act of 2002, The Environmental Management and Coordination Act (EMCA) of 1999, and The Water Resource Management Rules of 2006. These regulations also mandate regulatory institutions in groundwater management to include: County Governments, Water Resources Management Authority (WRMA), National Environmental Management Authority (NEMA), Kenya Forestry Service (KFS), Water Service Boards (WSB), Catchment Water Boards (CWB), and Water Resource Users Associations (WRUAs). WRMA however has overall mandate over groundwater and is charged with the duty of licensing borehole drilling and water abstraction. WRMA's mandate is devolved into sub-basins with its Nairobi County falling under the Nairobi Sub-Region. This Sub-Region extends South of Nairobi and includes: Isinya, Rongai, Kitengela and Olturotu Sub-Locations, (WRMA, 2011).

Kenya recently launched several policies such as the National Water Policy of 2012 (NWP) and the Nairobi Water Master Plan of 2012 (NWMP) by Athi Water Services Board. These two policies seek an integrated approach in water resources management and the NWMP seek to increase the abstraction of groundwater sustainably whilst also protecting the resource from pollution. The NWP will replace Sessional Paper 1 of 1999. The NWMP also seeks to achieve an Integrated Urban Water Management (IUWM) system in Nairobi promoting both supply and demand management interventions. In light of developments in the water sector a new water bill was drafted in 2012 and is currently under-going the legislative process to become the new water act of Kenya. It will transfer the roles of WRMA to the new Water Resource Regulatory Authority (WRRA) which will be created by the legislation. The WRRA will have the responsibility of the groundwater administration which will include issuance of permits, monitoring, compliance and enforcement of regulations (Republic of Kenya, 2012 (a); Republic of Kenya, 2012 (b); Republic of Kenya, 2012 (c); Jacobsen et al, 2012).

2.3.3 Borehole Permitting Process

Currently the permit process for groundwater abstraction starts with hydrogeological investigations which result in a hydrogeological survey report. This report is submitted to WRMA in application for a borehole drilling permit. A constructor or contractor can then drill after this drilling permit is issued and on completion a borehole completion report is then submitted to WRMA in application for a water abstraction permit. The information submitted to WRMA in the borehole completion report includes aquifer and geologic parameters, well coordinates, well designs, borehole depth, required pumping rates and a map of neighbouring boreholes. The format of the hydrogeological and borehole completion reports are given in the 2nd Schedule of the Water Resource Management Rules of 2006 which curtails the information that is submitted to WRMA, (Republic of Kenya, 2006).

An Environmental Impact Assessment is also prepared for boreholes as required by the 2nd schedule of the EMCA of 1999 and this is submitted to NEMA for approval as well as WRMA. A letter of no objection from the pertinent water service board is also required prior to the issuance of the water abstraction permit, (Republic of Kenya, 1999; Republic of Kenya, 2006). This process is illustrated by Figure 2-4.



Source: Republic of Kenya, 2006

Figure 2-4: Borehole Permitting Process in Kenya

The aim of these regulations are to enable sustainable management of water resources information and consumption of water resources. However as pointed out severally in the foregoing discussion several studies have observed that these regulations and safeguards are sometimes overlooked or are not adequate whilst the management of boreholes data has been a challenge as well, (CCN, 2007; Muthoni N., 2009; World Bank, 2011).

2.3.4 Regulatory Compliance in Nairobi

Amongst the challenges that face groundwater management in Nairobi is policy implementation and legislative compliance. The National Policy on Water Resource

Management, and Development (Sessional Paper 1 of 1999) pointed out several issues facing groundwater and proposes solutions although to date most have not been implemented whilst a new policy is being drafted. Some of the issues pointed out by the policy and other studies include: haphazard drilling by private contractors, lack of groundwater conservation zones, lack of an up-to-date database for groundwater and a weak institutional framework even after the enactment of the Kenya Water Act of 2002. Also no specific policy has been implemented on groundwater and it is only 2007 that WRMA proposed one, (World Bank, 2011; Republic of Kenya, 2012 (a)).

There are no strict or specific regulations in Kenya regarding the spacing of boreholes contrary to CCN, (2007) whereas the Water Management Rules of 2007 only require that when test pumping a newly drilled borehole, the water levels in all boreholes within a 0.8 km radius should also be monitoring. This regulation has been reported to be challenging to implement as it can increase the costs of drilling boreholes and the owners of the neighbouring boreholes may not always be willing to allow their boreholes to be monitored. Additionally it is the generally considered as good practice to limit the proximity of boreholes to 100 m however polices recommend that this limit should be set based on the area of influence of existing boreholes. However a constant challenge to the implementation of regulations is the demand on groundwater caused by an increasing population residing in relatively small parcels of land. The implicit understanding is that there is sufficient understanding of Kenya’s aquifers that the WRMA can assess each application on its own merits in the context of the particular aquifer from which an applicant proposes to abstract water, (WRMA, 2011).

The NAS also has a Groundwater Conservation Area (GCA) that was gazetted in 1951 by the Water Ordinance of 1951 and the Groundwater Legislations of 1953. Its establishment has been considered to be a recognition of the risks posed by over-abstraction. The GCA covers the peri-urban areas of Nairobi extending up to Kamiti. It has been recognized by both water acts of 1972 and 2002. However studies point that it was meant to control the borehole density based on reducing water levels but was only effective up to the mid-1990s. The findings of the BIS indicated that it should be extended and enforced in the entire NAS by considering the aquifer system as a whole in addition to subjecting different areas to different management rules, (Gevaerts 1964 as cited by WRMA, 2011; WRMA, 2011).

In assessing compliance on an individual borehole basis the BIS found a significant number of boreholes in Nairobi do not comply with regulations. The assessment carried out in the study firstly covered five main requirements on the construction of boreholes which are based on regulations and good practice and these were:

- Having a dipper tube installed,
- Having a flowmeter installed,
- Paying water charges,
- Having a water abstraction permit, and
- Having a Borehole Completion Record (BCR).

This assessment of the BIS observed the ratios presented in Table 2-3 which show that most boreholes (56%) had a dipper tube whilst a majority of borehole owners didn’t have a BCR whereas only 20% could potentially be fully compliant under the scrutiny undertaken.

Table 2-3: Borehole Compliance in Nairobi in 2011

Sub-regional office	No. boreholes	% w. dipper tube	% w. flowmeters	% pay water charges	% w. Permit	% w. BCR
Nairobi	2,139	56	45	30	48	20

Source: WRMA, 2011.

This results show lack of regulation compliance and enforcement in groundwater management in Nairobi and by implication, Kenya with regard to borehole location, permitting, pumping and construction.

2.3.5 Groundwater Abstraction Practice in Nairobi

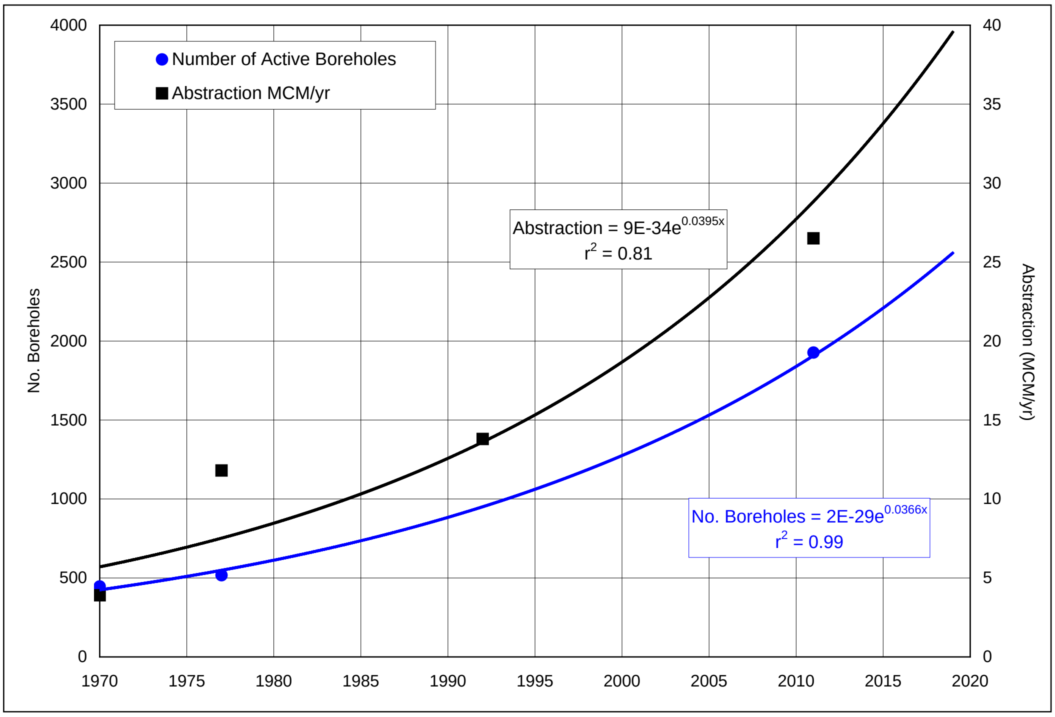
2.3.5.1 Number of Boreholes and Siting

Groundwater from the NAS has long been a supplementary water source for Nairobi residents with the earliest boreholes constructed in 1927. In 1964 there were at least 481 boreholes within what is now Nairobi County and by mid-2000 they were 1,150 registered boreholes in the same jurisdiction. By mid-2007 this number had risen to 3,639 in the then

Nairobi Province, with a total of 4,319 boreholes in the NAS which lies in the Athi catchment in an area of approximately 5,462 km^2. The total daily water demand in the NAS Area was estimated at 800,000 m^3/day in 2010, (WRMA, 2010; WRMA, 2011).

There has been various estimates on the number of boreholes in Nairobi from different studies that covered the NAS which includes the entire County of Nairobi. WRMA estimated that there were about 4,400 boreholes in NAS in 2011 whereas the BIS of Nairobi enumerated approx. 3,579 boreholes within the Nairobi sub-basin. Of these 3,579 boreholes 2,132 were located within the boundaries of the County. Moreover, 380 boreholes out of the 3,579 were inactive with the rest either being active or potentially active. Additionally other estimates from the NASWAP of 2010 estimated that there were about 4,800 boreholes in the County, (WRMA, 2010; WRMA, 2011).

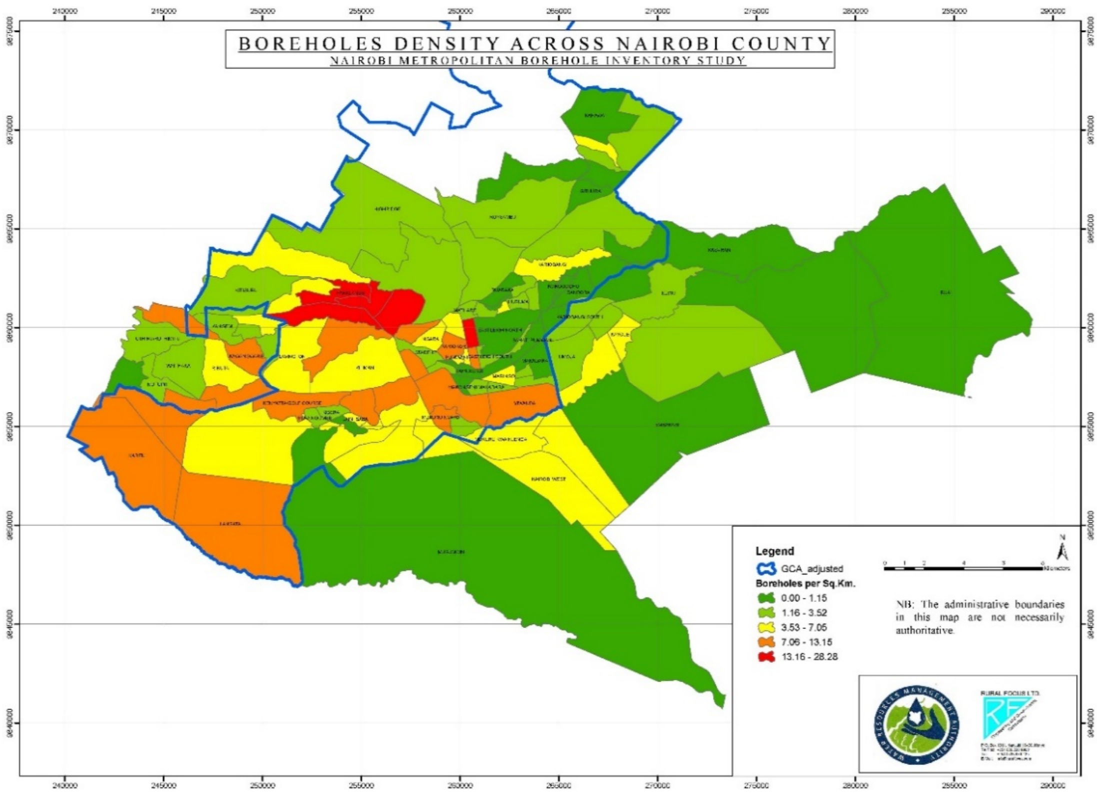
In view of this different estimates there is no single study that has conclusively answered the question of how many boreholes are in Nairobi and this is one of the challenges the management of groundwater faces. However the number of boreholes in Nairobi been steadily increasing. This has been attributed to a number of factors which include: the shortages in piped supply during the early 2000s, increases in GDP, population increase as well as changes in governance regimes, (WRMA, 2011). Figure 2-5 shows the annual trend and projections on the number of boreholes from the BIS and other census studies undertaken in the past.



Source: WRMA, 2011.

Figure 2-5: Annual Trend and Projections in Boreholes and Abstraction in Nairobi

The increase in the number of boreholes has also created hotspots where many boreholes have been drilled close to each other. The BIS of 2011 elucidated several hotspots in Nairobi to include the sub-locations of Eastleigh North, Highridge, Upper Parklands, Spring Valley and Muthangari. These Sub-locations had a borehole density of more than 15 BH/km^2 with the highest being Eastleigh North with a density 28.3 BH/km^2 and the BIS also showed that the number of boreholes in these hotspots increased in the 2 year period from the previous borehole hotspot mapping study undertaken by WRMA in 2009. The BIS calculated the density of boreholes in the entire region of the county to be 1.5 BH/km^2 and Figure 2-6 shows the borehole densities of the sub locations in Nairobi as calculated in the BIS, (WRMA, 2011). However this identification of hotspots was based on a ratio of the number of boreholes per unit area.



Source: WRMA, 2011.

Figure 2-6: Borehole Density in Nairobi in 2011

Of the 4,136 boreholes enumerated by the BIS it was observed that 20% lie within 100 m of another borehole although this varied from place to place. The study discovered that in Eastleigh North Sub-location hosted 25 boreholes, 12 were 100 m or less from a neighbouring borehole (48%). Whereas of the 584 boreholes captured in the Westlands/Kabete areas, no less than 139 were 100 m or less from another borehole (24%). The CBD/Upper Hill area was also similar whereby of 80 boreholes, 18 were 100 m or less from a neighbour (22.5%), of which three were abandoned/replacement borehole pairs (which reduced the ratio to 18.8%), (WRMA, 2011).

2.3.5.2 Abstraction Load

There have been few accurate studies on the abstraction loads of groundwater in Nairobi. It has been reported that in 1980 the total abstraction from 1,400 boreholes was 12 Mm^3/yr and this was based on the initial pumping rate during first test reduced by an annual utilization rate (‘UAR factor’) which took into account: the lower unit pumping rates compared to the initial test; the different pumping schedules typical of the given use, and the downtime periods. By 2000 the total abstraction was estimated (on the basis of an inventory of 175 ‘representative water wells’) to have increased to 32 Mm^3/yr from 2000 boreholes. In one study conducted by the World Bank, a ‘UAR factor’ of 0.2 was used to allow for more intensive pumping during a period of increased water shortage, and applying this to the 2,250 operating boreholes resulted in a total abstraction of 31 Mm^3/a (85 Ml/d) for the abstraction in the year 2002, (Stephen F. and Albert T., 2005).

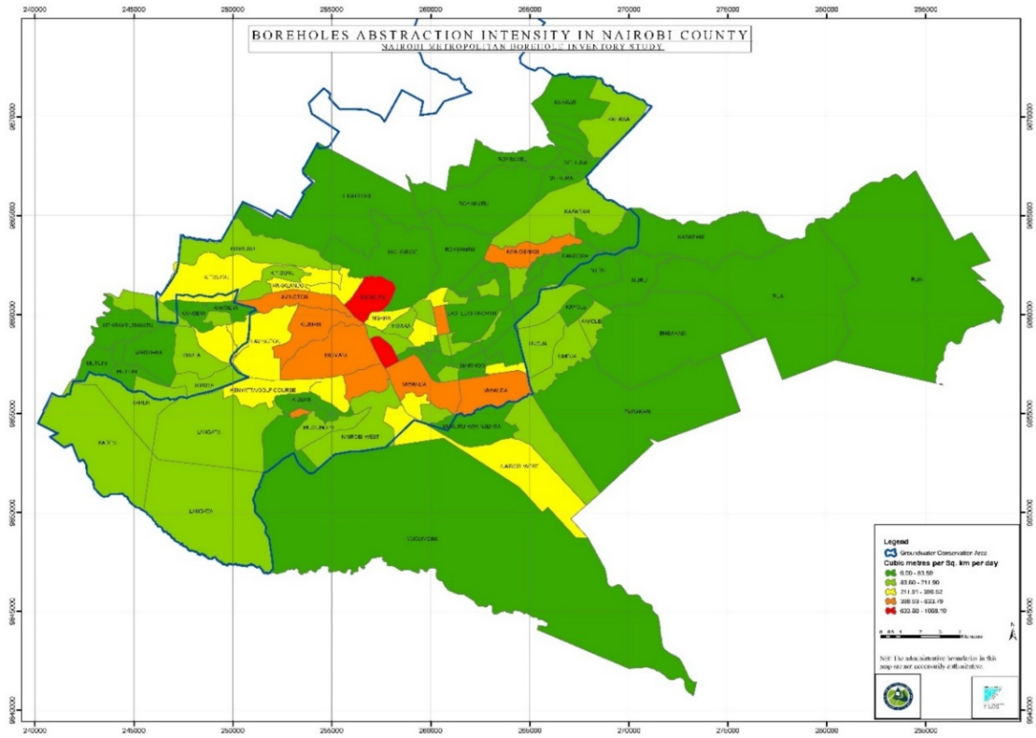
The Borehole Inventory Study of 2011 estimated a water abstraction rate of 72,541 m^3/d from 2,132 boreholes within the county. It further elucidated the annual trend from past studies of the NAS which included: The Nairobi Conservation Area Annual Survey Report of 1970; The National Water Master Plan of 1980; Howard Humphreys (K) Ltd 1984; Draft National Water Master Plan of 1992; MoLRRWD/BCEOM 1998; GW•MATE 2005, and The NASWAP of 2010. These studies covered different areas and their results are outlined in Table 2-4.

Table 2-4: Groundwater Abstraction in Nairobi from Past Studies

Year	No. BHs	Abstraction, m^3/BH/d	Abstraction intensity, $m^3/km^2/d$	Area, km^2	Mean abstraction,	
					m^3/d	MCM/yr
1970	446	23.7	17.5	602.8	10,570	3.9
1977	517	62.5	53.8	600	32,300	11.8
1984	245	15.9	54.5	71.6 (Zone 12)	—	—
1992	—	—	—	“Upper Athi”	52,300	19.1
	—	—	62.7	602.8	37,800	13.8
1997	2,000	45.0	56.3	1,600	90,000	32.9
2002	2,250	37.8		“Nairobi area”	85,000	32
2009	4,856	32.5	28.9	5,462	157,687	57.6
2011	3,848	37.5	48.9	2,727	133,302	48.7

Source: WRMA, 2011.

The BIS total estimate of the NAS presented in was based on 4,012 boreholes in area of 2,727 km^2 which includes Nairobi County whereas the NASWAP estimated an abstraction rate of 157,687 m^3/d from 4,856 boreholes in an area covering 5,462 km^2. Additionally the abstraction rate within the county alone was projected to rise above 40 MCM/yr by the year 2020. The BIS also calculated abstraction intensity in terms of $m^3/Km^2/d$ (See Figure 2-7) and identified five top abstracting Sub-locations to include: City Square (1,088.1 $m^3/km^2/d$); Highridge (904.7 $m^3/km^2/d$); Kongo Soweto (756.1 $m^3/km^2/d$); Muthwani (640.2 $m^3/km^2/d$), and Gatwikira (633.8 $m^3/km^2/d$), (WRMA, 2010; WRMA, 2011).



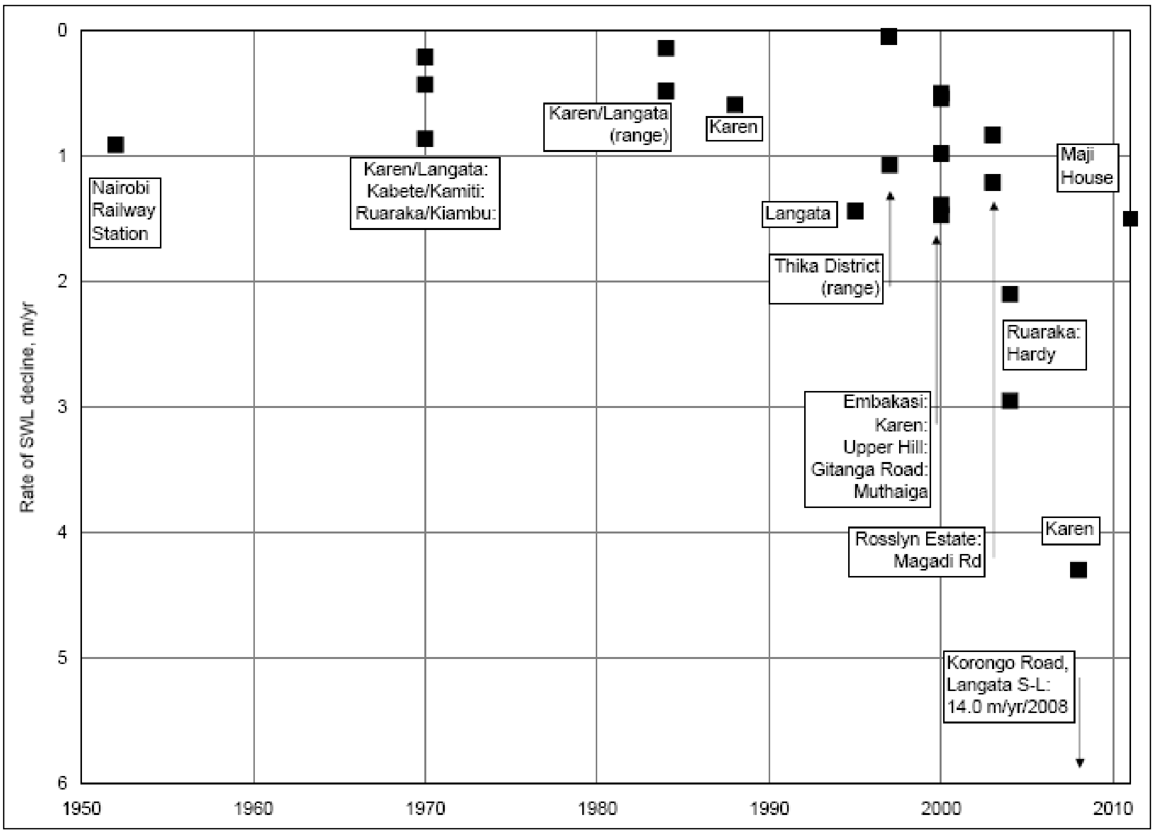
Source: WRMA, 2011.

Figure 2-7: Groundwater Abstraction Intensity in Nairobi in 2011

2.3.5.3 Groundwater Level

The number of boreholes in Nairobi has increased together the with the increasing population's water demand. This increase in boreholes has however not been met by sound management practices as has been observed catchment degradation and inadequate investment in water development have led to reductions in per capita volume of water in storage (NESC 2007 as cited in World Bank, 2011). Other studies have also pointed out that the increasing number of boreholes has led to falling water levels and increased pumping costs (WRMA, 2011; CCN, 2007; Mogaka et al, 2006). A 40 m decline was observed between 1958 and 1996 in one such study which was based on biannual measurements in a 275 m borehole. Generally lowering of water levels are observed in upper aquifer units as compared to deeper units (Stephen F. and Albert T., 2005).

The BIS compiled results from several studies of water levels within the NAS and its showed decline in water levels justifying the concern of the consensus that over-abstraction in the NAS is leading to falling water levels. The BIS assessed trends in 15 boreholes monitored by WRMA and confirmed this trend as illustrated in Figure 2-8. It was also noted that none of the studies had an aquifer wide scope. The study observed that the unit rate of depletion increased in the years previous to the study as compared to the period between the 1940s and 1980s, (WRMA, 2011).



Source: WRMA, 2011.
Figure 2-8: Depletion Rates in Nairobi

The possible effects of over-abstraction in Nairobi include: pumping lift and cost increase; borehole yield reduction; spring and / or river baseflow reduction; aquifer compaction and transmissivity reduction, and intrusion / migration of polluted water, (See Table 2-1 for the range of effects of over-abstraction). It has been estimated that lowering of water levels by up to 70 m increases annual pumping costs KES 870 million, (Mogaka et al, 2006). In the case of land subsidence there haven't any studies that have observed land subsidence as a result of over abstraction of groundwater in the County thus the effect remains uncertain, (WRMA, 2011). Additionally there are few studies that have modelled the flow or mapped the water table in Nairobi County.

2.3.5.4 Water Quality

Low water quality and over exploitation also limits the use of groundwater to supplement water supplies and in 2009 it was estimated that of the 1.04 BCM/yr considered safe yield only 0.18 BCM was used, (World Bank, 2011). Whilst Nairobi's groundwater often contains more than the WHO recommended maximum concentration of 1 mg/l of fluoride it generally meets the other requirements for drinking water, (Stephen F. and Albert T., 2005). In the case of fluoride it has also been observed from a study of 36 boreholes in the Embakasi area of Nairobi that deeper aquifers contain more fluoride, whereas aquifers with higher transmissivity contained less fluoride however all boreholes contained more than the standard 1.5 mg/l concentration, (Eliud W. and Douglas M., 2013). The principal sources of fluoride in Nairobi groundwater are the volcanic deposits of the East African Rift System which are richer in F^- than other analogous rocks in the world, (Gaciri S. and Davies T., 1993 as cited in Marleen C. et al, 2013).

2.4 GIS AND ITS APPLICATIONS IN GROUNDWATER

A GIS is defined as any system that collects, manages, updates, stores, presents and shares spatial information, (USGS, 2007). At the core of any GIS is data on the spatial aspects of the real world phenomena managed in a relational database (often called a 'geodatabase') together with descriptive attributes. This gives the GIS its strength since from this attributes behaviour and relationships can then be simulated and analysis carried out in the GIS through Object Oriented Programming (OOP). Additionally the Relational Database Management System (RDBMS) also enables GIS to manage spatial information in the computer environment. The spatial data is linked or referenced to a conventional coordinate system (mathematic model of the earth's surface) to give objects in the GIS position and direction (space and dimension) as an estimate of their state in the real world and a temporal dimension can also be added. Spatial data can be stored in the geodatabase or GIS in either of the four conventional formats which are: Vector, Raster, Triangulated Irregular Networks (TIN) or Addresses, (Zeiler M., 1999).

Spatial analysis or geospatial analysis is one of the most important tools and applications of GIS. This is because once real world aspects are mapped (linked by a common coordinate system together with their attributes) the user can answer real world spatial questions through queries and measurements in the computing environment. The field of spatial analysis has many applications, tools and models used across different fields and they can perform complex analysis such as in spatial statistics (both descriptive and inferential), data mining and simple analysis such as proximity measurements, (Paul A. et al, 2005; Manfred M. and Arthur G., 2010).

Proximity analysis is useful in answering distance based questions through queries that are applied to identify which features are within a certain radius of any feature of interest. ESRI's ArcGIS software has a proximity toolset which can be used in both 2D and 3D to discover proximity relationships by: creating buffers, calculating distances to a specific feature (near analysis), creating Thiessen polygons, and calculating Euclidean distances, (ESRI, 2010(a)).

GIS has many applications in hydrogeology and particularly groundwater. It has and can be used to: map boreholes and undertake spatial geospatial analysis on its quality or the fate and transport of pollutants, (Eliud W. and Douglas M., 2013, WRMA, 2011; George F., 2002); model and simulate the flow of groundwater, (George F., 2002); model and simulate the drawdown of caused by pumping, (Kouamé K. et al, 2013; Purjenaie A. et al, 2012); map users and catchment areas (WRMA, 2011), and model spatial and temporal variations in groundwater rest levels, (Caroline O. et al, 2012) amongst other numerous uses.

In Nairobi not many studies have been carried out targeting the mapping of boreholes and to show the extent of compliance with siting regulations. However as part of the permit process an impact assessment on near boreholes is required. One key study that was undertaken by WRMA was the Nairobi Metropolitan Borehole study which established a Microsoft Access database that linked field data and photos with Borehole Completion Records (BCR) and Authorisation/Permit Data. Part of the objectives of the study was to determine borehole proximity and manage borehole information. The study mapped 4,130 boreholes and discovered that over 820 boreholes lie within 100 m of each other whereas the central business district had the highest competition for water with pumping rates reaching as high as 1,100 m^3/km^2 d, (WRMA, 2011).

2.4.1 Spatial Data Analysis Models

Spatial data analysis is the terminology used to refer to the collective methods and models used in geographical sciences to perform quantitative and mathematical analyses on spatial data. The methods generally fall into four broad categories which include: spatial analysis (in general), pattern analysis, local spatial statistics, and empirical applications of spatial data analysis methods. The latter category consists of the applications of the other three categories, (Luc A. and Sergio J., 2010) and it generally remains broad and interrelated owing the numerous applications of GIS in different fields and subjects, (Stewart F. and Peter R., 2005).

Spatial analysis models are mainly spatial interaction and autocorrelation models such as the Getis Model; Moran's I Model; Variogram Models (Kriging), Joint Count Models; Second Order K Model; General Gravity Model; Geary's c Model; Semi-variance Model, and the Spatial Autoregressive Model amongst others. These models are generally considered to be a cross product statistic whereby their common elements include a matrix of values representing the association between locations and values representing a vector of the attributes of the various locations. Their cross product statistics is given as per Equation 2-2 whereas the construct of these models were used by Arthur Getis to develop the G*i* Models which link the spatial autocorrelation model to interaction models, (Getis A., 1991).

Equation 2-2: The Cross Product Statistic

$$\Gamma = \sum_{i,j} W_{i,j} Y_{i,j}$$

Where:

$W_{i,j}$ are elements of a matrix of measurements of spatial proximity of places *i* to places *j*

$Y_{i,j}$ is a measure of the association of *i* and *j* on some other dimension

Source: Getis A., 1991.

Pattern analysis models mainly focus on point data and are based on the theory second order theory which was developed by the motive that single measurements in between points is not sufficient to describe a set of point pattern data. The object of the theory is to find a cumulative distribution function based on all distances between pairs of objects. Since all inter-point distances taken together represent the total covariation in a set of points, the analysis of the distribution of these distances is considered as the study of the second moment or second-order analysis. Because attention is focused on the exploration of the arrangement of sets of points rather than on specific point locations, it follows that stochastic processes are the vehicle for analysis. Pattern analysis models include models such as the Ripley's K Model, The Clustering Model and The Inhibition Model, (Ripley, 1976, 1977 and 1979a as cited in Getis A., 1983; Getis A., 1983).

Pattern analysis models assume stationarity and their main construct is the Ripley's K Model which given by Equation 2-3 which produces an unbiased estimator by weighting paired objects, (Ripley 1981 as cited in Getis A., 1983).

Equation 2-3: Ripley's K Model

$$\widehat{K}(t) = A\frac{\sum k(x,y)}{N^2}$$

Where:

A is the area of the region under consideration.

$\sum k(x,y)$ is the sum of the weights associated with each of the ordered pairs of points labelled *x* and *y*.

N is the number of points in the sample.

$K(t)$ is the non-negative increasing function

Source: Getis A., 1983.

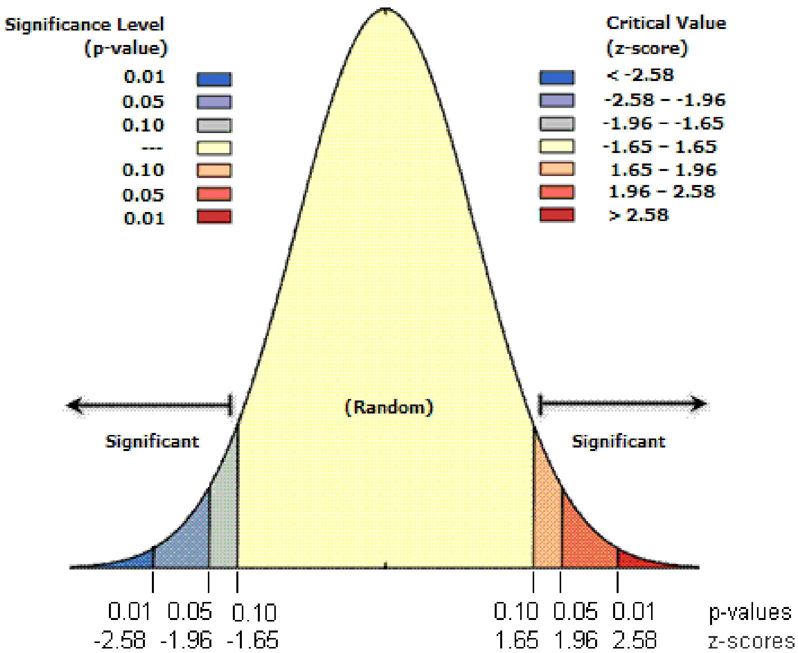
The last category of models are the Local Statistic Models which are a family of the G statistic developed by Getis A. (1991). These are of distance based statistics which evaluate the spatial association within a specified distance of a single point. The G statistic can be used together with Moran's I or some other measure of autocorrelation to deepen the understanding of the spatial series.

Pertinent considerations and applications or tools of these models in ESRI's ArcGIS Software are reviewed in the subsections that follow. These tools that are used in this study are based on the aforementioned models and include: Hotspots Analysis and Point Density for identifying clusters and Average Nearest Neighbour (ANN) and Near Analysis for proximity analyses.

2.4.1.1 Z-scores and P-values

In spatial autocorrelation models patterns, trends and clusters can be identified and analysed based on a null-hypothesis that assumes complete spatial randomness and the various methods for testing these patterns return a z-score and p-value for the target features. Based on the z-score and p-value the null hypothesis can either be rejected or accepted therefore determining whether a cluster or pattern is statistically significant or simply a random occurrence, (ESRI, 2013a).

The p-value is a probability and in the analysis methods in ESRI's ArcGIS it is the probability that the observed spatial pattern was created by some random process. When the p-value is very small, it means it is very unlikely (small probability) that the observed spatial pattern is the result of random processes, therefore the null hypothesis can be rejected. On the other hand z-scores are standard deviations return by the analysis methods and both scores are associated with the normal curve as shown in Figure 2-9, (ESRI, 2013a).



Source: ESRI, 2013a
Figure 2-9: Standard Normal Distribution Curve and Z-scores & P-values

Very high or very low (negative) z-scores, associated with very small p-values, are found in the tails of the normal distribution. When the analysis results small p-values and either a very high or a very low z-score, this indicates it is unlikely that the observed spatial pattern reflects the theoretical random pattern represented by the null hypothesis. For the null hypothesis to be rejected, a subjective judgement is typically made on the acceptable degree of risk associated in being wrong. In this respect a confidence level is selected and inform the decision on rejecting the null hypothesis unless the probability that the pattern is created by random chance is low (less than 1% probability). Table 2-5 shows the critical p-values and z-scores for different confidence levels and is useful as a guide in rejecting the null hypothesis, (ESRI, 2013a).

Table 2-5: Critical p-values and z-scores for different confidence levels

z-score (Standard Deviations)	p-value (Probability)	Confidence level
< -1.65 or > +1.65	< 0.10	90%
< -1.96 or > +1.96	< 0.05	95%
< -2.58 or > +2.58	< 0.01	99%

Source: ESRI, 2013a.

The analyses built on this model are founded on the spatial autocorrelation theory that objects close to each other tend to be more alike than those far apart.

2.4.1.2 Point Density Analysis

The Point Density Analysis method calculates the density of point features around a raster cell. Conceptually it works by defining a neighbourhood around each raster cell centre and the number of points that fall within the neighbourhood is totalled and divide by the area of the neighbourhood. The method uses a population attribute of the item to determine the number of times to count the point thus an item with a value of 3 would be counted as three points. In this respect the population field can be used to weight some points more heavily than others based on their meaning, (ESRI 2012).

The method is useful in finding areas where incidents or events are concentrated and in the context of this study areas where boreholes and water abstraction is high based on the boundary of Nairobi county.

2.4.1.3 Average Nearest Neighbour

This model involves identifying clusters by measuring the distance between each feature's centroid and its nearest neighbour's centroid then averaging all the distances of these nearest neighbours. Features are considered clustered if the average distance is less than the average distance of a hypothetical random distribution. In the same respect the converse is considered to be true for dispersed features. The Average Nearest Neighbour (ANN) is calculated as the observed average distance divided by the expected average distance (Equation 2-4), whereby the expected average distance is based on a hypothetical random distribution with the same number of features covering the same total area, (ESRI, 2013c).

Equation 2-4: Average Nearest Neighbour

$$ANN = \frac{\overline{D_O}}{\overline{D_E}}$$

Where $\overline{D_O}$ is the observed mean distance calculated as shown in Equation 2-5 and $\overline{D_E}$ is the expected mean distance calculated as shown in Equation 2-6.

Equation 2-5: Observed Mean Distance

$$\overline{D_O} = \frac{\sum_{i=1}^{n} d_i}{n}$$

Equation 2-6: Expected Mean Distance

$$\overline{D_E} = \frac{0.5}{\sqrt{\frac{n}{A}}}$$

Where:

d_i = Distance between feature i and its nearest neighbour

n = Total number of features

A = Area of a minimum enclosing rectangle around all features

The z-score for the ANN is calculated as shown by Equation 2-7.

Equation 2-7: Z-score for ANN

$$z = \frac{\overline{D_O} - \overline{D_E}}{SE}$$

Where:

$$SE = \frac{0.26136}{\sqrt{\frac{n^2}{A}}}$$

Source: ESRI, 2013c.

Features analysed through this model resulting in an ANN ratio/index less than 1 can be considered to be exhibiting clustering whereas those with a value greater than 1 can be considered to be dispersed. This model is useful for features which can be located in a study area without a direct relationship or influence. The model is also useful for assessing spatial distribution within a fixed study area, (ESRI 2013c).

2.4.1.4 Hotspots Analysis

This model identifies statistically significant hotspots and cold spots using the *Getis-Ord Gi** statistic on a set of weighted features. It does this by assigning a z-score and p-value on each input feature that enables the rejection or acceptance of the null hypothesis. It shows where features of high or low cluster spatially and it assesses each feature based on its neighbours. A feature with a high value may not be a statistically significant hot spot since to be a statistically significant hot spot, a feature will have a high value and be surrounded by other features with high values as well. The local sum for a feature and its neighbours is compared proportionally to the sum of all features; when the local sum is very different from the expected local sum, and that the difference is too large to be the result of random chance, a statistically significant z-score results, (ESRI, 2013b).

The Getis-Ord local statistic is calculated as shown by Equation 2-8.

Equation 2-8: Getis-Ord Local Statistic

$$G_i^* = \frac{\sum_{j=1}^{n} \omega_{i,\,j} x_j - \bar{X} \sum_{j=1}^{n} \omega_{i,j}}{S\sqrt{\frac{\left[n \sum_{j=1}^{n} \omega_{i,j}^2 - \left(\sum_{j=1}^{n} \omega_{i,j}\right)^2\right]}{n-1}}}$$

Where:

x_j is the attribute for the feature

$\omega_{i,j}$ is the spatial weight between feature i and *j*

n is the number of features

$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n}$

$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2}$

Source: ESRI, 2013b.

The Gi* statistic returned for each feature in a dataset is a z-score whereby for statistically significant positive z-scores, the larger the z-score is, the more intense the clustering of high values (hot spot). For statistically significant negative z-scores, the smaller the z-score is, the more intense the clustering of low values (cold spot), (ESRI, 2013b).

The hotspots analysis is useful in answering questions such as where certain incidents or events are concentrated based on input data of the location and nature of the incidents or events.

3 MATERIALS AND METHODS

The methods and data requirements that enabled this study to achieve its objectives are explained in the subsections herein.

3.1 DATA COLLECTION

Data identified from the literature review was collected data from WRMA and it included data on boreholes in the NAS which encompasses Nairobi County. The data was obtained from WRMA's data management system together with literature of recent studies conducted in the subject and area of interest of this study.

In general the data obtained included borehole location data which was used in mapping. It also included hydrogeological and borehole construction data from the borehole drilling and development process as well as operational data from the recommendations or permit conditions issued per borehole. The hydrogeological data included the data submitted as part of the application for borehole drilling and water abstraction permits as per the Water Resource Management Rules of 2006 and it included: drilling diameter, drilling and pumping depths, and pumping rates.

The data and literature obtained included these listed below with the key datasets explained in Section 3.2:

- MS Excel extract of all licensed boreholes in the Nairobi and Kiambu Sub-regions and their attributes from the WRMA MS Access database
- MS Excel file of listing all licensed boreholes in the Nairobi and Kiambu Sub-regions with their coordinates in UTM Zone 37S Arc 1960.
- Google Earth KMZ file of all licensed boreholes in the Nairobi and Kiambu Sub-regions mapped on the UTM Zone 37S Arc 1960 Projection.
- An MS Word copy of the report of the Nairobi Metropolitan Borehole Inventory Study.
- PDF Maps of boreholes and aquifers from the Nairobi Metropolitan Borehole Inventory Study.

An interview was conducted under the guidance of an interview guide (Appendix A1: Interview Guide), and it targeted WRMA's staff in the groundwater department in the Nairobi Sub-Region Office. It was done with the objective of obtaining first-hand information on groundwater abstraction practices in Nairobi as well as sourcing for insights on trends and challenges in groundwater management in Nairobi.

3.2 MATERIALS

Amongst the datasets obtained from WRMA, three were pre-qualified to perform the analyses to achieve the research objectives. These three include: the Extract from WRMA's Borehole Database; the list of Boreholes' Coordinates, and the KML/KMZ File of NAS's Boreholes. A shapefile of Nairobi County from GADM was also used to guide the study with regards to the boundaries of the county and its subdivisions.

3.2.1 Borehole Database Extract

The extract from WRMA's Borehole Database was created by copying all the data in WRMA's MS Access Borehole Database and pasting in an MS Excel spreadsheet. The WRMA Database is used by WRMA to manage all information on Boreholes based on BCRs. The spreadsheet contained information on 3,761 boreholes covering the following subjects: WRMA Permit Numbers, Borehole Number, Borehole Name, Administrative Location, Map/Sheet, Area, Coordinates (Geographic and Projected), Owner Name, Owner Address, Locality/Estate, LR No, Intended Use, Contractor, Construction Supervisor, Work Completed Date, Final Drilling Depth, Main Drilled Diameter, Cased Diameter, Depth of Main Aquifer Struck, Water Rest Level, Tested Discharge (lpm), Pumped Water Level, Recommended Yield (lpm), Alternate Units of Recommended Yield, and Pumping Depth.

This dataset was the most comprehensive since the database is meant to be main repository for managing borehole data by WRMA. However the dataset had various shortcomings which limited the type of analyses that could performed using it. This dataset information on the most boreholes as compared to the Borehole Coordinate List but only 1,077 (approx. 29%) boreholes had complete and utilizable coordinates. Additionally since the database was created from WRMA's previous system and included old records dating back to 1900 and significantly from the 1920s, it had data gaps on the attribute information of the boreholes. One key aspect of the dataset was the WRMA Permit No which included information on permits issued before WRMA's current system of permits. Thus these permits were numbered as NOAUTH and they were the majority of the dataset composing 67% of all records. The coverage of this dataset was analysed by calculating the percentage of entries per category the results are presented in Table 3-1.

Table 3-1 : Borehole Database Extract Data Coverage

Attribute	Entries	Percentage
WRMA Permit No	3758	99.92%
Borehole No	3596	95.61%
Borehole Name	2022	53.76%
Location	2166	57.59%
Map/Sheet	1345	35.76%
Area	1797	47.78%
East (°)	1017	27.04%
East (Min)	998	26.54%
East (Sec)	889	23.64%
North (°)	1006	26.75%
North (Min)	1004	26.70%
North (Sec)	908	24.14%
East (DD)	324	8.61%
North (DD)	324	8.61%
UTM X	438	11.65%
UTM Y	451	11.99%
Zone	2826	75.14%
Owner Name	3730	99.18%
Owner Address	2734	72.69%
Locality/Estate	3122	83.01%
LRNo	2370	63.02%
Intended Use	1776	47.22%
Contractor	2760	73.38%
Supervisor	1856	49.35%
Work Completed	3600	95.72%
Final Depth (m)	3676	97.74%
Main Drilled Diameter (mm)	3201	85.11%
Cased Diameter (mm)	2368	62.96%
Main Aquifer Struck (m)	2806	74.61%
Water Rest Level (m)	2607	69.32%
Tested Discharge (lpm)	2320	61.69%
Pumped Water Level (m)	1791	47.62%

Attribute	Entries	Percentage
Recommended Yield (lpm)	1560	41.48%
Alternate Units	1075	28.58%
Pump At (m)	1837	48.84%

Thus this dataset was used to perform analysis on borehole characteristics and water abstraction and together with the Borehole Listing it was used in the spatial analysis conducted in this study.

3.2.2 List of Borehole Coordinates

This dataset was prepared by the WRMA Sub-Region office based on the information submitted in applying for borehole permit. It is used by the Nairobi Sub-regions office to identify existing boreholes in the neighboured of a proposed borehole and thus determine the fate of borehole permit application or license conditions. It contains data covering: the borehole permit number, the name of the borehole owner, date and the coordinates of the borehole in UTM. The dataset contains this information for 3,016 boreholes whose dates range from the year 2007 to 2013 and thus has more recent entries as compared to the database extract. The permit information stored in this dataset includes only the permit number issued through WRMA's current system of permit information management.

This dataset limitations mainly included erroneous entries in the coordinate information and these only were on 115 boreholes (approx. 4%) thus this dataset was mainly utilized to generate the borehole multi-point feature class. This dataset was supplemented with the accurate coordinates from the Database Extract Dataset and duplicate entries in the resultant table/dataset were identified and removed using MS Excel.

3.2.3 NAS Borehole KML File

This dataset was created by WRMA's Nairobi Sub-region Office for undertaking quick assessments on borehole locations when a new permit is applied for. The dataset maps boreholes based on the name of the borehole owner and contains 2,925 boreholes. In terms of accuracy it only had 35 entries outside of the NAS area and it was used together with the Database Extract and Borehole Listing to enumerate the boreholes in Nairobi as perform the spatial analyses undertaken in this study.

3.2.4 GADM Boundary Shapefiles

Administrative shapefiles used in this study included Nairobi County's, divisions, locations and sub-locations which were created from the GADM[1] shapefiles of each of these levels of administration for Kenya. The county boundary was taken to be that of the former Nairobi province and district whereas the other boundaries included: 8 divisions, 30 locations and 62 sub-locations. These datasets were the only one this study was able to obtain whereas a more recent dataset on Sub-locations was obtained from ArcGIS Community but it was inaccurate in terms of the coordinates of the boundaries. Additionally the data on population from the 2009 census was added onto the Sub-location shapefiles using ArcGIS feature editing tools and join table method.

3.3 SOFTWARE AND HARDWARE

The softwares that were used for this study were mainly the following:

- ESRI's ArcGIS
- Microsoft Excel
- Global Mapper

The hardware that was used in this study was be a personal computer with the following features:

- Model: Acer Aspire 3750G
- Operating System: Windows 8 Pro
- Processor: Intel Core i5-2430M
- Architecture: 64 bit
- Processor Speed: 2.4 GHz
- RAM: 8 GB

[1] www.gadm.org

3.4 METHODS

3.4.1 Data Preparation

3.4.1.1 Data Sorting and Assessment

The collected data was prepared for analysis in MS Excel firstly by sorting and assessing them particularly the Borehole Database Extract and the List of Borehole Coordinates and secondly assessing the adequacy and coverage the two datasets. MS Excel was also used to sort the data in the Borehole Database Extract into the respective categories of assessment: drilling depth, pumping rate and location. It was also used to sort the water monitoring data in preparation for analysis.

3.4.1.2 Geodatabase Development & Borehole Mapping

An ArcSDE Geodatabase was created to manage of all spatial data in this study and some background datasets were loaded into it and these included: administrative jurisdictions in Nairobi County from GADM, and Towns and Villages from WRI. All datasets were projected to the UTM Zone 37S Projected Coordinate System on the Arc 1960 Datum which is based on the Clarke 1880 Spheroid.

The List of Borehole Coordinates and Database Extract were merged in a spreadsheet and duplicates identified in a three-fold assessment. The first identification of duplicate entries was based on a scrutiny of WRMA permit numbers, coordinates, dates and names of borehole owners. The second identification was based on names of borehole owners and coordinates, and the third identification was based on the coordinates alone. The identified duplicate entries were removed from the table and on each identification the entries were sorted and MS Excel's method of formatting duplicate entries differently was used to identify them. The KMZ file of Boreholes was converted to a Shapefile, using Global Mapper's Export method, which was then accessed in ArcGIS and its entries were exported to a database file (.DBF file). The database file was then accessed in MS Excel and used to identify Borehole which may have been present in the KMZ file but not in the other two datasets using the three-fold assessment of duplicates.

The table containing the resultant de-duplicated boreholes table was a union of three datasets in which the KMZ and Borehole Listing had similar attribute categories and the Database Extract had more attribute categories. Therefore, this meant that entries from the

KMZ and Borehole Listing had null values in respect to the categories which were specific to the database extract. In this respect the attribute categories that matched (Permit Number, UTM X, UTM Y and Borehole Owner) were intersected and those that differed (Work Completed Date from the Database Extract and Application Date from the other two datasets) were maintained separately. Thus this also meant that any attribute from one dataset that was not present in the other dataset had a null value. Table 3-2 shows the sources of attributes in the resultant dataset from these three datasets.

In preparation for mapping the coordinates in the resultant table were then analysed for their consistency and accuracy those with discrepancies were removed. A table of boreholes with utilizable coordinates resulted. It was prepared to create a feature class in ArcGIS by splitting it into two separate tables curtailing the boreholes which were to be mapped using UTM and Decimal Degrees (DD) coordinates. In the case of the entries from the database extract the best coordinates were used to categorize into either of these two tables where the entries had both UTM and Decimal Degree coordinates. Also these two tables' headers (attribute categories) were formatted in a syntax that was parsable by ArcGIS's Create Feature Class from XY Table Tool as shown in Table 3-2.

Table 3-2: Mapping Attribute Conversion & Sources

Attribute Before Formatting	**Source[2]**			**Attribute After Formatting**
	1	**2**	**3**	
WRMA Permit No	■	■	■	Permit_No
Borehole No	■			BH_No
Borehole Name	■			BH_Name
Location	■			Location
Map/Sheet	■			Map_Sheet
Area	■			Area
East (°)	■			Long_D
East (Min)	■			Long_M
East (Sec)	■			Long_S
North (°)	■			Lat_D
North (Min)	■			Lat_M
North (Sec)	■			Lat_S
East (DD)	■			Long_DD
North (DD)	■			Lat_DD

[2] 1 = Database Extract; 2 = Borehole Listing; 3 = KMZ File

Attribute Before Formatting	**Source[2]**			**Attribute After Formatting**
	1	**2**	**3**	
UTM X	■			X
UTM Y	■			Y
Zone	■			Zone
Owner Name	■	■	■	Owner_Name
Owner Address	■			Owner_Add
Locality/Estate	■			Locality_Estate
LR No	■			LRNo
Intended Use	■			IntendedUse
Contractor	■			Contractor
Supervisor	■			Supervisor
Work Completed	■			WC_Date
Application Date		■	■	AP_Date
Final Depth (m)	■			Final_Depth_M
Main Drilled Diameter (mm)	■			Main_Drilld_Dia_MM
Cased Diameter (mm)	■			Cased_Dia_MM
Main Aquifer Struck (m)	■			M_Aquif_Struck_M
Water Rest Level (m)	■			WRL_SL_M
Tested Discharge (lpm)	■			Tested_Q_LPM
Pumped Water Level (m)	■			PWL_M
Recommended Yield (lpm)	■			Reco_Y_LPM
Alternate Units	■			Alt_Units_LPH
Pump At (m)	■			PD_M

A shapefile was created in the geodatabase for each of the two tables using the Create Feature Class from XT Table tool in ArcGIS. The UTM shapefile/feature class had a UTM Arc 1960 Zone 37S projection whereas the DD Shapefile/feature class had the WGS 1984 geographic coordinate system. The latter shapefile was projected to the UTM Arc 1960 Zone 37S PCS, and both were added to a borehole Feature Dataset in the geodatabase. They were then merged to result in a feature class of all mapped boreholes (Figure 3-1) which was then clipped using the Nairobi County feature class/shapefile to produce a feature class containing only the boreholes located within the boundaries of the County.

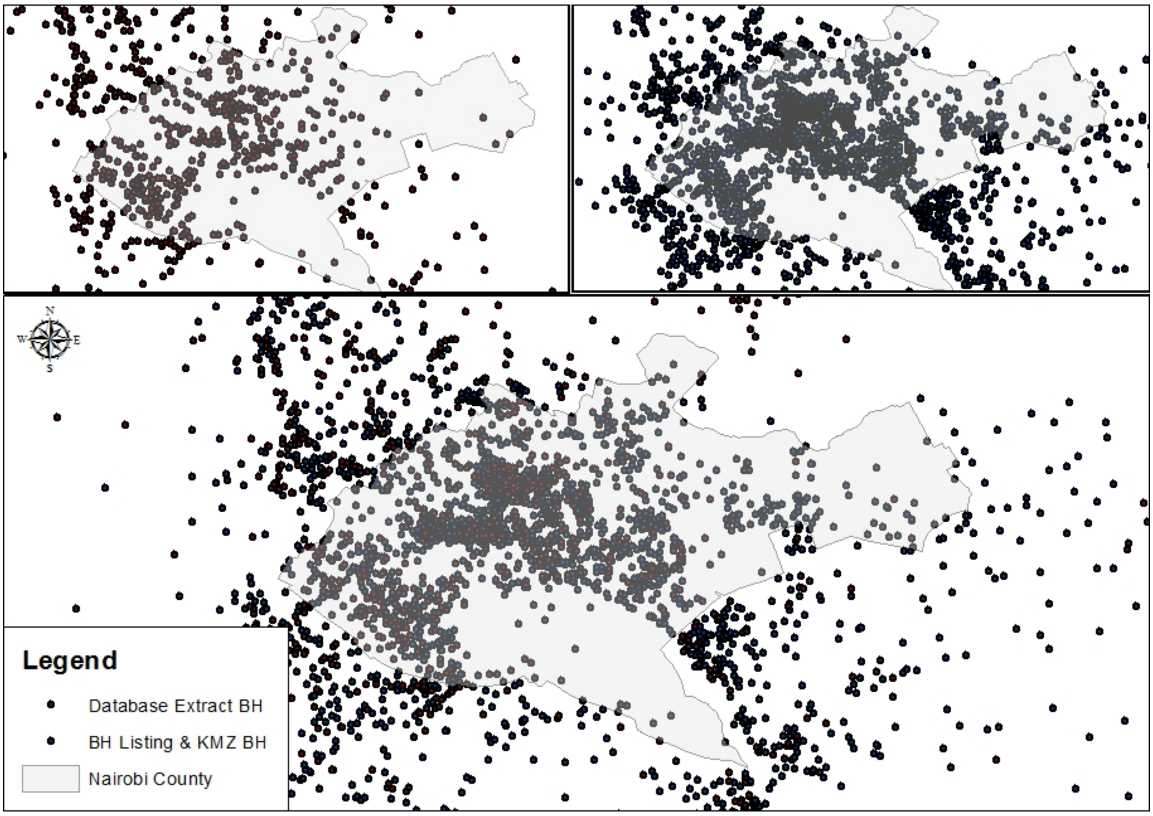


Figure 3-1: UTM and DD Boreholes

3.4.2 Data Analysis

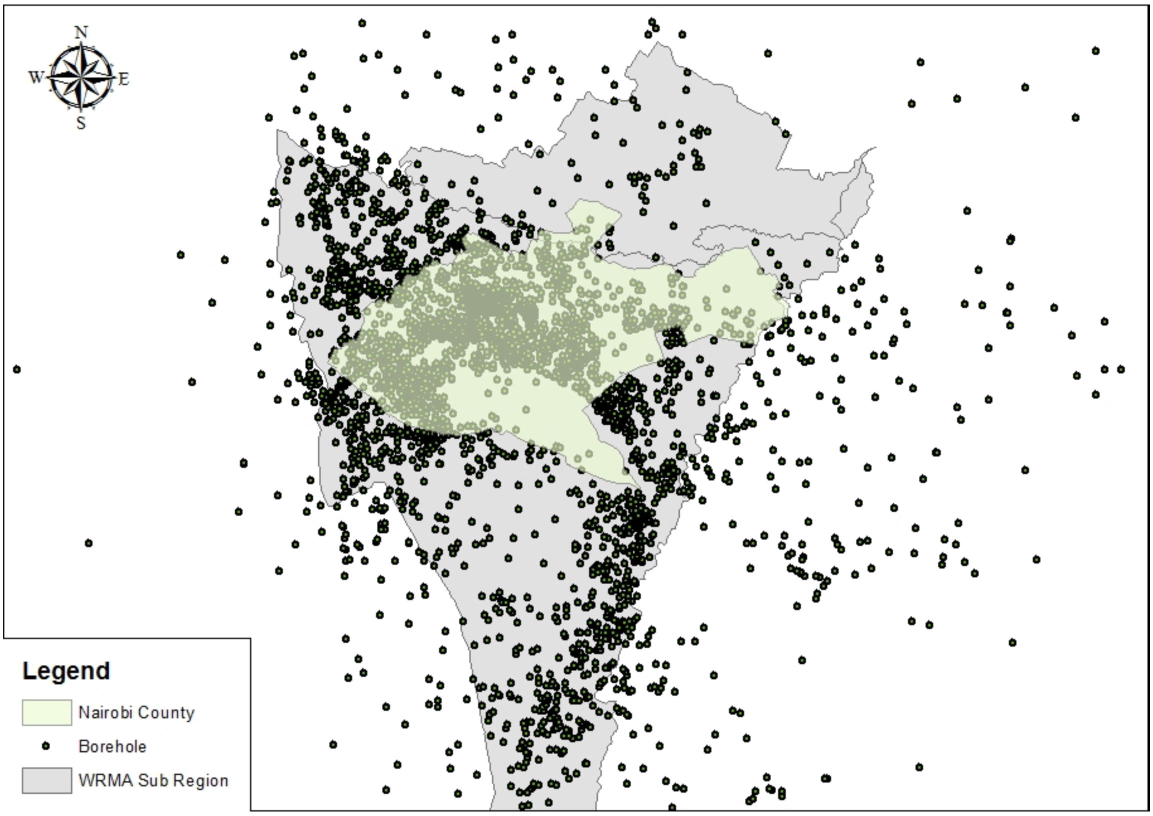
3.4.2.1 Interview Interpretation

The collected data was analysed by first categorizing the information from the interview to elucidate the major challenges and trends in groundwater management practices in Nairobi. The insights gained from the interview were used to confirm and inform the findings of the analyses.

3.4.2.2 Borehole Siting and Spatial Density

The mapped boreholes from the Database Extract and Borehole Listing were combined by first appending their coordinates to their database tables using ArcGIS Add XY Data tool and the tables were then extracted a spreadsheet into MS Excel. They were then combined in MS Excel and a feature containing all mapped boreholes was created using ArcGIS's Table to Feature Class tool with their generated coordinates (See Figure 3-2). This process was a work-around since multi-point shapefiles can't be combined using the Union Method of ArcGIS's geoprocessing tools.

This feature class was then clipped using the Nairobi County Shapefile to result in only the boreholes that lie within the county. A spatial join was then performed to add attributes of administrative units (District, Division, Location and Sub-location) to each borehole depending on its location. These Nairobi County Boreholes were then exported to MS Excel and combined with the unmapped Boreholes from the Database Extract. The resultant table was used to count the boreholes in each administrative unit using the borehole's location from the spatial join and the original administrative location of the unmapped boreholes using their location and locality attributes. In this process unmapped boreholes which had no information on these two attributes were ignored and whilst the information was added to the last administrative unit identifiable. This resulted in a categorization of administrative information based on available data and the number of boreholes in Nairobi County was calculated by summing these boreholes in each administrative unit.



Source: WRMA, 2014
Figure 3-2: Combined Mapped Boreholes

For purposes of adding the information of the number of boreholes to the administrative unit shapefiles, a spatial join was performed on each shapefile with the count operation applied to the mapped boreholes. The resultant shapefiles contained an attribute of the number of boreholes whose centroid was completely contained in the jurisdiction and this number was adjusted to that achieved from aforementioned process of enumerating all the boreholes in Nairobi County from all the datasets provided. Distribution statistics of mean, percentage and standard deviation were calculated in each category of administrative jurisdiction, using the total number of boreholes in Nairobi which included both mapped and unmapped boreholes, since the unmapped boreholes were considered to lie in Nairobi.

Administrative borehole spatial density maps were created by adding calculated fields were added to the shapefiles which divided the number of boreholes by the area of the shapefile in km^2. The maps were produced using the shapefile's symbology property using intervals to quantify density and display the features differently. In addition to this the same methodology was used to create another set of spatial discrimination maps that distinguished administrative features based on the number of boreholes in the jurisdiction.

The population and number of households of the different administrative units in 2009 from the 2009 Housing and Population census was added to each of the shapefiles and projected geometrically to 2014 using the average growth rate of 2.11% p.a (CIA, 2014). This data was added manually since the shapefile's location and sub-location boundaries differed from the 2009 boundaries and thus the different values were aggregated where subdivisions were done. The resultant value was used to calculate the distribution of: boreholes per capita and boreholes per capita per unit area. The results of this assessment linked the number and distribution of boreholes to the populous and was used to create spatial discrimination in the different administrative units.

3.4.2.3 Abstraction and Drilling Depth Trends

The four sets of data obtained for this study had incomplete data with respect to recommended pumping rates whereby the attribute was only complete for 713 boreholes (~27%). Thus the abstraction rates were estimated using:

- An estimate of the number of active boreholes in each administrative unit obtained by subtracting the inactive boreholes enumerated in the BIS of 2011 and the ratio of groundwater supply from the total supply (12.5%);

- The total of daily demand of 579,000 m^3/d of 2010 from Jacobsen (2012) projected geometrically to 2013 based on the projected population from the 2009 census;
- The area of the administrative unit, and
- The population of the administrative unit.

The sets of equations used were as follows:

Equation 3-1: Total per Daily Groundwater Demand

$$Q_{tg} = 0.125 Q_T$$

Equation 3-2: Demand per Borehole

$$Q_{BH} = \frac{Q_{tg}}{BH_a}$$

Equation 3-3: Total Groundwater Demand per Region

$$Q_R = Q_{BH} BH_{ar}$$

Equation 3-4: Per Capita Demand per Region

$$Q_{PcR} = \frac{Q_R}{P_R}$$

Equation 3-5: Per Capita Demand per Region per Unit Area

$$Q_{PcRA} = \frac{Q_{PCR}}{A}$$

Where:

Q_{tg} = Total daily groundwater demand in Nairobi, m^3/d

Q_T = Total daily water demand in Nairobi, m^3/d

P = Estimate population of Nairobi in 2014, person or pers or p

Q_{BH} = Demand per borehole, m^3/d

BH_a = Estimate number of active boreholes in Nairobi

BH_{ar} = Number of active boreholes in the region

Q_{PcR} = Per Capita Demand per Region, $m^3/d/p$

Q_R = Total Groundwater Demand per Region, m^3/d

P_R = Population of the region, p

Q_{PcRA} = Per Capita Demand per Region per Unit Area, m3/d/p/Km^2

A = Area of the region, km^2

Equation 3-4 and Equation 3-5 gave the estimate abstraction intensities in terms of the population and the unit area of the region and their results were mapped to develop groundwater discrimination maps at the Sub-location level.

In the case of drilling depths all available data was plotted against time to elucidate the temporal trends whereas average, maximum and minimum available drilling depths were also mapped in each Sub-location to draw comparisons.

3.4.2.4 Geospatial Trends and Analyses

3.4.2.4.1 <u>Proximity - Near Analysis</u>

A near analysis on boreholes was undertaken for each location in ArcGIS and this calculated or measured the distances from each borehole to the nearest borehole in the multipoint shapefile of boreholes. This was the shapefile of the boreholes which had coordinates and fell within the county.

ArcGIS's near analysis tool was used for this analysis and it calculates the Euclidean distance between different features. This proximity analysis was performed focussing on only the nearest borehole from each individual borehole. This analysis was focussed to identify the number of boreholes within 50 m, 100 m and 200 m from other boreholes. These distances were chosen relative to the 100 m spacing limit used by WRMA. Further to this the Near Analysis were performed at the locational level to ensure that a significant number of boreholes would be used in the calculations and the results of these analyses were mapped to develop discrimination maps of average nearest boreholes in the county's locations.

3.4.2.4.2 Point Density Analysis

ArcGIS's Point Density Analysis tool was used to calculate the density of boreholes within regions of 250 m by 250 m and with a circular neighbourhood. This tool calculated the borehole density in this neighbourhood in square kilometres and the resultant raster was then clipped with the boundary of Nairobi County.

3.4.2.4.3 Average Nearest Neighbour

ArcGIS's Average Nearest Neighbour tool was utilized to elucidate whether the clustering amongst the boreholes was statistically significant based on the null hypothesis. The tool was used measuring Euclidean distances between boreholes and it calculated the following:

- The P and Z Scores,
- The Observed mean distance,
- The Expected mean distance, and
- The Nearest Neighbour Ratio.

3.4.2.4.4 Hotspots Analysis

To undertake the Hotspots Analysis a fishnet with a resolution of 250 m by 250 m was created in a rectangle covering Nairobi using ArcGIS's Create Fishnet Tools. The fishnet was then clipped with the boundaries of the county and a spatial joint was performed to count the number of boreholes in each cell. The resultant shapefile is shown in Figure 3-3 and it had a maximum count of 5 boreholes and minimum of 0 with an average of 0.15 boreholes and a standard deviation of 0.47.

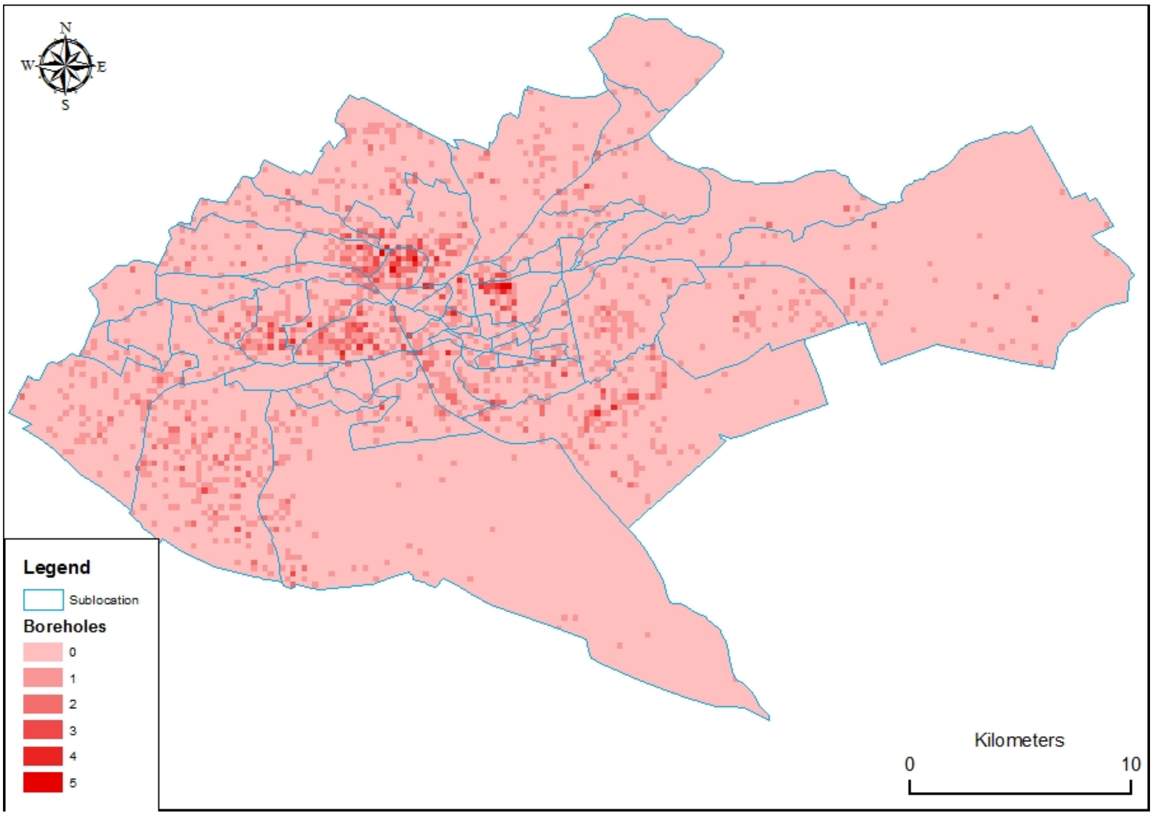


Figure 3-3: Nairobi Fishnet with Boreholes

This fishnet was used to perform the hotspots analysis through the zone of indifference method with the number of boreholes per cell as the weight. The analysis was performed measuring Euclidean distance with a threshold of 800 m and no self-potential arguments. This meant every cell had more than one neighbour since all cells within a radius of 800 m from its centroid were considered neighbours and this meant that each cell had at least 8 neighbours as per the recommendations of ESRI (2010 (b)). The zone of indifference was chosen since when test pumping a borehole boreholes within 800 m are required to be monitoring and the zone of influence of a borehole reduces with distance thus the 800 m was considered to the fixed distance after which the influence reduces.

This analysis was also applied for the polygon shapefile of boreholes of Sub-locations with the abstraction intensity per person per region as the weight, using the zone of indifference method and with threshold or distance band of 5,000 m based on the larger area of sub-locations.

3.4.2.5 Interpretation of Results

Using this information the study made recommendations to guide stakeholders on best practices to adopt in the future. These recommendations were also based on an assessment of the implementation, relevance and adequacy of groundwater regulations on well location as well as other connected practices.

4 RESULTS AND DISCUSSIONS

4.1 RESULTS

This research undertook analysis and gathered information on the following aspects in response to the objective of identifying trends in groundwater management practice and compliance:

- Number of boreholes and their locations.
- Borehole Density.
- Pumping Rates.
- Drilling Depths.
- Geospatial and Temporal Analysis on Boreholes.
- Compliance with regulations.
- Challenges in Groundwater Management Practice.

The results of this processes are presented in the subsections herein.

4.1.1 Borehole Mapping and Number of Boreholes

The process of filtering out duplicate borehole entries from the combination of the database extract, borehole listing and KMZ file resulted in a total of 3,726 boreholes which had coordinates. These were clipped using the county boundary resulting 1,837 boreholes within the boundaries of Nairobi County (Figure 4-1). Administrative jurisdictions were added to these boreholes which were combined with unmapped boreholes from the database extract. These unmapped boreholes were located to be in the county using the available information they had on their location based on their attributes of: location, locality, borehole name, borehole owner, land registration number and address. Using this method 795 boreholes were found to be located in Nairobi and 761 of these were located to their sub-location.

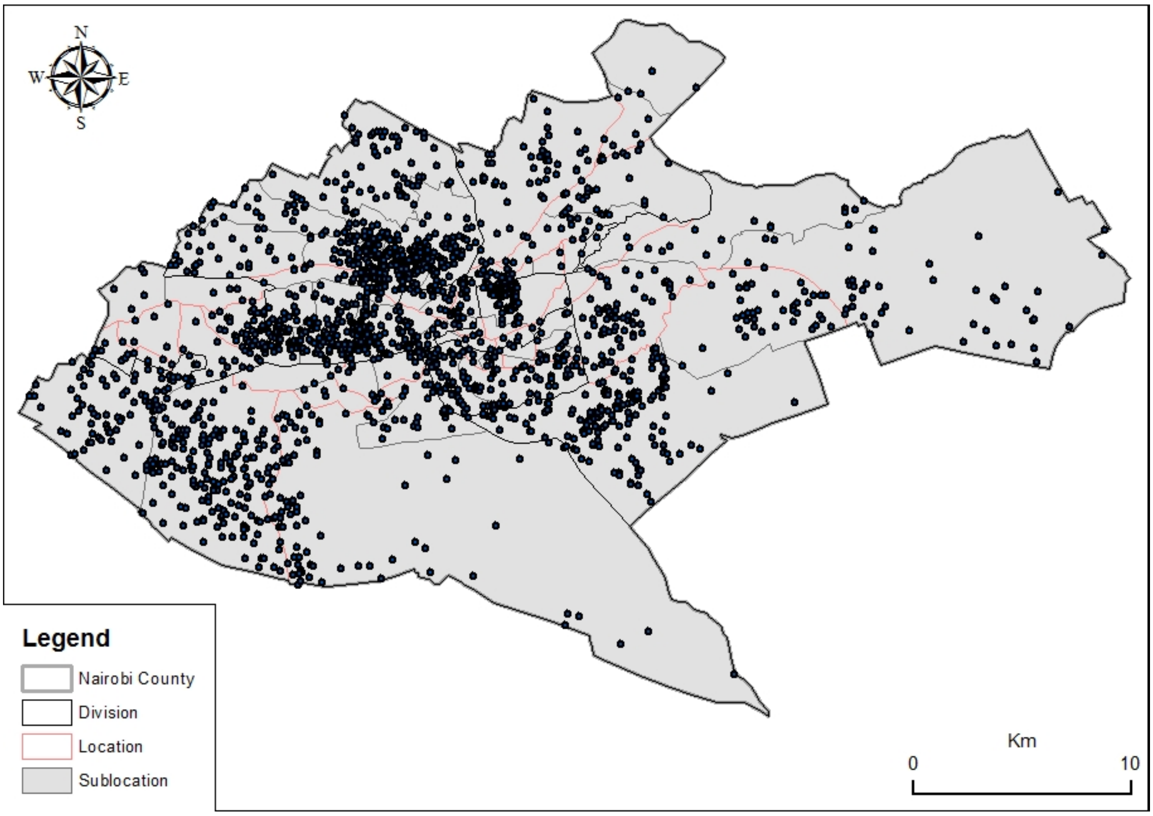


Figure 4-1: Mapped Boreholes in Nairobi County

Combining the two sets of data resulted in 2,632 boreholes which were considered to lie in Nairobi and thus the boreholes were summed in each Sub-location, Location and Division using this value as presented in Table 4-1. Using ArcGIS spatial join method the number of boreholes was added to each administrative unit and the number of boreholes corrected using the values in Table 4-1. Thus a map prepared to show the discrimination of the number of boreholes in each administrative unit and the result of this process is shown in Figure 4-2 for Divisions, Figure 4-5 for Locations and Figure 4-7 for Sub-locations.

Table 4-1: Summation of Boreholes in Nairobi's Administrative Units

Division	BHs	Location	BHs	Sub-location	BHs
Central	84	Ngara	18	Ngara East	10
				Ngara West	8
		Starehe	66	City Square	20
				Nairobi Central	9
				Pangani	16
				Ziwani/Starehe/Kar'ir	21
Dagoretti	117	Kangemi	17	Uthiru/Ruthimitu	9
				Kangemi	8
		Kawangware	32	Kawangware	32

Division	BHs	Location	BHs	Sub-location	BHs
		Waithaka	10	Waithaka	10
		Riruta	46	Riruta	46
		Mutuini	12	Mutuini	12
Embakasi	447	Dandora	21	Dandora	18
				Kariobangi South	3
		Njiru	155	Ruai	55
				Koma Rock	23
				Umoja	77
		Embakasi	271	Embakasi	227
				Mihango	44
Kasarani	226	Kahawa	38	Kahawa North	17
				Kahawa South	21
		Kariobangi	2	Kariobangi North	2
		Korogocho	3	Korogocho	3
		Kasarani (Ruaraka)	92	Kasarani	40
				Ruaraka	52
		Mathare	22	Huruma	4
				Mathare	18
		Roysambu	69	Roysambu	69
Kibera	620	Karen/Langata	434	Karen	197
				Langata	237
		Kenyatta/Golf Course	36	Kenyatta Hospital	15
				Golf Course	21
		Kibera/Woodley	28	Woodley	13
				Kibera	15
		Mugumoini	122	Nairobi West	31
				Mugumoini	91
Makadara	202	Kaloleni/Makongeni	8	Kaloleni	3
				Makongeni	5
		Makadara	21	Harambee	4
				Lumumba	6
				Hamza	11
		Maringo/Mbotela	5	Ofafa	5
				Mbotela	0
		Viwanda	168	Nairobi South	68
				Viwandani (Ind. Area)	100
Parklands/Westlands	808	Kilimani	290	Kileleshwa	67
				Masiwa	64
				Muthangari	19
				Kilimani	140
		Parklands	518	Loresho/Kyuna	64
				Karura	81
				Muthaiga	111
				Kitisuru	34
				SP. Valley/U. Parklands	117
				Highridge	111
Pumwani	94	Bahati	5	Uhuru	3
				Kimathi	2
		Eastleigh	80	Eastleigh North	74

Division	BHs	Location	BHs	Sub-location	BHs
				Eastleigh South	6
		Kamukunji	8	Shauri Moyo/Kamukunji	5
				Muthurwa	3
		Pumwani	1	Majengo	1
Only in Nairobi	34	Only in Nairobi	34	Only in Nairobi	34
Total	**2632**		**2632**		**2,632**

At the division level it can be observed that Parklands/Westlands has the most boreholes with 808 boreholes consist of 31% of all boreholes followed by Kibera with 620 (24%) and Embakasi with 447 (17%). Whereas apart from the 34 boreholes which were only located to be in Nairobi, Central and Pumwani had the least number of boreholes with 84 (3%) and 94 (4%) boreholes respectively (See Figure 4-2 and Figure 4-3). Additionally it was also observed that there's an average of 329 boreholes per division with a standard deviation of 253.72 in 8 divisions, (See Table 4-2).

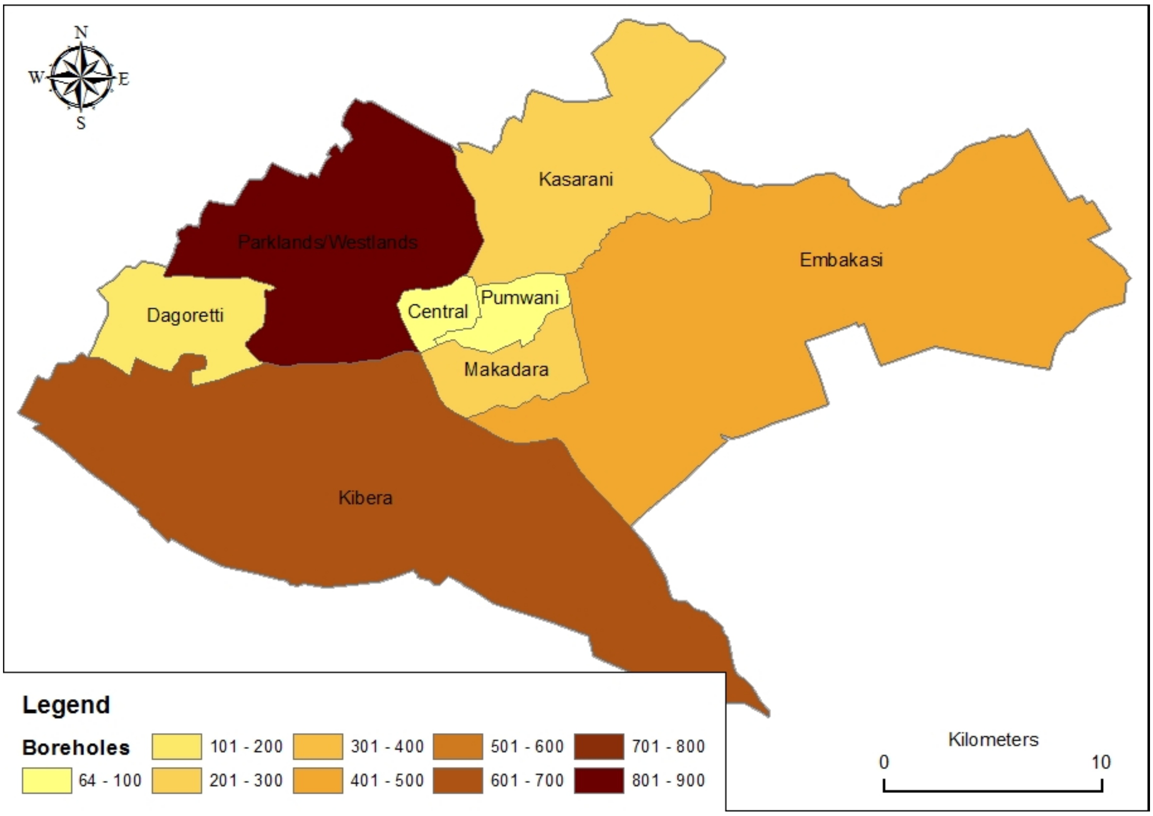


Figure 4-2: Map of Boreholes per Division

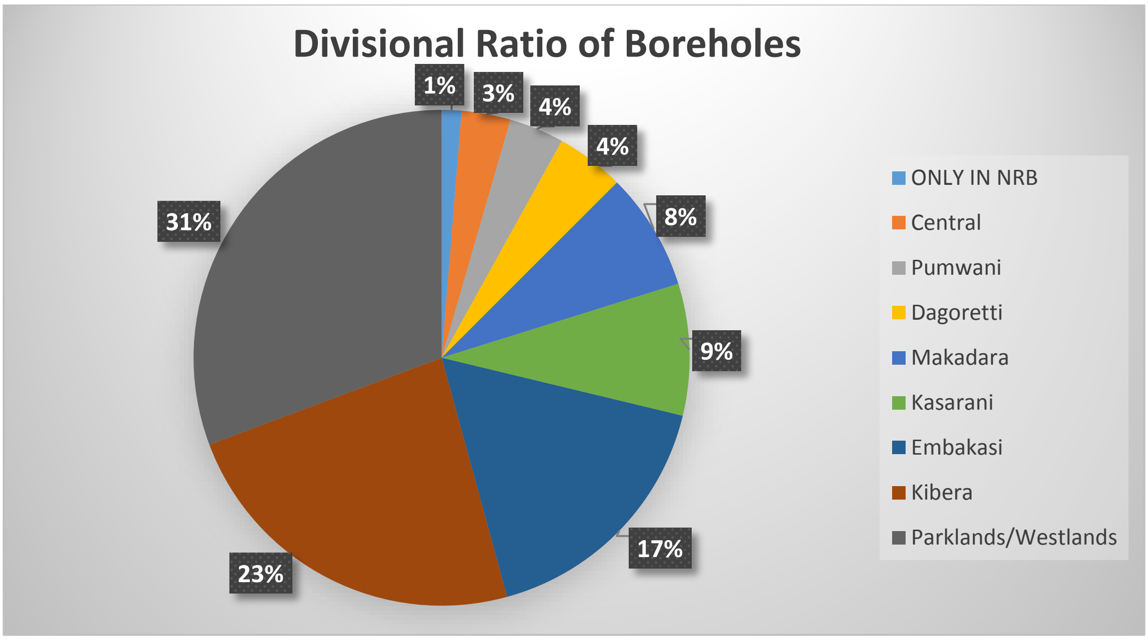


Figure 4-3: Divisional Ratio of Boreholes

As illustrated by Figure 4-5 and Figure 4-4 at the location level Parklands, Karen/Langata and Kilimani had the most boreholes with 518 (19.68%), 434 (16.49%) and 290 (11.02%) respectively. On the lower end Pumwani, Kariobangi and Korogocho locations had the least number of boreholes with 1 (0.04%), 2 (0.08%) and 3 (0.11%) boreholes respectively. It was also observed there was an average of 88 boreholes per location with a standard deviation of 127.73 in the 30 locations, (See Table 4-2).

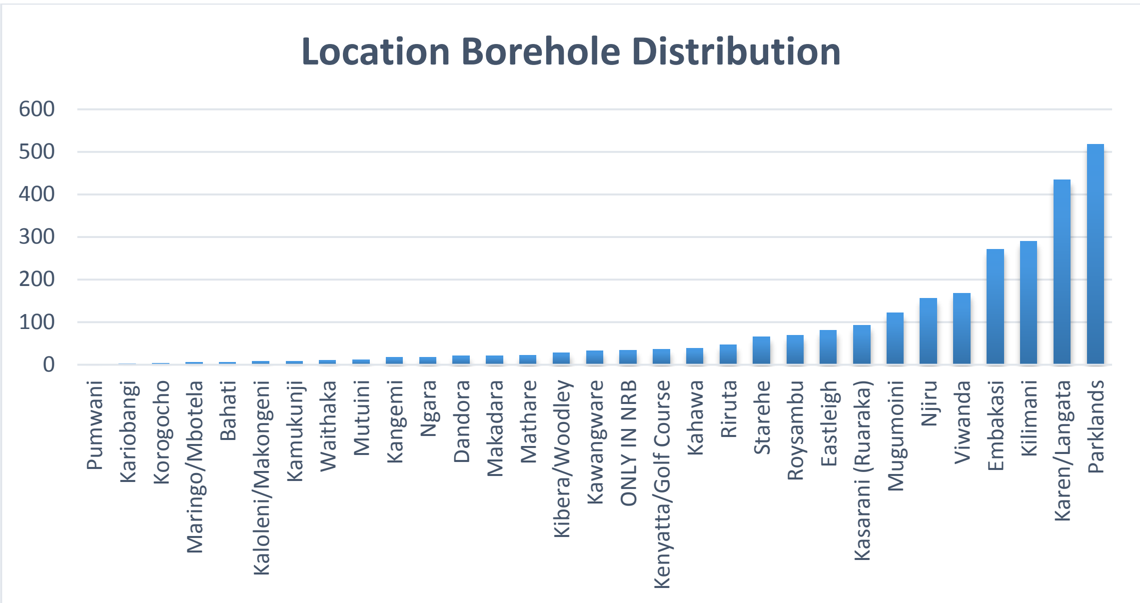


Figure 4-4: Locations Ascending Order of Number of Boreholes

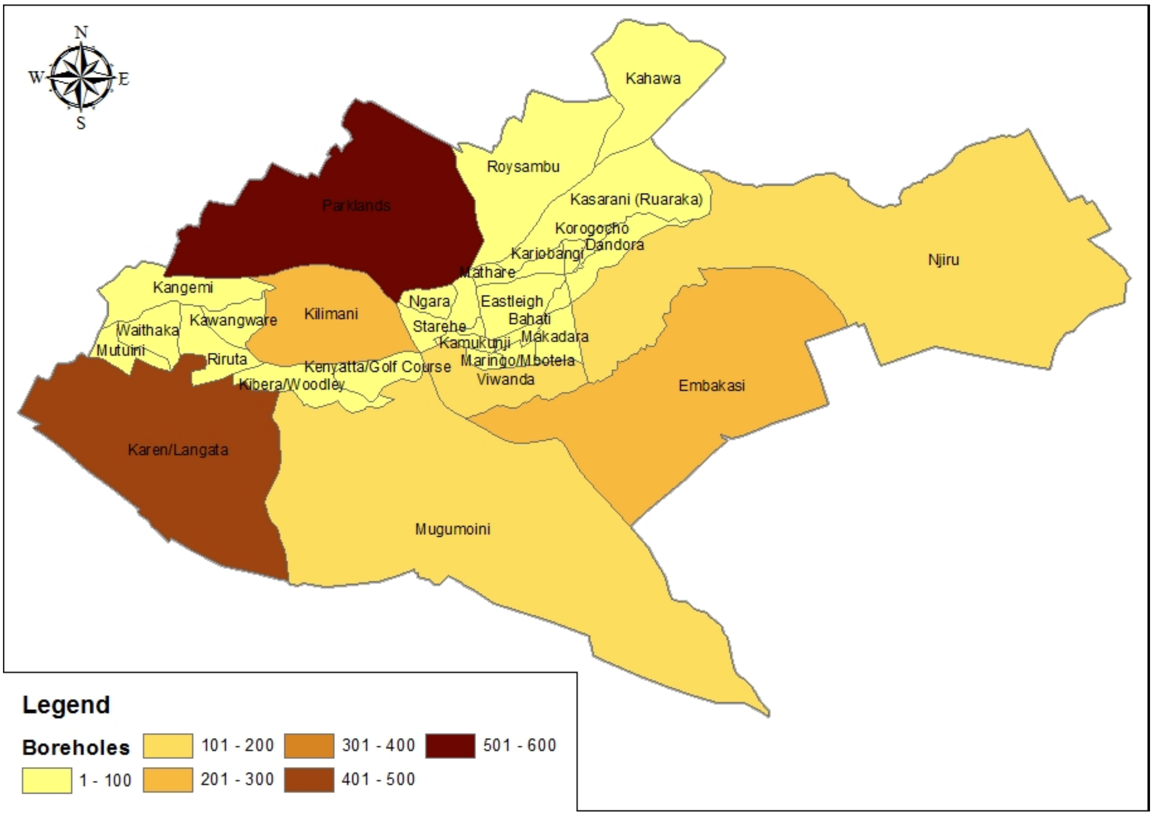


Figure 4-5: Map of Boreholes per Location

At the Sub-location level as illustrated by Figure 4-6 and Figure 4-7 it was observed that Langata with 237 boreholes (9.00%), Embakasi with 227 (8.62%) and Karen with 197 (7.48%) were the sub-locations with highest number of boreholes. On the converse Mbotela Sub-location had no boreholes and thus had the least number of boreholes following by Majengo with 1 borehole (0.04%) and then Kariobangi North with 2 boreholes (0.08%) completing the three sub-locations with the least number of boreholes. On average it was observed that there were approx. 42 boreholes per Sub-location and a standard deviation of 52.95 as presented in Table 4-2.

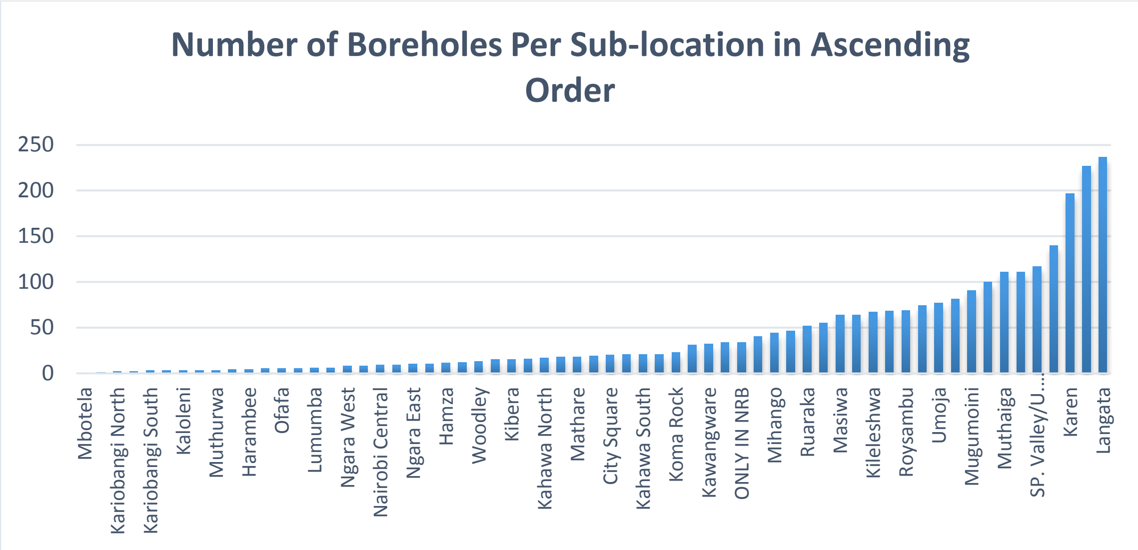


Figure 4-6: Number of Boreholes per Sub-location in Ascending Order

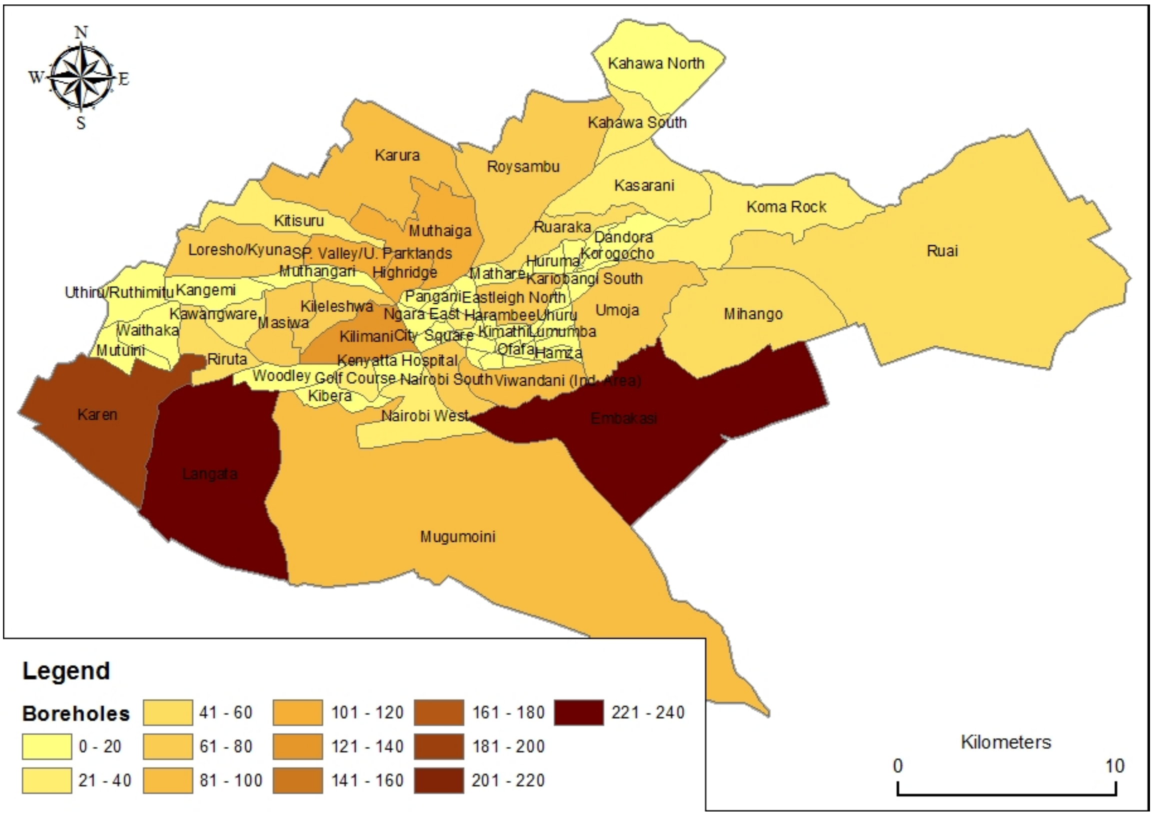


Figure 4-7: Map of Boreholes per Sub-location

Table 4-2: Summary Statistics of Number of Boreholes

Statistic	Sub-locations	Locations	Divisions
Administrative Units	62	30	8
Minimum Value	0:Mbotela	1:Pumwani	84:Central
Maximum Value	227:Embakasi	518: Parklands	808:Parklands/Westlands

Statistic	Sub-locations	Locations	Divisions
Sum	2632	2632	2632
Mean	42.45	87.73	329
Standard Deviation	52.95	127.73	253.72

4.1.1.1 Borehole Spatiotemporal Trends

In the generated dataset of mapped and located boreholes in Nairobi it was observed that 97% (2,555) of the boreholes had complete information on their dates which was either when the permit was applied for or when drilling was completed. The remaining 3% either erroneous or missing dates. However from these 2,555 boreholes it was observed that the oldest borehole had a record of the year 1900 and the most recent borehole was drilled in 2013 whereas the data also showed that no boreholes were drilled in the county from this sole borehole in 1900 up to 1929. Additionally it was generally observed that there was an upsurge of boreholes primarily from 1980 and significantly from 2010. This is shown by Figure 4-8 in which a bar graph was drawn from the boreholes constructed per decade and a line was plotted for the total number of boreholes in the county.

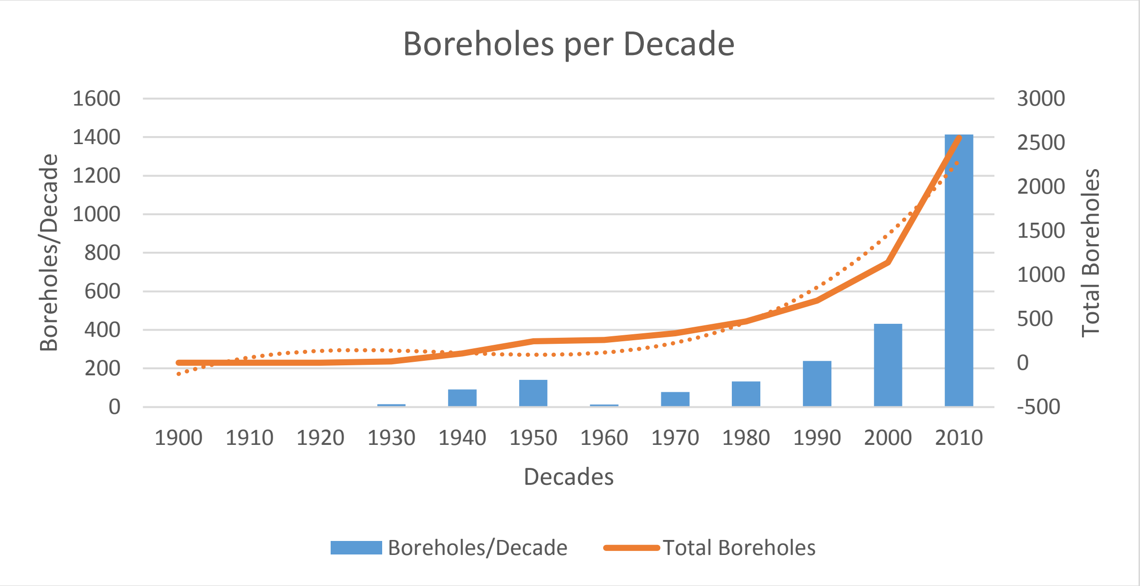


Figure 4-8: Graph of Boreholes per Decade

Figure 4-9 presents a bar graph of boreholes per year and a line graph of total boreholes. It shows a similar trend where boreholes small peaks were observed in the 1950s, 1970s, 1980s and 1990s before dropping towards the year 2000 before significantly from around 2004.

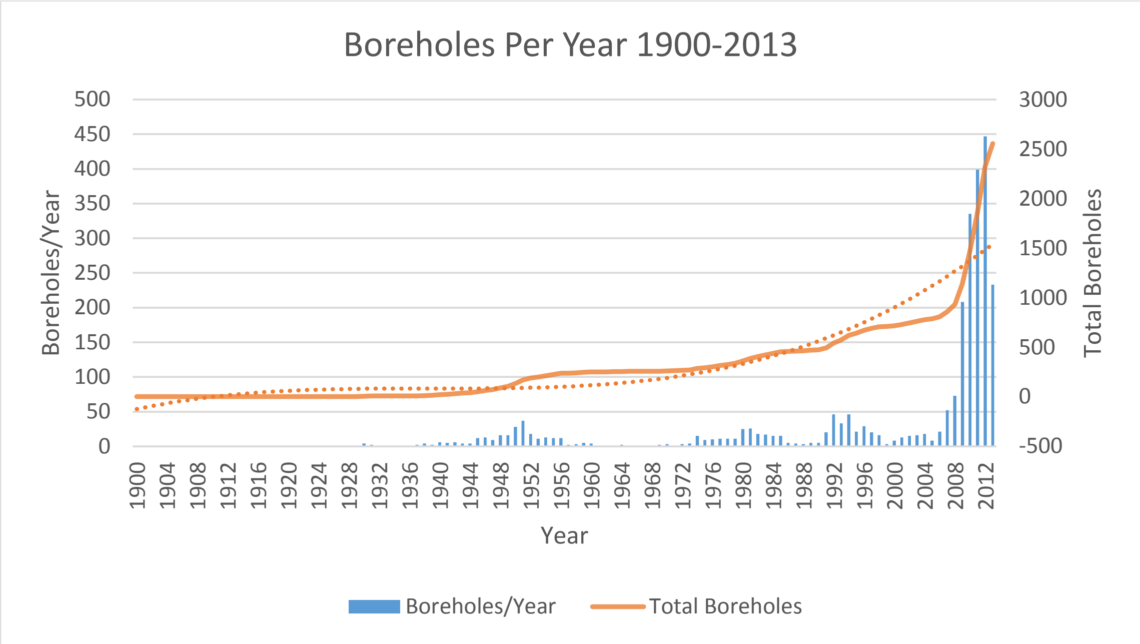


Figure 4-9: Boreholes per Year from 1900 to 2013

Table 4-3 presents a summary of the number of boreholes in the Sub-locations in this period and identifies the Sub-locations in which the most boreholes were drilled. In general most boreholes were drilled in the Sub-locations which had the highest number of boreholes in 2013 and these are Karen, Langata, Embakasi and Kilimani. A series of spatiotemporal maps is attached in Appendix B1.

Table 4-3: Summary of Spatiotemporal Borehole Trends

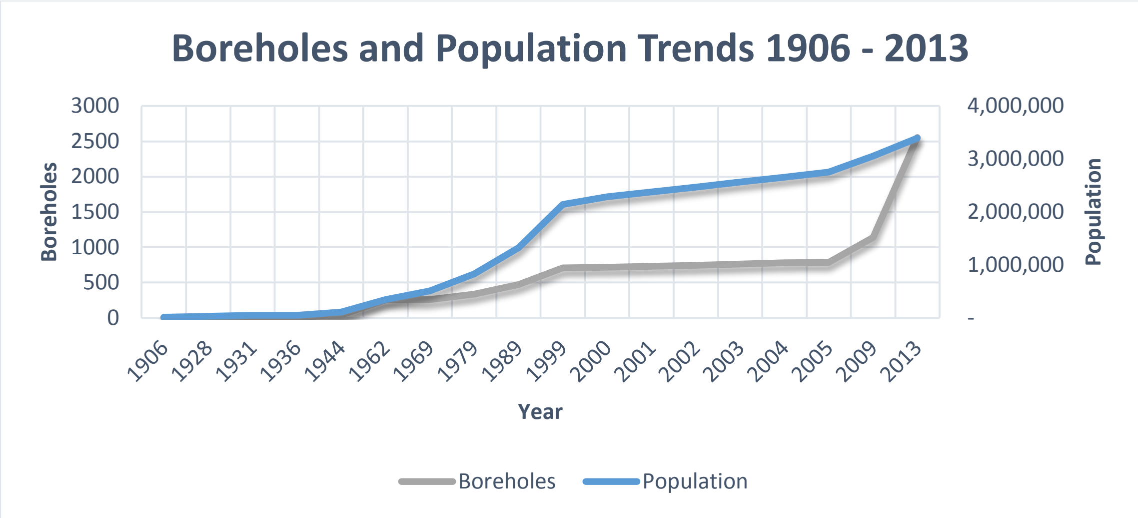
Decade	Total BHs	Top Sub-locations and Boreholes
1900s	1	SP. Valley/U. Parklands (1)
1910s	0	-
1920s	0	-
1930s	14	Karen (3) SP. Valley/U. Parklands (3) Riruta (1) Unknown Location (4)
1940s	91	Karen (13) Loresho/Kyuna (12) Riruta (8) Unknown Location (14)
1950s	141	Karen (36) Embakasi (12) Loresho/Kyuna (12) Langata (11)
1960s	12	Embakasi (4)

Decade	Total BHs	Top Sub-locations and Boreholes
		Highridge (1), Karen (1), Karura (1), Kilimani (1), Langata (1), Mugumoini (1), Riruta (1), Woodley (1)
1970s	78	Karen (14) Viwandani (Ind. Area) (8) Roysambu (7) Unknown Location (9)
1980s	133	Langata (26) Karen (19), Viwandani (Ind. Area) (19)
1990s	239	Langata (48) Karen (30) Muthaiga (12), Viwandani (Ind. Area) (12)
2000s	432	Embakasi (56) SP. Valley/U. Parklands (33) Karen (28)
2010s	1414	Embakasi (132) Langata (109) Kilimani (97)

4.1.1.2 Boreholes and Population

The population of Nairobi County and the number of boreholes both increased since the time the first documented census was undertaken in 1906. Whilst several factors drive the number of boreholes drilled the population is one of the main drivers since it directly increases the demand for water. Figure 4-10 presents a graph comparing population and the number of boreholes in Nairobi from 1906 to 2013[3] whereas the subsequent Figure 4-11 plots the population against number of boreholes in the same period. From Figure 4-10 it can be observed that both the number of boreholes and the population peaked significantly from 1962 to 2013 and followed a rather similar trend.

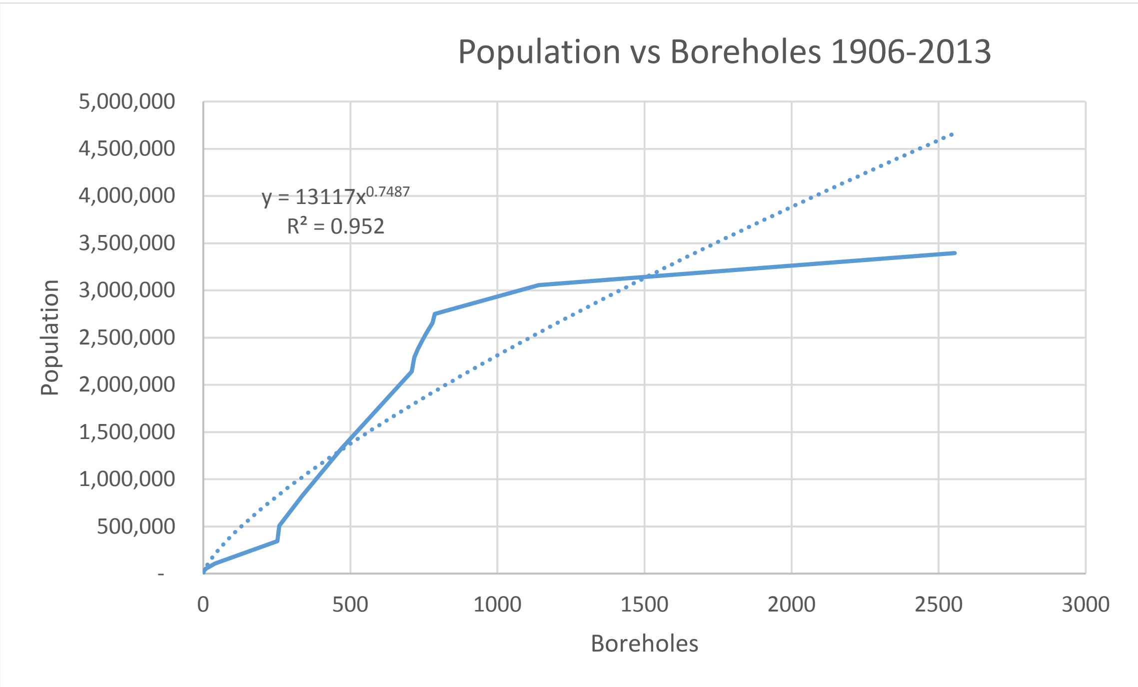
[3] The 2013 population value is a calculated estimate using a growth rate of 2.11% (CIA, 2014) based on the 2009 value.



Sources:
Population Growth Rate: CIA 2014
2009 Population: MoPNDV2030, 2009
1906-1999 Population: Olima, 2001 as cited in CCN, 2007

Figure 4-10: Graph of Comparison between Population and Boreholes 1906-2013

Similarly Figure 4-11 shows that the number of boreholes has greatly increased with increasing population in the period between 1906 and 2013 whereas an estimate power line with a coefficient of determination of 0.952 is estimated to predict this trend.



Sources:
Population Growth Rate, CIA 2014
2009 Population, MoPNDV2030, 2009
1906-1999 Population, Olima, 2001 as cited in CCN, 2007

Figure 4-11: Plot of Boreholes and Population 1906-2013

4.1.2 Borehole Density

4.1.2.1 Spatial Density

Borehole spatial density was calculated by dividing the number of the boreholes allocated to an administrative unit by its area. This gave better representation of the concentration of boreholes in each administration unit in order to identify areas or regions where boreholes were most concentrated. As a general trend it was observed that the whole county has an average of 3.8 Boreholes/Km^2 (approx. 4).

On the division level it was observed as illustrated by Figure 4-12 and Figure 4-13 that Makadara (10.11), Parklands/Westlands (8.30) and Pumwani (8.08) had the highest number of boreholes per Km^2 whilst Kibera (2.78), Kasarani (2.65) and Embakasi (2.16) had the lowest. However on average it was observed that there was a density of 5.63 (~6) Boreholes/Km^2 per division with a standard deviation of 3.04.

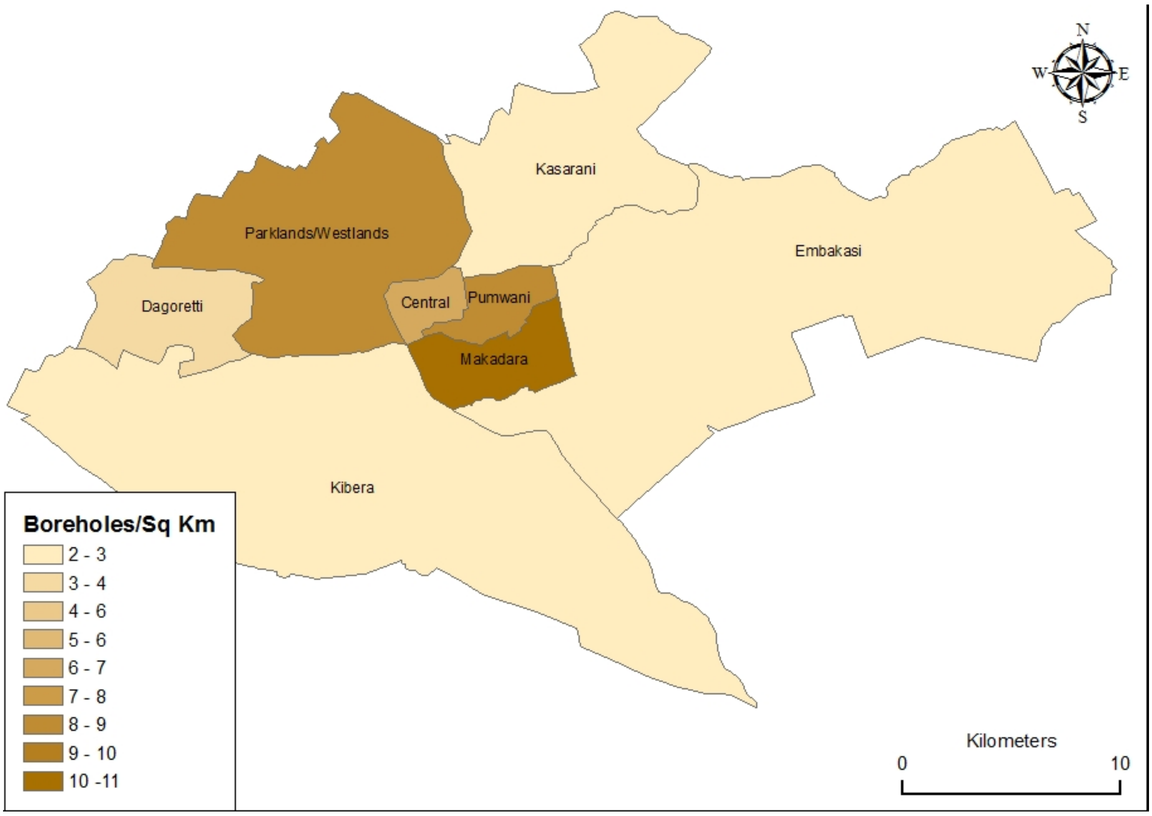


Figure 4-12: Map of Boreholes/Km^2 in Nairobi's Divisions

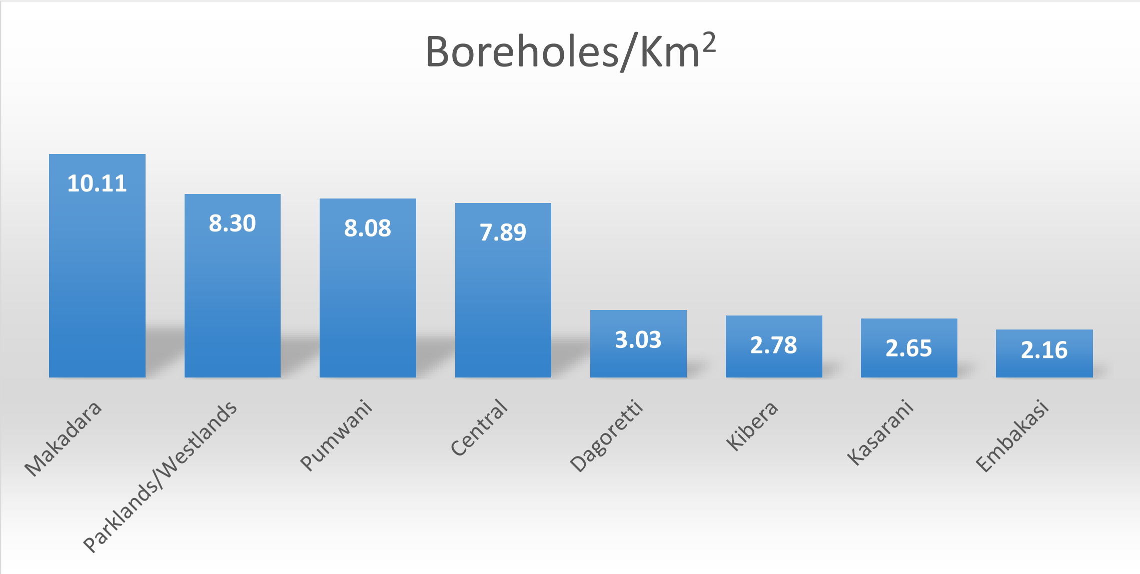


Figure 4-13: Graph of Borehole Spatial Density per Division

From these two figures it is observed that there's a higher concentration of boreholes in the first four divisions which fall in central Nairobi toward the North-East. However these divisions occupy less area as compared to other four with lower densities.

At the location level it was observed as depicted by Figure 4-14 that Starehe (13.18), Viwanda (12.31) and Kilimani (11.55) had the highest number of boreholes/Km^2 whilst Njiru (1.28), Mugumoini (0.83) and Kariobangi (0.43) had the lowest borehole spatial densities. On average there were 5.24 (~5) Boreholes/Km^2 in the 30 locations with a standard deviation of 3.60 Boreholes/Km^2.

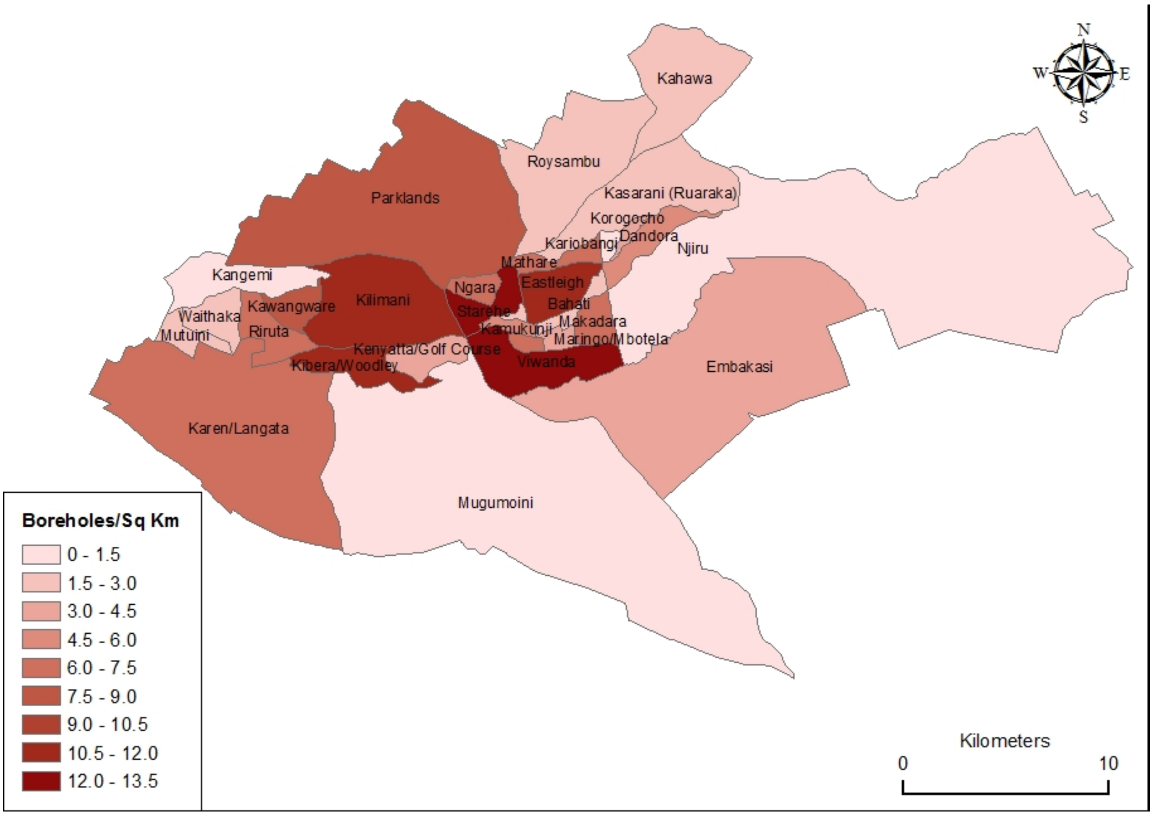


Figure 4-14: Map of Boreholes/Km^2 in Nairobi's Locations

From Figure 4-14 it can also be observed that most boreholes are concentrated in the central and western locations of Nairobi. In the case of Mugumoini the low density can be attributed to development restrictions presented by the Nairobi National Park that intersects much of the location.

At the Sub-location level it observed that Highridge (30.61), Nairobi South (28.98) and SP. Valley/U. Parklands (25.37) had the highest number of boreholes/Km^2. On the lower end it was also observed that Mugumoini (0.65), Ruai (0.56) and Mbotela (0.00) had the lowest borehole spatial densities. On average it was observed that there were at least 6.85 (~7) Boreholes/Km^2 in Nairobi's sub-locations with a standard deviation of 6.42. Figure 4-15 illustrates the distribution of these borehole densities, and it can be observed that there is a general trend of higher concentration of boreholes in the central and western regions of Nairobi as was the case for divisions and locations.

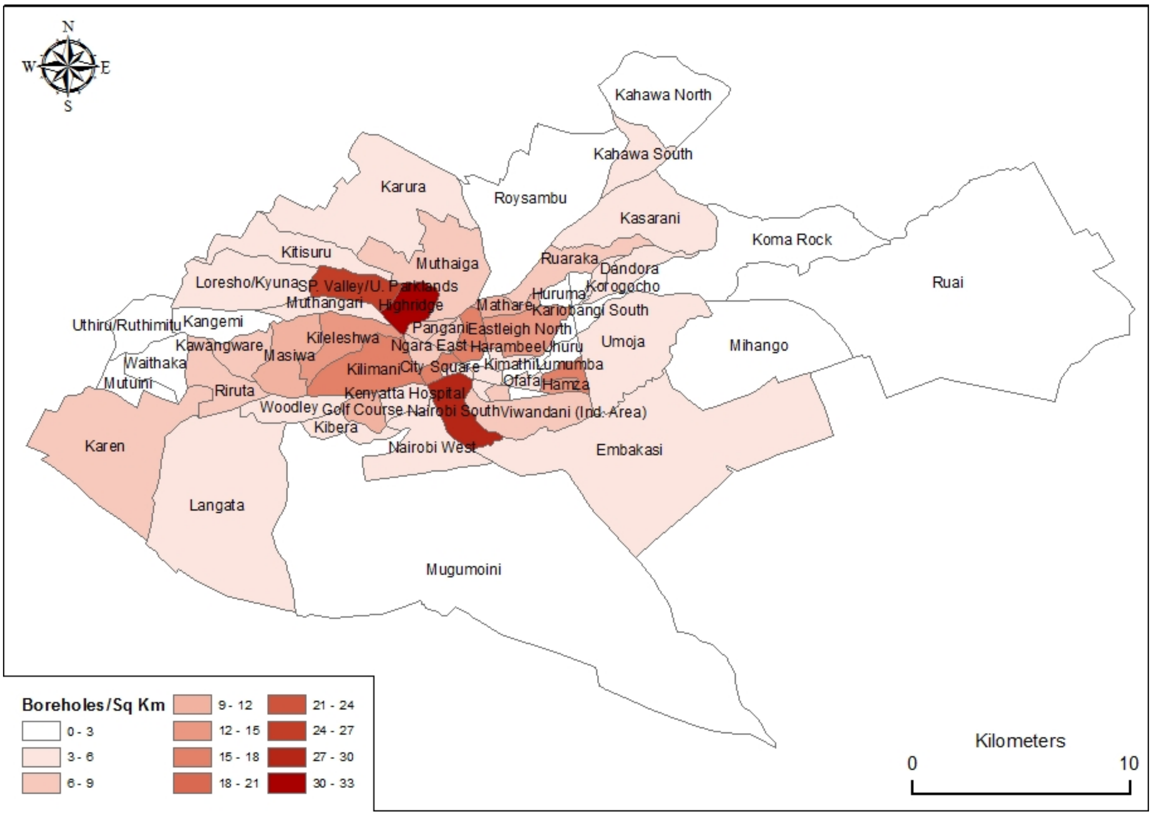


Figure 4-15: Map of Boreholes/Km2 in Nairobi's Sub-locations

Table 4-4 presents a summary of the statistics of the Borehole Spatial Densities.

Table 4-4: Summary Statistics of Borehole Spatial Density

Statistic	Sub-locations	Locations	Divisions
Administrative Units	62	30	8
Minimum Value	0: Mbotela	0.43: Kariobangi	2.16: Embakasi
Maximum Value	30.61: Highridge	13.18: Starehe	10.11: Makadara
Mean	6.85	5.24	5.63
Standard Deviation	6.42	3.60	3.04

4.1.2.2 Boreholes Per Capita Density

The density of boreholes was also calculated in relation to the population in each of the administration units Nairobi to elucidate spatial differences and trends. A growth rate of 2.11% pa was used to project the 2009 population to the year 2014 which was used in the calculations, (CIA, 2014). In the scope of the entire county it was observed that there was an average of approx. 1,290 Pers/BH and 1.86 Persons/BH/Km^2.

At the divisional level it was observed as shown in Figure 4-16 and Figure 4-17 that Parklands/Westlands with 339 and Kibera 636 Persons/BH had the highest densities whereas Pumwani with 3,092 and Central with 3,629 Persons/BH had the lowest densities. In relation to area, it is observed that Kibera has the highest density with 2.86 Pers/BH/Km^2 followed by Parklands/Westlands with 3.49. On the lower end a similar trend was observed with Central and Pumwani having 340.86 and 265.89 Pers/BH/Km^2.

It is important to note that the less the number of people per borehole the more concentrated the boreholes in the region. It was also calculated that there was an average of 2,059 Pers/BH and 98.65 Pers/BH/Km^2 across Nairobi's divisions with a standard deviation of 1,135 Pers/BH and 122.3 Pers/BH/Km^2.

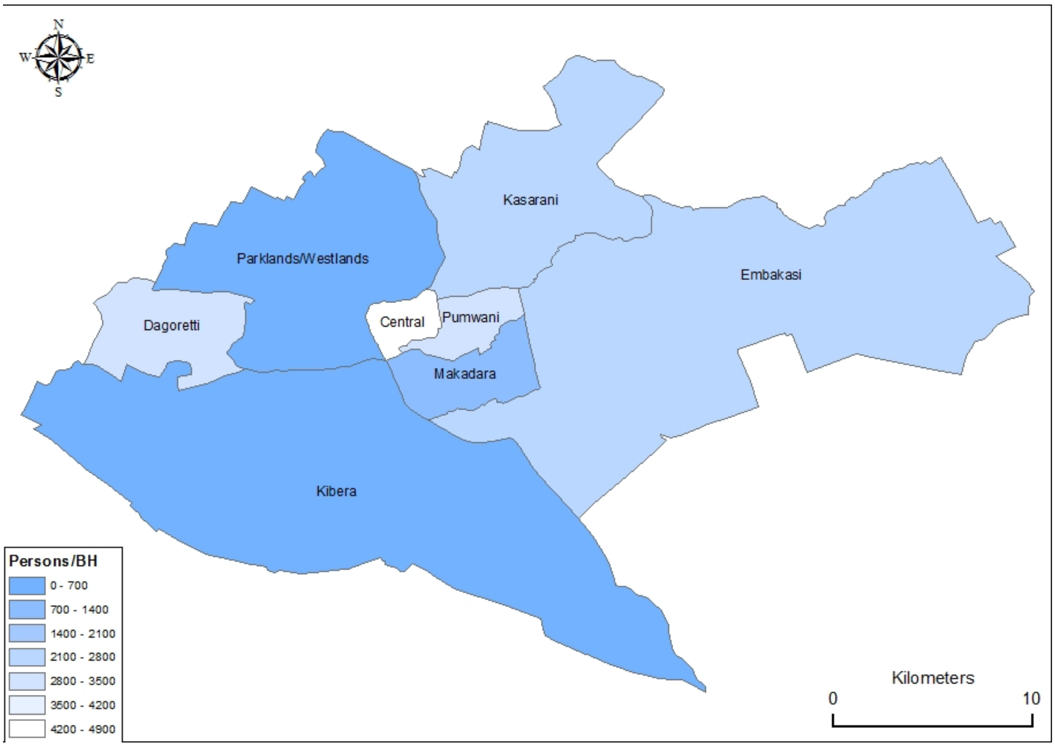


Figure 4-16: Map of Pers/BH in Nairobi's Divisions

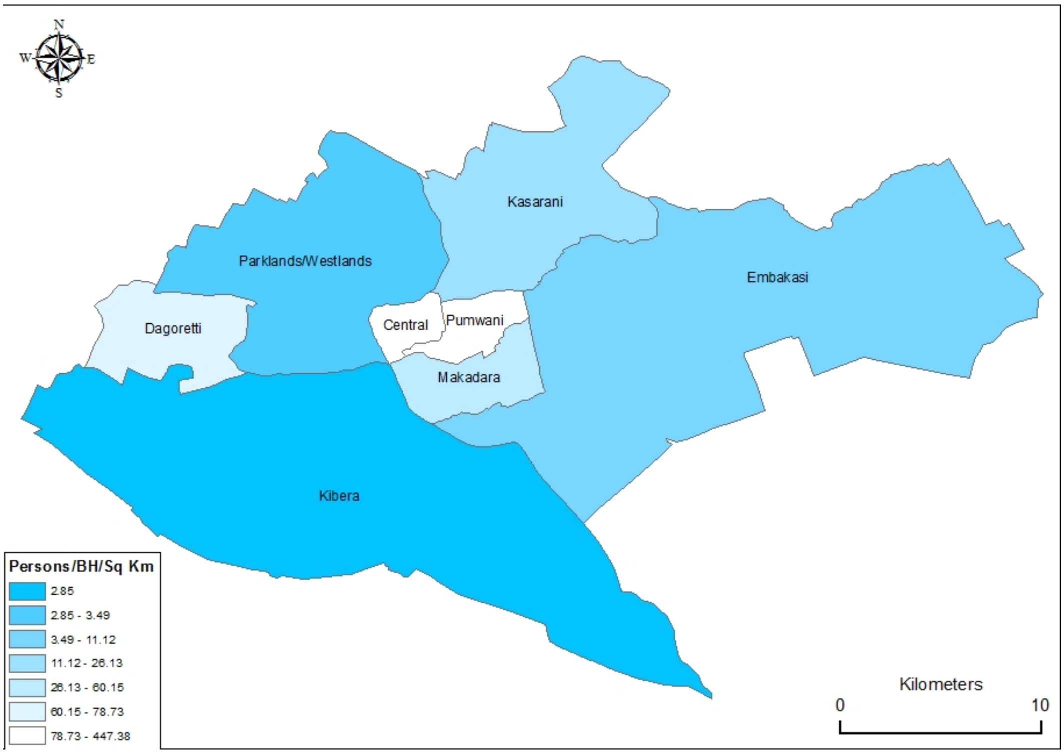


Figure 4-17: Map of Pers/BH/Km² in Nairobi's Divisions

Figure 4-18 further compares the number of persons and boreholes amongst the different divisions in Nairobi. It generally illustrates the inverse nature of the Pers/BH and Per/BH/Km^2 wherein the lower the statistic the higher the density.

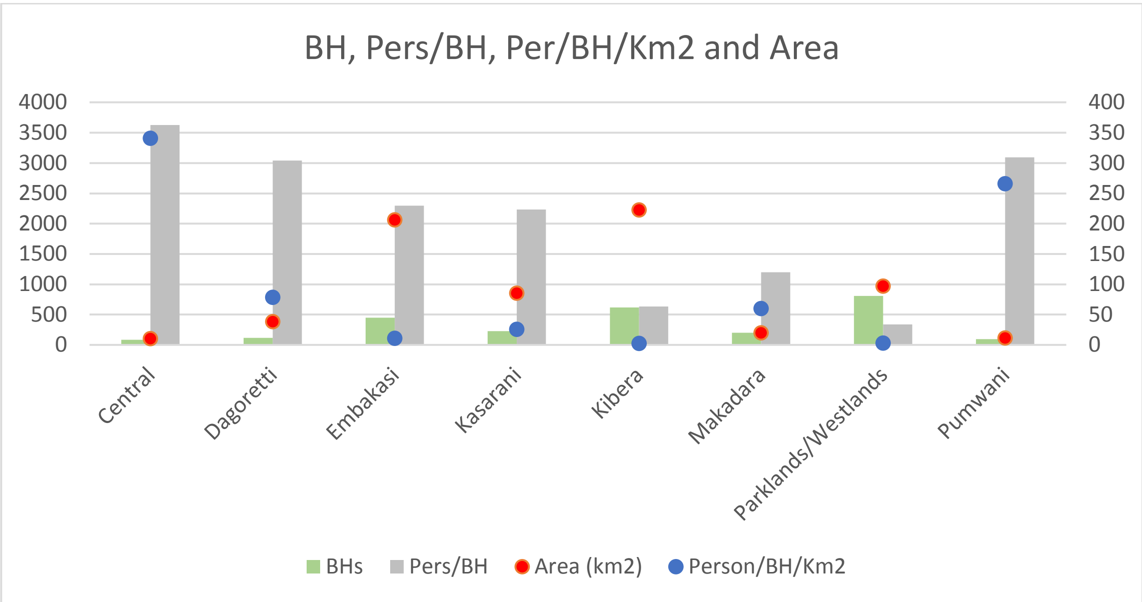


Figure 4-18: Graph of Relationship amongst Pers/BH, Area and Pers/BH/Km²

At the locational level it was observed that Karen/Langata, Parklands and Mugumoini had the highest densities with 85, 206 and 1161 Pers/BH respectively and similarly 1.19, 3.04, 7.86 Pers/BH/Km^2. Additionally for Pers/BH Korogocho (11,681), Pumwani (25,589) and Kariobangi (31,075) had the lowest densities in that order whereas for Pers/BH/Km^2 they had the lowest densities in the order of Kariobangi (6,745.76), Korogocho (12,849.63) then Pumwani (51,587.10).

These trends are illustrated in Figure 4-19 and Figure 4-20 from which it can be generally observed that according to the rating most locations of the county have higher than median level density according to the two statistics.

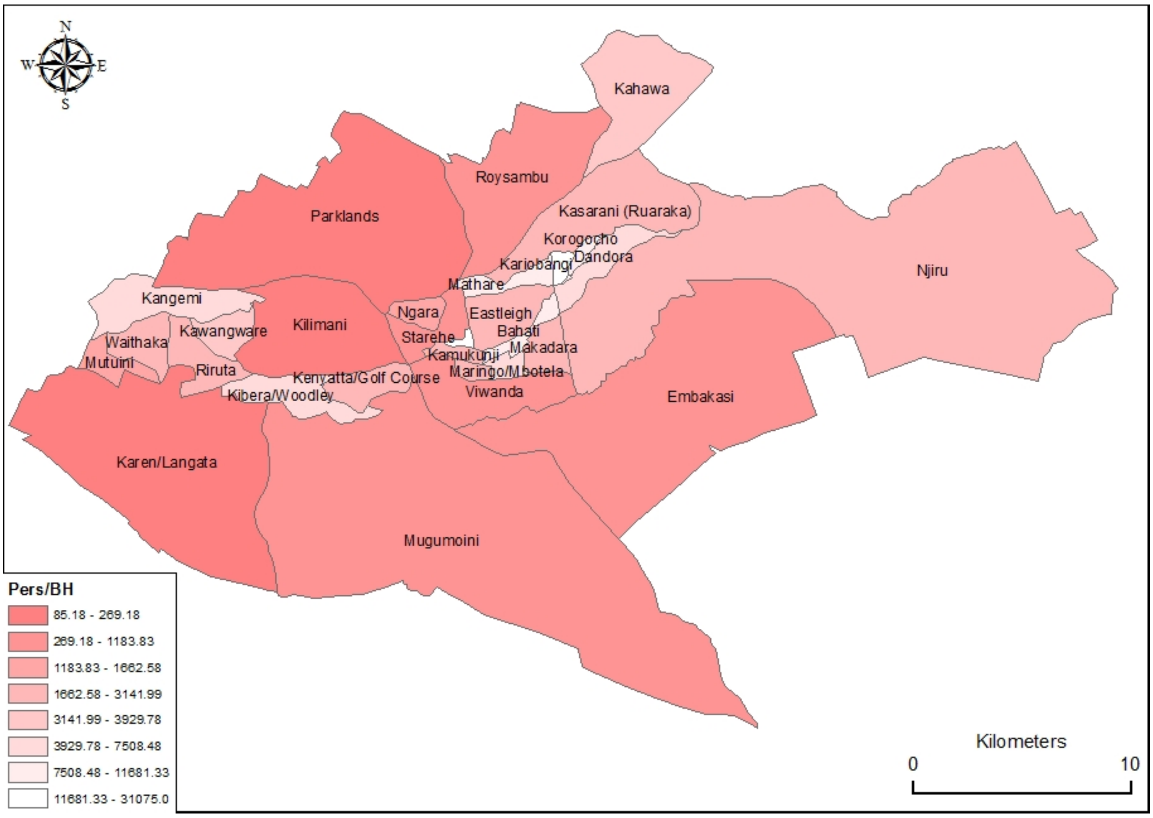


Figure 4-19: Map of Pers/BH in Nairobi's Locations

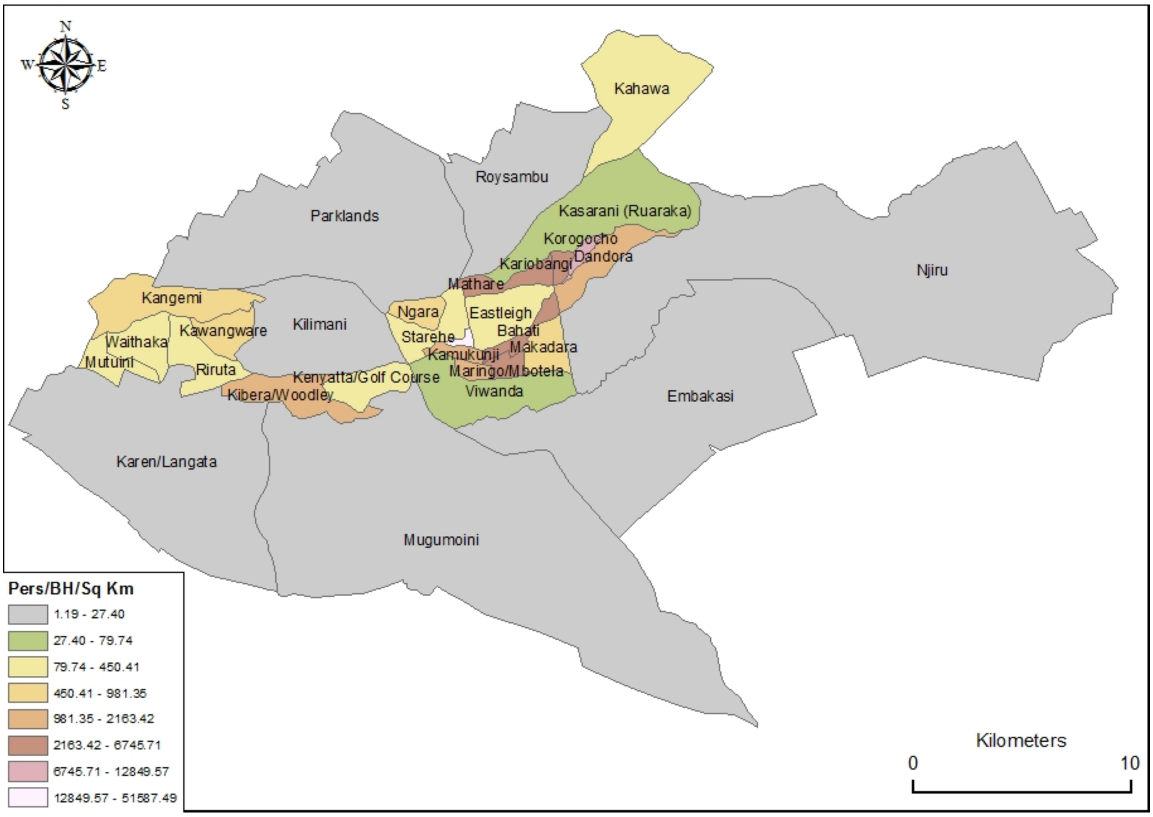


Figure 4-20: Map of Pers/BH/Km^2 in Nairobi's Locations

Lastly at the Sub-location level it was observed that the sub-locations with the highest densities of Pers/BH were City Square (13.65), Karen (77.69) and Langata (91.40) whereas those with the lowest densities included Kariobangi North (21,836), Majengo (25,589) and Huruma (29,505). Additionally in terms of Pers/BH/Km^2 an almost similar trends was observed with the highest densities falling in Langata (2.06), Karen (2.85) and Ruai (7.39) whilst the lowest falling in Kariobangi North (18,982), Huruma (21,502) and Majengo (51,587). These trends are shown in Figure 4-21 and Figure 4-22.

It is also observed that Mbotela had no boreholes and thus exhibited a null value in these statistics. Also in general it was seen that there was an average of 4,163 Pers/BH in all the sub-locations with a standard deviation of 6,205.91 Pers/BH, wherein Pers/BH/Km^2 an average of 3,180 and standard deviation value of 7,626.

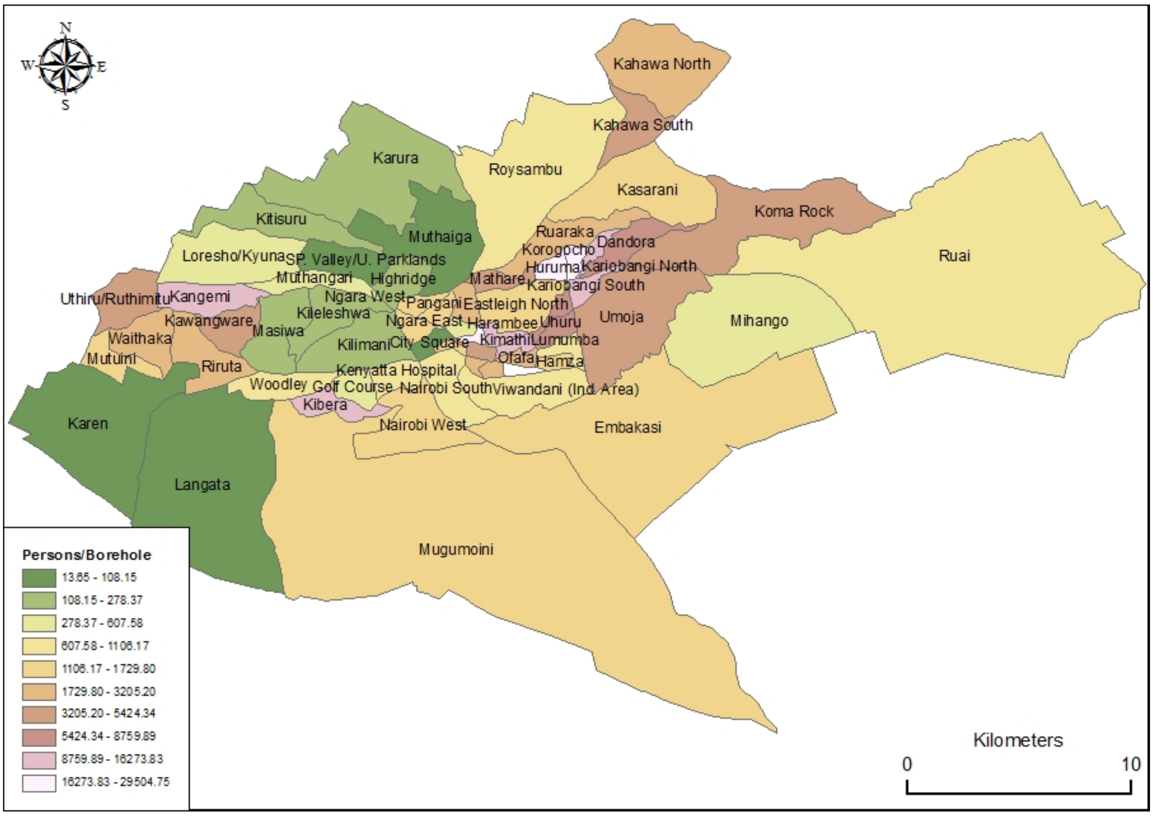


Figure 4-21: Map of Pers/BH in Nairobi's Sub-locations

From Figure 4-21 it can be generally observed that there are higher densities of persons per borehole in the South-East and North-East Sub-locations of the county. Whilst from the Figure 4-22 a similar trend is observed as to that of the locations whereby the higher densities are found in the sub-locations in North, North-East and Southern lying sub-locations.

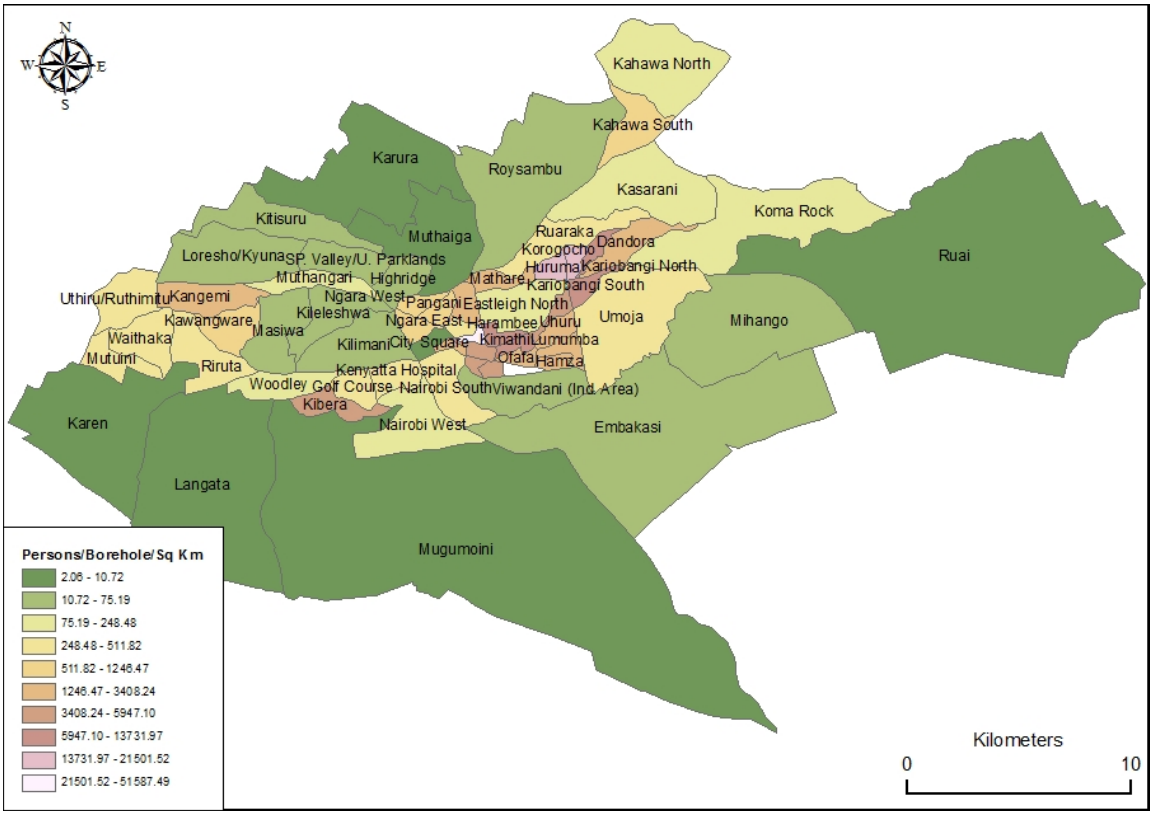


Figure 4-22: Map of Pers/BH/Km2 in Nairobi's Sub-locations

4.1.3 Pumping Rates

To estimate the groundwater abstraction rates in Nairobi, this study projected the 2010 total demand 579,000 m^3/d with a population of 3.2 million in Nairobi from World Bank (2010) to 2014. The 2014 population used in the calculation was a geometric projection of the 2009 population with a growth rate of 2.11%. This resulted in the total demand of 629,436.13 m^3/d for a population of 3,394,678. The percentage of this demand supplied by groundwater was estimated using a value of 12.5% which was obtained as a ratio of the 2010 total demand and the estimate abstraction rate from the BIS of 2011 which was a value of 72,336 m^3/d. Therefore, this estimate resulted in a total abstraction rate of 78,637.1 m^3/d and thus an average abstraction rate of 35.25 m^3/d per active borehole. The number of active boreholes was obtained from the BIS of 2011 and assumed to be the prevailing inactive boreholes thus the number of active boreholes was calculated to a value 2,231 boreholes.

The total abstraction rate was used to calculate the abstraction per Sub-location and abstraction intensity using Equation 3-4 and Equation 3-5, and the results produced the maps presented in Figure 4-23 and Figure 4-24. It was observed that whilst there were Sub-locations without boreholes which had the lowest demand and intensities the highest demand and intensity was in City Square. Additionally averages of 0.083 m^3/pers and 0.042 m^3/km^2/pers was observed in the counties sub-locations with standard deviations 0.28 m^3/pers and 0.22 m^3/km^2/pers.

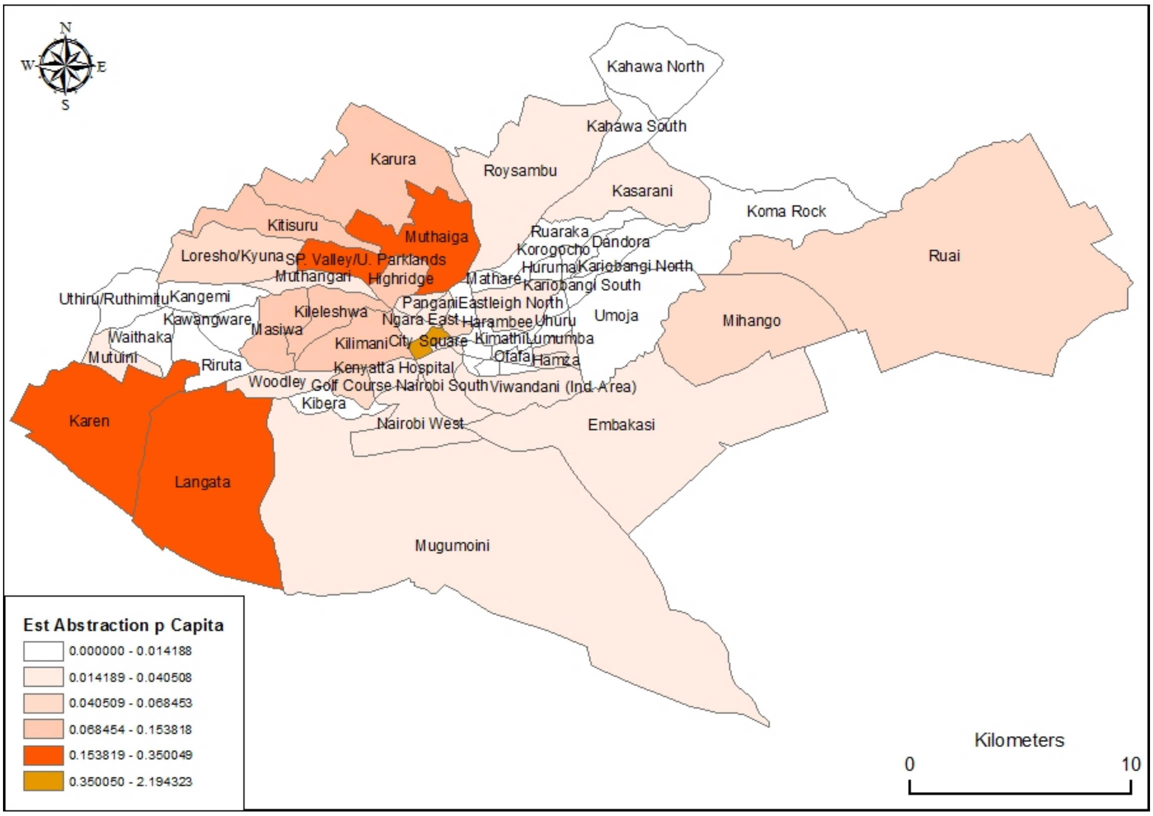


Figure 4-23: Estimate per Capita Groundwater Demand

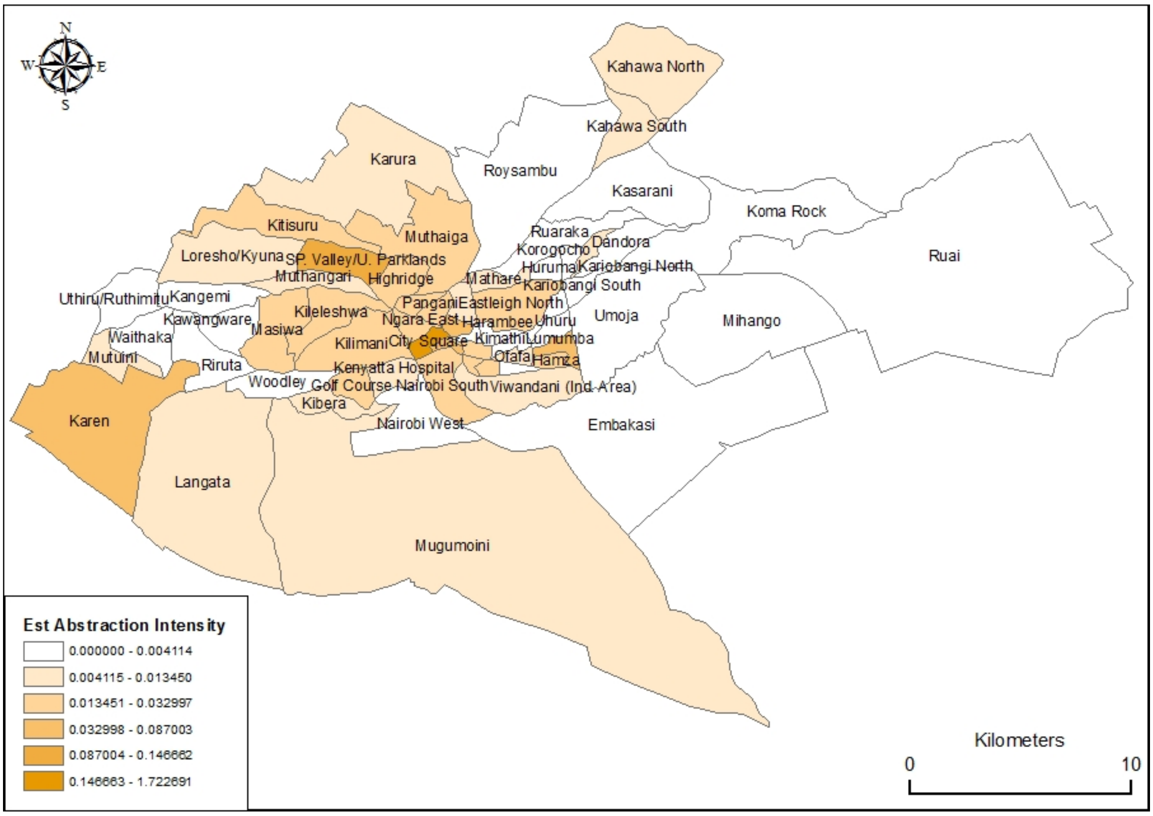


Figure 4-24: Estimate Groundwater Abstraction Intensity

From these two maps its can be observed that the eastern regions of Nairobi abstract more groundwater as compared to the western region of the county. Additionally while City Square occupies one of the least space it has a higher intensity based on these results.

4.1.4 Drilling Depths

Based on the datasets obtained for the study only a total 1,141 of the 2,632 boreholes in Nairobi had adequate information on drilling depths as well as dates and these were majorly from the Database Extract. These boreholes were used to perform analysis on drilling depths and it was observed that drilling depths ranged from 30.5 m to 820 m with a county wide average of 202.07 m and a standard deviation of 63.91 m. The depths of these 1,141 boreholes were plotted against time in Figure 4-25 and it can be observed that drilling depths generally increased with time from 1900 to 2012.

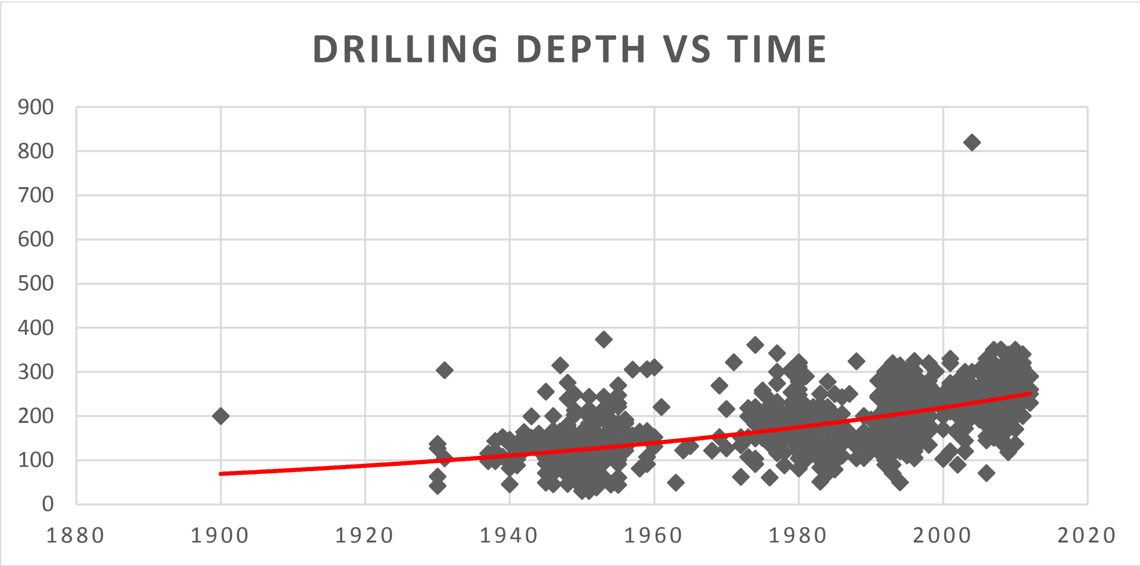


Figure 4-25: Drilling Depths vs Time

The average drilling depths for each Sub-location was calculated to give a comparison of areas where deeper and shallower boreholes exist and the results were also mapped. Figure 4-26 shows the map developed, and it is observed that the sub-locations in the central and southern regions of the county had deeper boreholes whereby Kahawa North had the lowest average with 111.01 m and Muthangari the highest with 421.3 m.

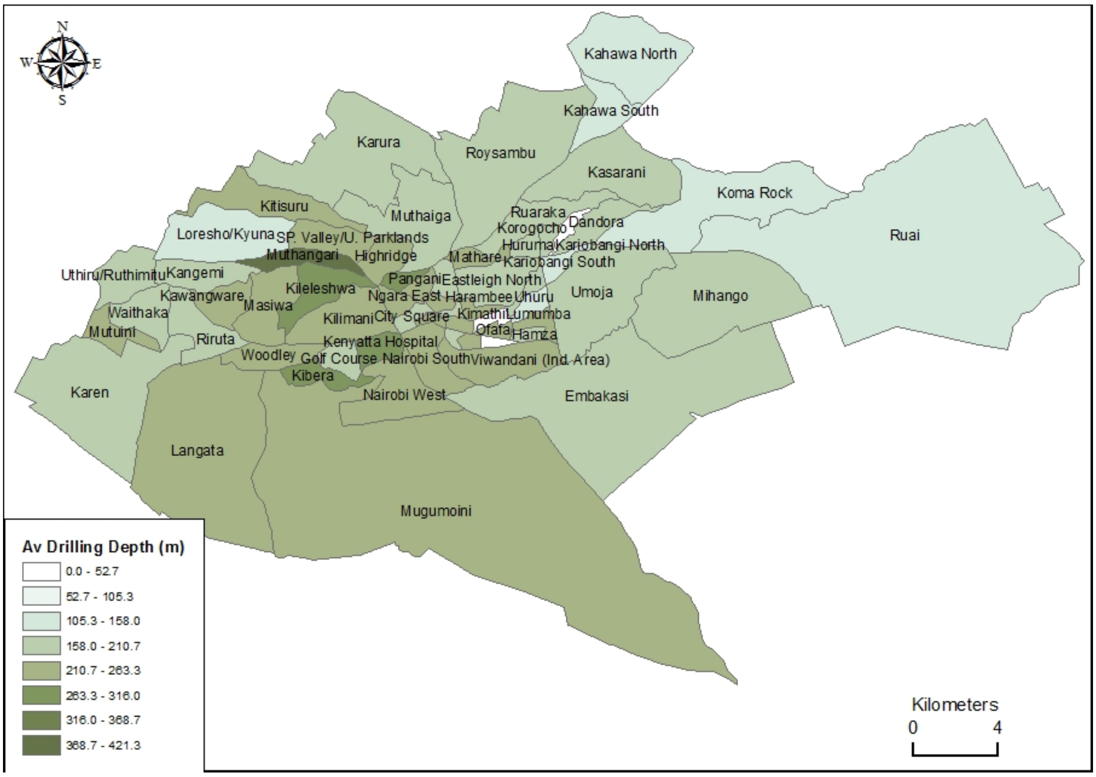


Figure 4-26: Map of Average Drilling Depths

4.1.5 Geospatial & Temporal Analyses

4.1.5.1 Proximity – Near Analysis

The analysis on proximity was undertaken using ArcGIS's Near Analysis and Average Nearest Neighbour tools on the 1,837 mapped boreholes within the County and only searching for the nearest borehole to each borehole. It yielded that the minimum distance between boreholes was 1.69 m whilst the average closest distance to the nearest borehole was 246.68 m with a standard deviation of 269.77 m. It was also observed from the results that 56% of boreholes lie within 200 m of another borehole whereas 26% lie within 100 m and 8% lie within 50 m of another borehole. Figure 4-27 presents the distribution of boreholes according to their distances to their nearest boreholes in ranges of 50 m.

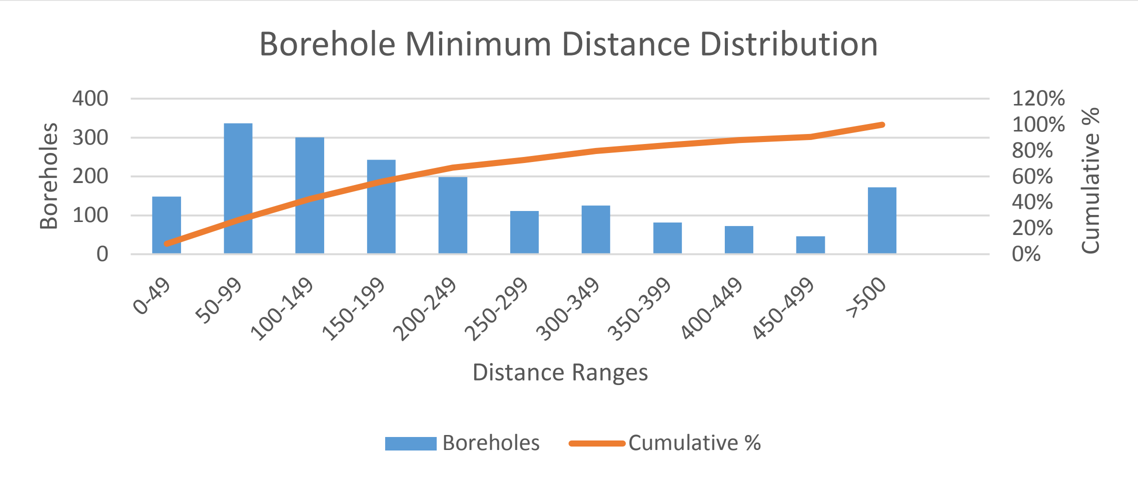


Figure 4-27: Borehole Minimum Distance Distribution

The same proximity analysis was undertaken for each location to identify spatial trends in boreholes as well as locations where borehole more closely spaced than others. The average near distance was calculated for each location and mapped as shown in Figure 4-28. It is observed from this map that the five locations with lowest average distances between boreholes were Eastleigh (92.72 m), Kilimani 139.91 m), Starehe (171.81 m), Viwanda (177.05 m) and Parklands (188.66 m).

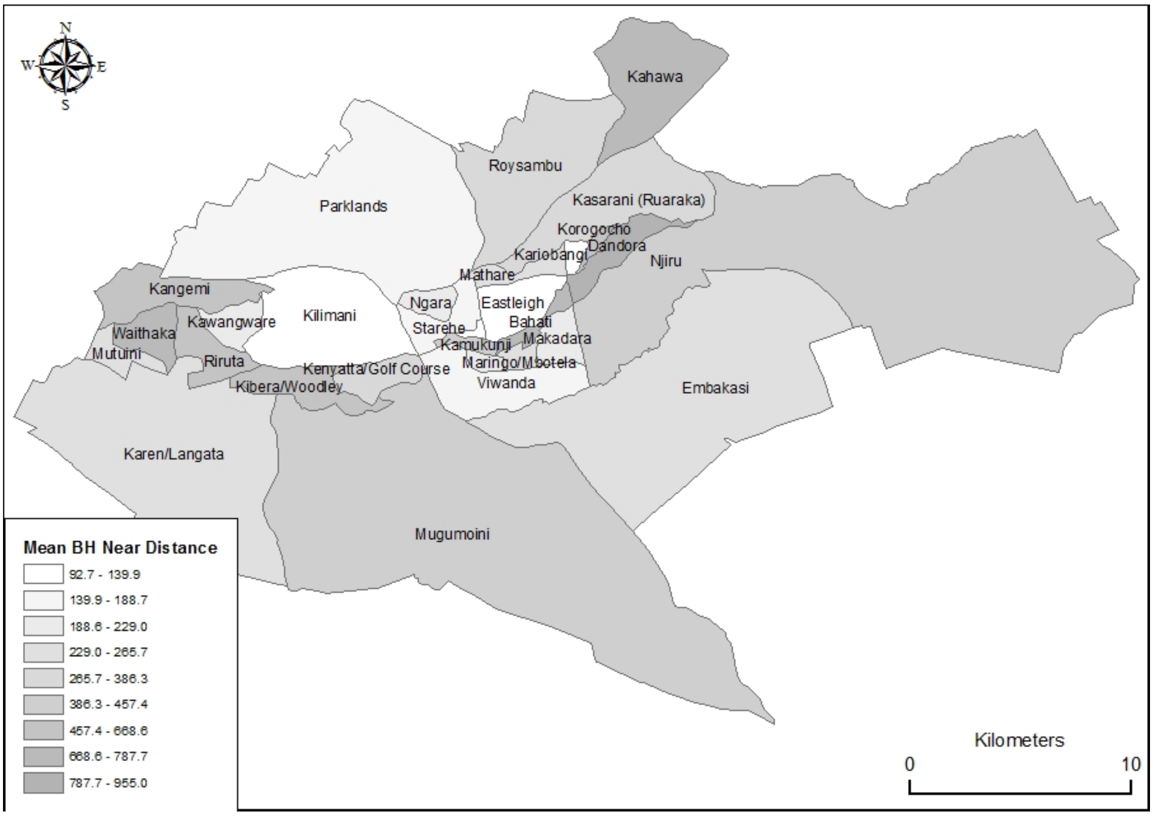


Figure 4-28: Average Near Distance in Nairobi's Locations

The ANN tool returned expected mean of 408.85 m and a Nearest Neighbour ratio of 0.603. The resultant P-score was 0.0 and Z-score -32.52 and this indicated that there was a less than 1% chance that the clustering observed was the result of a random distribution and thus the clustering of boreholes in the county was statistically significant. Figure 4-29 shows results of the ANN analysis against the P and Z-score graph.

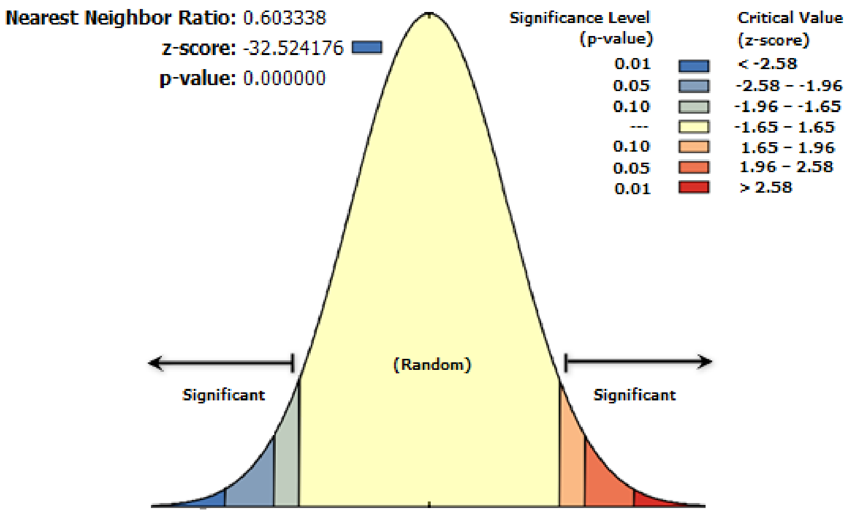


Figure 4-29: ANN Results

4.1.5.2 Point Density

The point density analysis undertaken within square neighbourhoods of 250 m sides resulted in a raster with 11,478 values within Nairobi County and the extremity of the mapped borehole shapefile. The raster had a maximum value of 29.54 Boreholes/Km^2, an average of 2.47 and a standard deviation of 3.59. The resultant raster is shown in Figure 4-30 from which it was observed that the high concentrations of boreholes were found in the central, north-west and south-west regions Nairobi. From this dataset specific high values are observed in the sub-locations of Muthaiga, Spring Valley & Upper Parklands, Highridge, Kilimani, Mathare and Eastleigh.

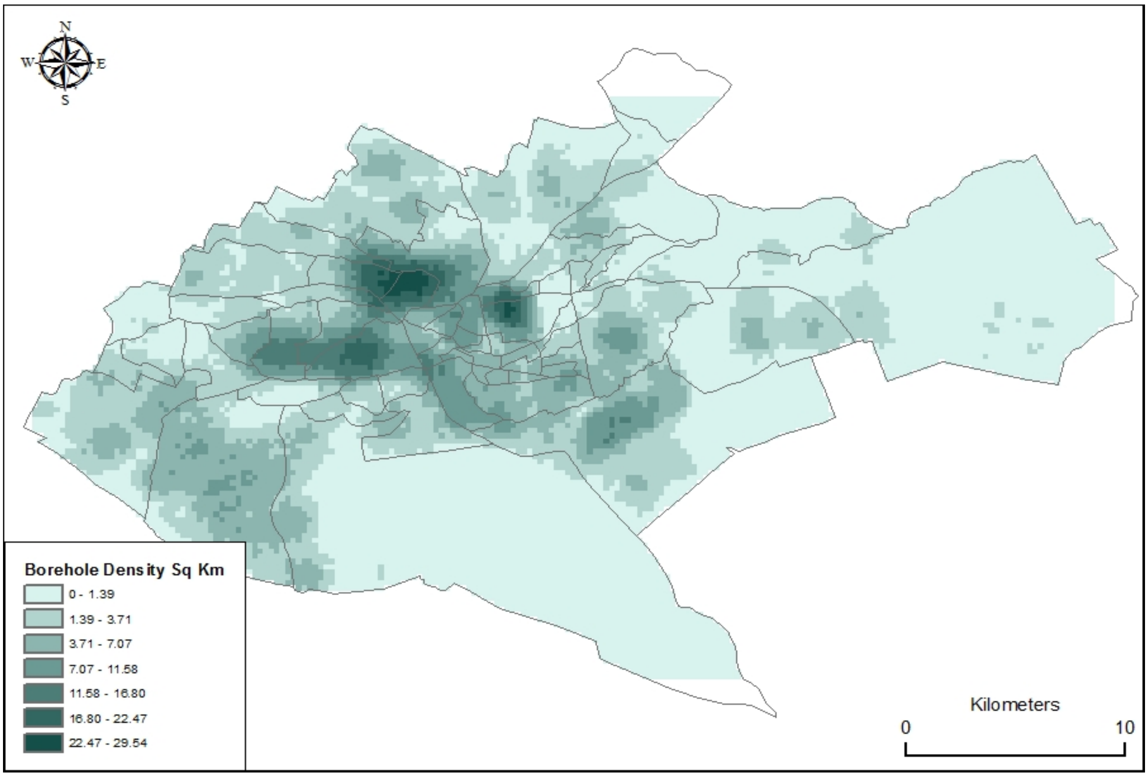


Figure 4-30: Borehole Point Density

4.1.5.3 Hotspots Analysis

The hotspots analysis performed on the 12,239 250 m squares with boreholes spatially joined returned z scores which ranged from -2.05 to 23.96 with a mean of 0.04 and standard deviation of 2.93. These were presented in the map given by Figure 4-31 which shows the statistically significant hotspots and cold spots. It was observed that hotspots are found in the central region of the county and specifically stretching from Embakasi to Viwanda, Parklands, Pangani, Mathare, Eastleigh Muthaiga, Muthangari, Kilimani, Kileleshwa and Masiwa. Another belt of hotspots can also be seen in Karen and Langata.

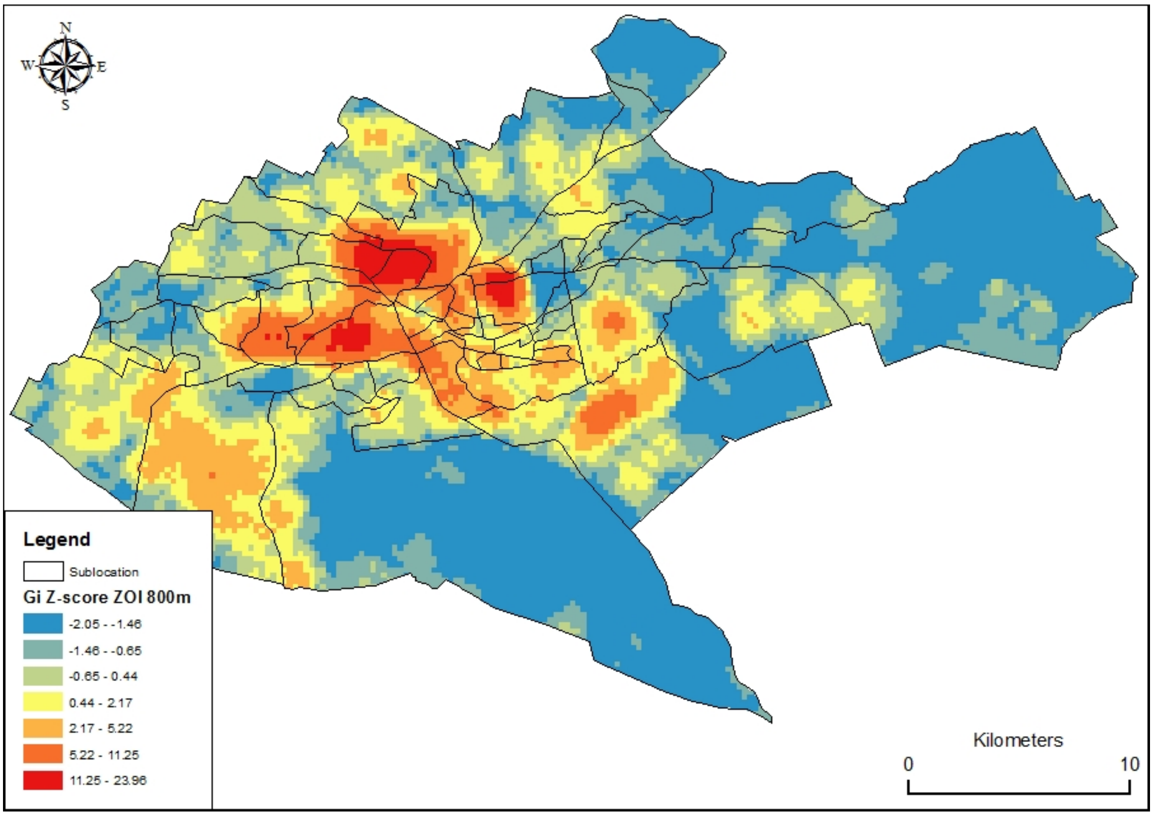


Figure 4-31: Hotspots and Cold spots from Mapped Boreholes

The same analysis was performed on the sub-locations with the abstraction intensity (m^3/d/pers/km^2) as the weight and with a distance band of 5,000 m. This resulted in hotspots being identified mainly in central Sub-locations of the county. These resultant map is shown in Figure 4-32.

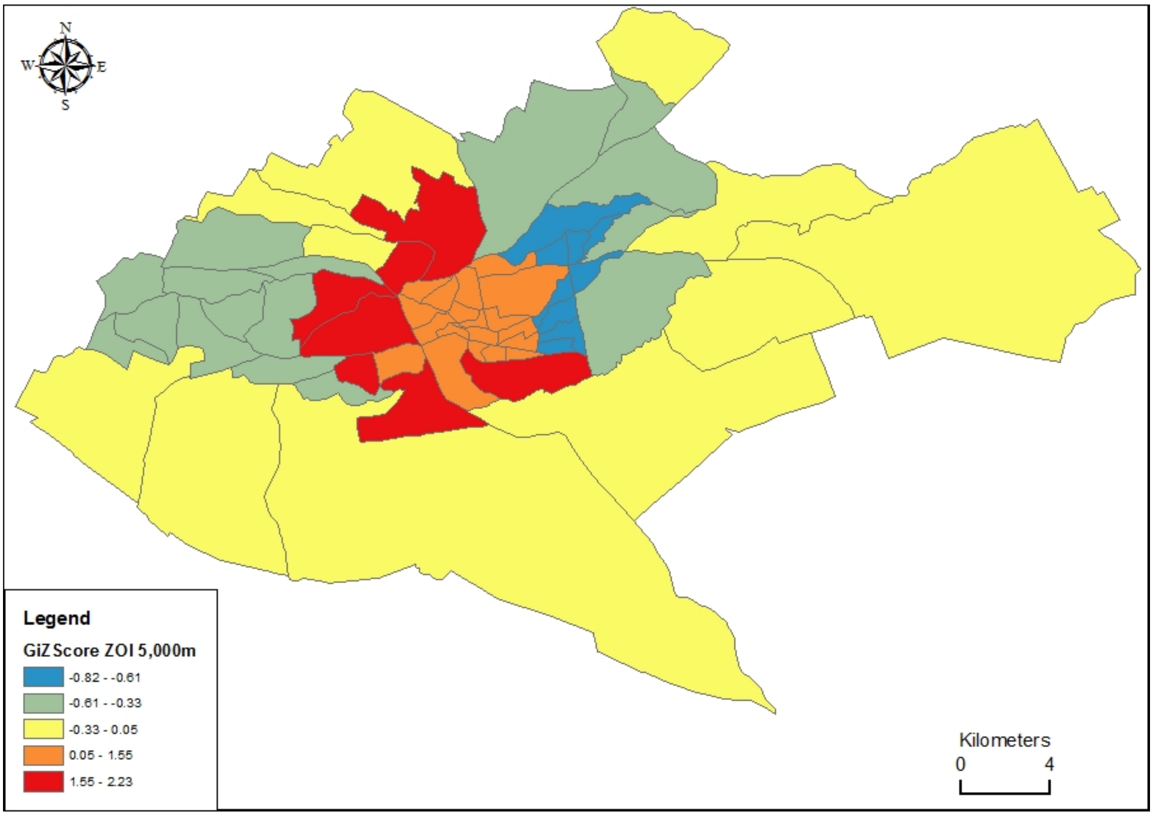


Figure 4-32: Sub-location Abstraction Hotspots and Cold spots

4.1.6 Compliance with Regulations

In this study an interview was conducted with WRMA's staff in-charge of the groundwater department at the Nairobi Sub-region Office. They informed the study that compliance with groundwater regulations in Nairobi is poor. In terms of borehole location they confirmed, as observed in the Water Management Rules of 2006, that there are no strict or definite regulations given on how far boreholes should be spaced. This results in WRMA using a guiding distance of 100 m and several people mistake the 800 m for the boreholes that should be monitored during test pumping as the Rules. Further to this they added that water regulations in Kenya are not attached to land regulations and policies and thus particularly in residential areas residents of the county often consider that they own the groundwater and develop boreholes close to each other.

WRMA's staff also noted that population growth in Nairobi has increased water demand and thus groundwater is over-exploited. This also leads to incompliance with regards to abstraction limits set out water abstraction permits and thereby borehole owners also don't pay usage charges whereas most owners don't understand the reason behind usage charges.

Additionally since Nairobi has groundwater almost everywhere errant drillers take advantage of this and forego the due process as given in Figure 2-4.

WRMA's staff also noted that in several occasions the authority has allowed groundwater development in contrast to good practice on borehole location. This has been in cases such as where large institutions require groundwater or where people have constructed major developments and apply for drilling permits whilst there are boreholes closer than 100 m. WRMA mentioned that this has been done mainly since the success of the developments hinges on groundwater.

WRMA's staff also informed the study that over time boreholes have gotten deeper in Nairobi and this is due to the topmost aquifer being polluted and over-abstracted. Additionally people still abstract from the second aquifer in as much as it is also over-abstracted. They added that compliance with other natural resource and environmental regulations in Nairobi is poor and this has in turn affect groundwater such as in cases where people build on riparian lands or manage waste poorly and thus contaminating groundwater. In addition to this Nairobi old or ill-maintained infrastructure also contributes to the problem and particularly in cases where sewers burst and contaminate both surface and groundwater.

Other factors that affect groundwater and its management also included land use changes which WRMA's staff mentioned that it greatly reduces recharge of groundwater. As a result thus the county's groundwater is mainly recharged in the Limuru and the Ngong areas.

Lastly, according to WRMA the following areas can be considered to be hotspots of groundwater abstraction and borehole proximity:

- High: Parklands, Eastleigh, Karen, Kilimani, Kileleshwa, Westlands.
- Mid-level: Industrial Area, Mombasa Road and Imara Daima.

4.1.7 Challenges in Groundwater Management

Part of the interview held with WRMA also focussed on the challenges faced in the management of groundwater. The first major noted was understaffing in that there was only one staff in-charge of the groundwater department whose mandate covers the entire NAS. WRMA's staff added that the authority faces challenges of finances to procure office and field equipment whereas the authority also depended on 15 borehole owners to monitor groundwater and this led to inconsistent data and it was only recently (a month before the interview) that authority started undertaking the construction of its own piezometers.

The situation of groundwater compliance has also contributed to challenges in data management since borehole owners who don't comply with regulations also don't furnish the authority with data on groundwater as required by the regulations. This challenge is also compounded by the fact that WRMA has used several systems in the post-colonial era to manage their data and their current database was not considered up to date whereas as observed in the datasets provided many boreholes lacked all the information required. According to WRMA's estimates there may be up to 6,000 boreholes in the county if both legal and illegal boreholes are enumerated.

Legal awareness was seen as a challenge in groundwater management by WRMA's groundwater staff. This was in relation to the county's residents understanding what is required from them to develop a borehole and abstract water. Additionally WRMA's staff observed that the legal framework on water is also not adequate, particularly since it is not attached to land regulations and policies. Compliance with specific regulations such as monitoring all boreholes within an 800 m radius is also faced with the challenge of cost since this would make the drilling process more expensive.

4.2 DISCUSSIONS

4.2.1 Borehole Siting

In this study 2,632 boreholes were located with only 34 not to their specific sub-locations whilst 1,837 were fully mapped with their coordinates. This total number of boreholes in the county was 500 more than those enumerated in the BIS study of 2011 and surpasses the projection of the Water Allocation Plan of 2009 which estimated that 2,500 boreholes would be drilled by 2018. However in as much more boreholes were located in Nairobi all could not be mapped due the completeness of the datasets provided by WRMA and this study was also not able to obtain an up-to date shapefile of Nairobi's Sub-locations.

In spite of this, the data shows that general clusters of boreholes exist in Central, Westlands, Parklands, Karen, Langata and Embakasi. In particular these areas also had statistically significant hotspots and this can be attributed to the regions having smaller Sub-locations and a high number of borehole density. These hotspots were also confirmed by the BIS and the interview held with WRMA. It can also be deduced that these regions are also the more affluent areas of the county thus they have more residents who can afford to drill boreholes whilst developers also target these areas.

Spatiotemporally, the results obtained also show that over time the number of boreholes has increased with the population which is the major driver of change in the management of natural resources. Additionally over time boreholes also concentrated in the regions that can be considered hotspots. This study also observed that a significant increase in the number of boreholes from the 1990s and this has been attributed to: increases in GDP, population growth and increased water demand, and confidence in the economy (WRMA, 2011).

The analysis on borehole proximity showed that 56% of the mapped boreholes lie within 200 m of each other and 26% within 100 m as compared to the 20% observed in the BIS (WRMA, 2011). Thus in relation to the guiding limit of 100 m used by WRMA this means that would future and currently drilled boreholes increase this ratio and in particular in the identified hotspots. This study also observed that proximities and densities are higher in the GCA as compared to other regions in county whereas the number of boreholes has generally increased across the entire county (See Figure 4-33).

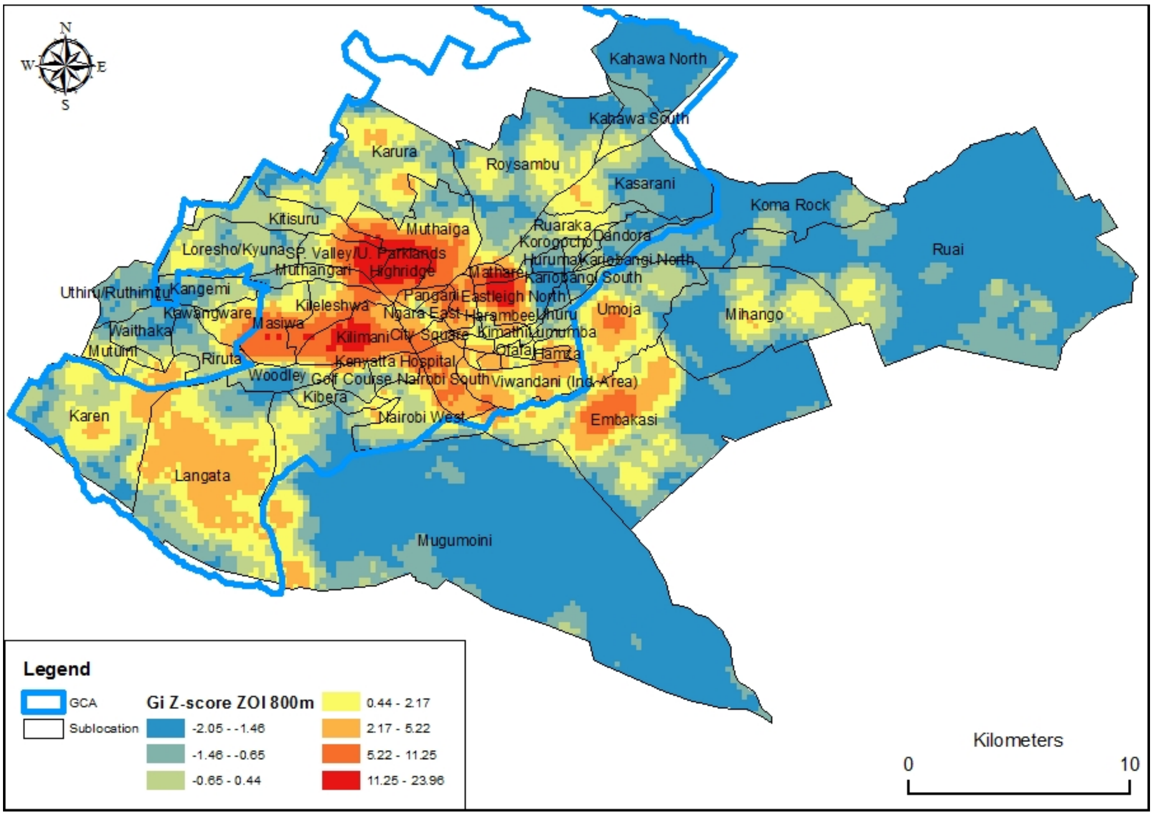


Figure 4-33: Hotspots and the GCA

It was also observed that these statistically significant hotspots were also had high borehole densities from the point density analysis. Thus this therefore means that individually and globally, in the context of the map, these areas are hotspots because they contain higher number of boreholes within relatively small areas as compared to the cold spots.

These results were pertinent to this study's objective of assessing trends in borehole siting and thus achieved this objective. The information from this study can enable the wise management of water resources since they enable practitioners or stakeholders to identify geographic areas of concern. These are the regions which are the statistically significant hotspots. It is these areas where regulations and good practice should be enforced.

Furthermore, monitoring efforts should be more focussed on these areas since they currently pose the most threats to the sustainability of groundwater resources. This is because they are the regions where more intensive abstraction is undertaken in the county. On the side of developers these results can enable them to be aware of the density of boreholes in their area of influence or concern. This is important since most multi-storey developments in the county often use groundwater to ensure a consistent supply of water for their establishments. These results can enable them to predict their potential impact as required by the Environmental Management and Coordination Act of 1999.

4.2.2 Drilling Depths and Pumping Rates

In response to its objective of assessing trends in pumping rates this study estimated a geometric groundwater abstraction rate of 78,637 m^3/d which was 8.4% more than estimated by the BIS of 2011. This was considered a sound estimate given that the study was not able to obtain complete data on the recommended pumping rates for all the boreholes mapped since only 27% of the boreholes in the mapped boreholes had this data. This was also true for the BIS since the researchers report that they encountered non-operational and potentially operational boreholes whereas in some cases they were not allowed to enumerate boreholes by the boreholes owners. This situation makes it challenging to estimate the total amount of water abstracted in the county and particularly since most borehole owners who don't comply with regulations don't furnish WRMA with the required data as per the water management rules of 2006.

In light of this, this study's abstraction rate was based on the number of boreholes in a region and thus pointed out that the significant abstraction hotspots include: Central, Parklands/Westlands and Karen/Langata divisions. These were also borehole density hotspots which are also noted to be hotspots from the interview held with WRMA as well as the BIS of 2011. Therefore, these areas can be considered to be areas of concern in terms of groundwater management.

On the aspect of assessing drilling depths as was part of the objectives of this study, an increase of average drilling depths from 80 m in the 1930s to 250m in the 2010s based on 43% of all mapped boreholes was observed. This is attributed to several factors which firstly include increased pollution of the top most aquifer as identified by WRMA's staff. Secondly, this study observes that the Sub-locations with high borehole densities also have deeper boreholes on average. This provides evidence to deduce that competition for groundwater has resulted in development of deeper boreholes. Thirdly several studies have deduced that this is because of a falling water table. This study deduces that all these factors have contributed to this situation moreover due to the proximity of borehole particularly in the hotspot areas. It is common practice for new boreholes to be licensed on condition that they are drilled deeper than their neighbouring boreholes and the intersecting areas sealed. This is considered to prevent and interface between the deeper borehole and the aquifers of the neighbouring boreholes.

4.2.3 Compliance and Challenges

From the interview with WRMA it was noted that compliance with groundwater regulations in the county is low and this is also corroborated by the BIS which observed that only 20% of boreholes in Nairobi could have potentially met their compliance criteria. Taking the 100 m borehole spacing limit used by WRMA as a guide to legal compliance this study observed that at least 26% of the mapped boreholes lie within 100 m of another borehole. Thus they would be incompliant with this standard or guide. Compliance with this spacing limit is also encumbered by small land parcel sizes in urban areas of the county. This is because the sizes of neighbouring land parcels may often mean that locations of boreholes would fall within 100 m of each other.

Additionally due to low level of compliance and errant drilling this study was not able to identify all the boreholes in Nairobi based on WRMA's data. This is because illegally drilled boreholes would not feature in their records and this also affects the quality of decisions that can be achieved on groundwater management in the county. Furthermore it was gained from the interview that it is a common practice for borehole owners not to pay usage charges or abstract beyond their recommended limits. This also lowers the accuracy of abstraction data or estimates in previous studies.

This study learned from WRMA that the cost implications of complying with borehole development regulations in some cases is a disincentive towards compliance. An example of this monitoring the water levels of boreholes within a radius of 800 m when test pumping a borehole as required by the Water Resource Management Rules of 2006. In the areas identified by this study to have high densities of boreholes this would require a significant effort and collaboration from private owners of boreholes.

Enforcing compliance is mainly challenged by understaffing and a low level monitoring undertaken by WRMA. This is related to its capacity as the regulator. On the contrary it is difficult to establish how much groundwater is abstracted in Nairobi since not all borehole owners pay usage fees. A summation of these fees would enable stakeholders to determine how much groundwater is abstracted from the county. The Water Resources Management Rules of 2006 also require a 5% surcharge on the abstraction of groundwater with GCAs. This regulation is however not enforced since the GCA in the county is not enforced.

On the legislative aspect it was noted that Kenya doesn't yet have streamlined regulatory framework on groundwater and this has partly led to it poor management. Whereas its management is also affected by the enforcement of existing legislations as well as the overarching natural resource management regulations. Thus as observed by Hilda et al (2012) if proper governance are put in place then technical solutions would suffice. Borehole siting was investigated by this study and it observed that there are no explicit regulations on the minimum distance between boreholes. WRMA, (2010) recommends that borehole spacing should be based on:

(a) Existing borehole or well spacing;
(b) Individual aquifer characteristics, including water quality;
(c) Existing aquifer use, and
(d) Existing bodies of surface water.

WRMA, (2010) further recommends that a minimum distance of 500 m should be enforced within the NAS. Based on this study's results this would mean that more boreholes would be incompliant with regulatory guidelines.

The situation on compliance is observed to be mainly driven by population increase and the associated increase in water demand. Studies have pointed out that future scenarios indicate that more water supply systems and demand side management measures would be required to meet Nairobi's demand, (Jacobsen et al, 2012; Transworld Publishers, 2013). However with the increased demand that has led to the drilling of more boreholes since 1990, it can generally drive incompliance to satisfy the water demand although not sustainably. The Water Resource Management Rules of 2006 establish the minimum reserve of any aquifer to 40% of the mean annual aquifer recharge and this study observes that without a water balance analysis of the NAS this is difficult to establish. Therefore, this is not established for the NAS.

Managing groundwater resources is challenged by various factors and this include the level legal awareness of Nairobi's citizen or borehole owners. This was expressed by WRMA's staff that in some cases users don't know why they should pay for water usage and they often consider that the groundwater is their property. This situation WMRA's staff believed could be salvaged by linking the land policy with groundwater. Additionally with the regulatory authority facing challenges on finances and human resources the enforcement of regulations in the county will be trivial and further complicate the situation by creating an environment for illegal activities.

This study also noted that the lack of the central and publicly available database on groundwater is a challenge. This was directly observed in that the quality of data obtained from WRMA which were not adequate to perform all the analyses undertaken to their full scope. This was also observed by the BIS which also sought to develop a database for WRMA and to the time of the study WRMA still uses different systems to manage borehole data.

In this respect this study achieved its objective of assessing the situation on compliance with regulations. These findings can inform efforts towards ensuring compliance. This is because gaps in the legislative requirements have been identified by this study. On the other hand concern areas which this study terms to be borehole location and abstraction hotspots have identified using statistically methods. In these regions groundwater abstraction not only be closely monitoring but also enforced. Lastly, to complement this the enforcing other supporting regulations such as those dealing with environmental management and land use would ensure sustainable management of groundwater resources. This is because they would prevent pollution and or ensure adequate recharge.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 STUDY CONCLUSIONS

In response to its first objective this study mapped 2,632 boreholes in the sub-locations of Nairobi County whereas despite data availability challenges encountered 1,837 boreholes were fully mapped with their coordinates. However as identified in the BIS and WRMA (2009) the total number of boreholes in the county is not well known but estimated by WRMA's groundwater staff and NASWAP to be almost 6,000. In addition to this hotspots or areas of concern were also identified in the divisions of Central, Parklands/Westlands, Karen/Langata and Embakasi. These were statistically significant hotspots and thus they are areas in which more sustainable management could be focussed on. Spatiotemporally it was also observed that in the decades since 1900s the most boreholes were also concentrated in these areas more than other divisions and except for Embakasi they also majorly intersect the GCA.

This study also observed that the borehole density hotspots were also hotspots for water abstraction based on a geometric estimate of groundwater demand that stands at 78,637 m^3/d. Additionally in review of drilling depths it was observed that average of 170 m has increased in the depth of boreholes from the 1900s to 2013.

In answer to its second objective this study observed that there are several factors that drive incompliance with groundwater regulations in the county with the major underlying factor being population increase and its commensurate water demand. It was elucidated from the interview that as the regulatory authority, WRMA mainly faces challenges of understaffing and finances in enforcing its mandate. On the other hand, the level of legal awareness and baseline situation of abundance of groundwater allows for errant drilling. In conclusion this study therefore generally observed that the situation on compliance in one way reinforces itself due the exigent factors in the county which include:

- Population increase,
- Water demand increase,
- Intermittent piped supply,
- Unclear legal framework,
- Poor enforcement of supportive regulations,

- Lack of a publicly available groundwater database for decision making,
- Low capacity of the regulator in terms of financial and human resources,
- Groundwater availability that allows errant drillers to forego due processes, and
- Low level of awareness of residents and borehole owners.

5.2 RECOMMENDATIONS

5.2.1 Recommendation for Sustainable Groundwater Management

In response to this study's final objectives it was noted from the finding and discussions that several key measures can be undertaken and promoted to ensure groundwater resources in the county are managed sustainably. These include:

- Enforcing the GCA and extending it to include the identified statistically significant hotspots in the county.
- Controlling settlements as per regulations and good practice to prevent land use changes from limiting the recharge of the NAS.
- Creating awareness amongst borehole owners and future borehole owners when applying for drilling permits on the legislative requirements for operating a borehole and importantly on the reason behind the requirements.
- Monitoring groundwater in the county by constructing more piezometers and collecting more data from operators.
- Focussing monitoring in the areas identified as statistically significant hotspots and controlling borehole development in these regions.
- Promoting Integrated Water Resource Management in groundwater management and involving all stakeholders in the strategic resource planning process.
- Developing a publicly available database on groundwater and boreholes using industry models such as the Arc Hydro Groundwater Data Model[4] and updating the data on existing boreholes.
- Increasing WRMA capacity through training, financial and human resources.
- Enforcing both water and other complementary natural resource management regulations and developing a clear legal framework on groundwater management

[4] ArcHydro Groundwater (2013). Arc Hydro Groundwater Data Model. Accessed June 24, 2015 from http://archydrogw.com/Arc_Hydro_Groundwater_Data_Model.

in the county. This includes establishing strict and definite regulations on borehole siting.

- Improving infrastructure in the County as direct technical measure to prevent pollution of groundwater.
- Modelling the catchment to estimate recharge and production, and assessing the impact of future scenarios as well as the implications of uncertainties such as climate change.

5.2.2 Recommendations for Future Studies

Several research gaps were also identified in the course of this study and they are given below as recommendations for future studies:

- Mapping all boreholes with their coordinates in the County.
- Modelling the catchment to develop a water balance on recharge and abstraction to elucidate the sustainability of prevailing practices.
- Modelling the flow of groundwater in the county.
- Assessing the direct and indirect impacts of Nairobi's land use changes (real estate growth) on groundwater and aquifer characteristics.

REFERENCES

Caroline O., Sagi D., David S., and Monika S., 2012. ***Modelling of Spatial and Temporal Variations in Groundwater Rest Levels In Nairobi City Using Geographic Information System***. Nile Water Science and Engineering Journal, Vol. 5(1): pp. 26-33.

CCN, 2007. ***City of Nairobi Environment Outlook***. City Council of Nairobi.

Chen F. and Liew Y., 2003. ***The Civil Engineering Handbook***. Second Edition. Groundwater Engineering Article by the Jacques W. Deulleur. CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431.

CIA, 2014. ***Kenya Population Growth Rate July 2014 Estimate***. The World Factbook, Kenya, People and Society. Retrieved 04 June 2014 from https://www.cia.gov/library/publications/the-world-factbook/geos/ke.html

Eliud W. and Douglas M., 2013. ***Geospatial Analysis of Groundwater Fluoride Contamination in Embakasi Area, Nairobi***. ESRI Eastern Africa Education User Conference. 17 – 18 September, 2013. Kenyatta University, Kenya

EPA, 2013. ***Getting Up To Speed: Groundwater Contamination***. EPA Teachers and Students Program Curricula, Magnificent Groundwater Connection. Retrieved 06 March 2014 from http://www.epa.gov/region1/students/pdfs/gwc1.pdf

ESRI, 2010(a). ***Proximity Analysis***. ArcGIS Resource Center. Desktop 10. 380 New York Street, Redlands, CA 92373-8100

ESRI, 2010(b). ***Hot Spot Analysis - Part 2***. ArcGIS Resource Center. Desktop 10. 380 New York Street, Redlands, CA 92373-8100

ESRI, 2012. ***How Point Density works***. ArcGIS Resource Center. Desktop 10.1 Help. 380 New York Street, Redlands, CA 92373-8100

ESRI, 2013(a). ***What is a z-score? What is a p-value?*** ArcGIS Resource Center. Desktop 10.1 Help. 380 New York Street, Redlands, CA 92373-8100.

ESRI, 2013(b). ***How Hot Spot Analysis (Getis-Ord Gi*) works***. ArcGIS Resource Center. Desktop 10.1 Help. 380 New York Street, Redlands, CA 92373-8100

ESRI, 2013(c). ***How Average Nearest Neighbour works***. ArcGIS Resource Center. Desktop 10.1 Help. 380 New York Street, Redlands, CA 92373-8100

ESRI, 2013(e). ***How Spatial Autocorrelation (Global Moran's I) works***. ArcGIS Resource Center. Desktop 10.1 Help. 380 New York Street, Redlands, CA 92373-8100

Ferris J.G., Knowles D.B, Brown R.H and Stallman R.W, 1962. ***Theory of aquifer tests***, U.S. Geological Survey Water-Supply Paper 1536 E, 174p.

Fred K., 1960. ***Time, Distance and Drawdown Relationships in a Pumped Ground-Water Basin.*** Geological Survey Circular 433.

George F., 2002. ***Groundwater Modelling Using Geographical Information Systems***. John Wiley & Sons, Inc., 605 Third Avenue, New York, NY 10158-0012.

Getis, A., 1983. ***Second-Order Analysis of Point Patterns: The Case of Chicago as a Multi-Center Urban Region***. The Professional Geographer 35:73-80.

Getis, A., 1991. ***Spatial Interaction and Spatial Autocorrelation: Across-Product Approach***. Environment and Planning A 23:1269-1277.

Getis, A., Ord, J., 1992. ***The analysis of spatial association by use of distance statistics***. Geographical Analysis 24, 189–206.

Google Earth, 2013. ***Nairobi Satellite Image***. Retrieved 08 August 2013 from https://maps.google.com/maps?ll=-1.3182905,36.873479&z=10&t=h&hl=en

Gulf Power Ltd., 2010. ***Geology and Hydrogeology Report***. ESIA Study of the Proposed IPP Power Plant, Mombasa Road, Athi River, Kenya.

Hilda M., Albert O. and Anne S., 2012. ***Water governance in Kenya: Ensuring Accessibility, Service delivery and Citizen Participation***. iHub Research Kenya.

ICRC, 2010. ***Technical Review: Borehole Drilling And Rehabilitation Under Field Conditions***. International Committee of the Red Cross 19, avenue de la Paix 1202 Geneva, Switzerland.

Jacobsen, Michael, Michael W. and Kalanithy V., 2012. ***The Future of Water in African Cities: Why Waste Water?*** Directions in Development. Washington, DC: World Bank. Doi: 10.1596/978-0-8213-9721-3. License: Creative Commons Attribution CC BY 3.0.

Kouamé K., Jourda J., Saley M., Deh S., Anani A., Le Blanc Y., Cloutier V. and Biéme J., 2013. ***Modelling of Groundwater Flow and Drawdown Evolution Simulation of Abidjan Aquifer (Côte D'ivoire)***. Journal of Asian Scientific Research, 2013, 3(4):344-364.

Leake S., 2013. ***Land Subsidence From Ground-Water Pumping***. Retrieved 03 March 2014 from http://geochange.er.usgs.gov/sw/changes/anthropogenic/subside/. U.S. Geological Survey

Luc A. and Sergio J., 2010. ***Perspectives on Spatial Data Analysis***. Springer Heidelberg Dordrecht London New York. Springer-Verlag Berlin Heidelberg 2010.

Manfred M. and Arthur G., 2010. ***Handbook of Applied Spatial Analysis***. Software Tools Methods and Application. Springer Heidelberg Dordrecht London New York.

Marleen C., Fidelis K. and Kristine W., 2008. ***Hydrochemistry and source of high fluoride in groundwater of the Nairobi area, Kenya***. Hydrological sciences journal 53 (6), 1230-1240.

Michael F., n.d. ***GIS and Modelling Overview***. National Center For Geographic Information And Analysis. University Of California. Santa Barbara, California.

Mogaka H, Gichere S, Davis R & and Hirji R 2006: ***Climate variability and water resources degradation in Kenya: improving water resources development and management***. World Bank Working Paper no. 69, ISBN-10 0-8213-6517-7, Washington DC.

MoPHS, 2011. ***Water Safety and Quality Control***. Department of Environmental Health and Sanitation. Retrieved 09 August 2013 from http://www.publichealth.go.ke/water-safety-and-quality-control.

MoPNDV2030, 2007. ***Kenya's Vision 2030 – Towards a Prosperous Nation***.

MoPNDV2030, 2009. ***2009 Housing and Population Census***.

Mulwa, J., Gaciri, S., Barongo, J., Opiyo N. and Kianji, G., 2005. ***Geological And Structural Influence On Groundwater Distribution And Flow In Ngong Area, Kenya***. African Journal of Science and Technology (AJST). Science and Engineering Series Vol. 6, No. 1, pp. 105 – 115.

Muthoni N., 2009. ***Challenges of Groundwater Management in the City of Nairobi***. Master's Thesis. School of the Built Environment, University of Nairobi.

Olima, 2001. ***Dynamics and implications of sustaining urban spatial segregation in Kenya – Experiences from Nairobi Metropolis***. A Paper Presented at the International Seminar on Segregation in the City held at Lincoln Institute of Land Policy in Cambridge, MA, USA, July 25-28, 2001. World Health Organisation (WHO).

Onyancha C. and Getenga Z., 2013. ***Geochemistry of Groundwater in the Volcanic Rocks of Nairobi City***. Global Journal of Science Frontier Research. Environment & Earth Science. Volume 13 Issue 3 Version 1.0 Year 2013.

Paly. Melissa and Lee Steppacher, n.d. ***The Power to Protect: Three Stories about Ground Water***. U.S.E.P.A. Massachusetts Audubon Society and NEIWPCC.

Paul A., Michael F., David J., and David W. 2005. ***Geographic Information Systems and Science***. 2nd Edition. John Wiley & Sons, Ltd.

Purjenaie A., Moradi M., Noruzi A. and Majidi A., 2012. ***Prediction of Aquifer Drawdown Using MODFLOW Mathematical Model (Case Study: Sarze Rezvan Plain, Iran)***. Geosciences 2012, 2(5): 112-116. DOI: 10.5923/j.geo.20120205.02.

Ralph C., 1983. ***Basic Ground-Water Hydrology***. United States Geological Survey. US Geological Survey Water-Supply 2220.

Republic of Kenya, 1999. ***The Environmental Management and Coordination Act of 1999***. No 8 of 1999.

Republic of Kenya, 20072006. ***The Water Resource Management Rules of 2006***.

Republic of Kenya, 2010. ***Constitution of Kenya 2010***.

Republic of Kenya, 2012(a). ***National Water Policy.***

Republic of Kenya, 2012(b). ***National Water Master Plan.***

Republic of Kenya, 2012(c). ***Draft Water Bill 2012.***

Richard B., 2000. ***Graphical User Interface for MODFLOW, Version 4***. U.S. Geological Survey. Open-File Report 00-315

Stephen F. and Albert T., 2005. ***The Role of Groundwater in the Water-Supply of Greater Nairobi, Kenya***. Sustainable Groundwater Management. Lessons from Practice. The World Bank.

Stewart F. and Peter R., 2005. ***Spatial analysis and GIS***. Taylor & Francis Ltd, 4 John St, London WC1N 2ET.

Transworld Publishers, 2013. ***Africa Water, Sanitation and Hygiene***. November - December 2013 Vol 8 No. 5.

UN HABITAT, 2006. ***Nairobi Urban Sector Profile***. United Nations Human Settlements Programme. Regional Office for Africa and the Arab States.

UNEP, 2009. ***"Kenya: Atlas of Our Changing Environment"***. Division of Early Warning and Assessment (DEWA). United Nations Environment Programme (UNEP). P.O. Box 30552 Nairobi 00100, Kenya.

USGS, 2007. ***Geographic Information Systems Poster, What is GIS***. Retrieved 16 February 2013 from http://egsc.usgs.gov/isb/pubs/gis_poster/#what

Wamwangi E., 2013. ***Geospatial Analysis Of Groundwater Fluoride Contamination In Embakasi Area, Nairobi***. Department of Geomatic Engineering and Geospatial Information Systems, Jomo Kenyatta University of Agriculture and Technology, Juja, KENYA. 1st ESRI Eastern Africa Education User Conference, Paper Session 17 September 2013.

World Bank, 2011. ***Kenya Groundwater Governance Case Study***. Water Papers. Water Unit, Transport, Water and ICT Department, Sustainable Development Vice Presidency.

WRI, 2010. ***Kenya Atlas of Our Changing Environment***. ESRI Shapefile. Geomorphology of Kenya.

WRMA, 2010. ***Water Allocation Plan***. Preliminary Water Allocation Plan, Nairobi Aquifer Suite. P. O. Box 45250 - 00100 Nairobi, Kenya

WRMA, 2011. (b). ***Nairobi Metropolitan Borehole Inventory Study***. P. O. Box 45250 - 00100 Nairobi, Kenya

WRMA, n.d (a). ***Aquifer Maps Summary***. Retrieved 12 August 2013 from http://wrma.or.ke/images/pdf/AQUIFER%20MAPS-summary.pdf.

Zeiler M., 1999. ***Modelling Our World***. Environmental Systems Research Institute Inc. 380 New York Street. Redlands, California 92373-8100.

APPENDICES

APPENDIX A: DATA COLLECTION TOOLS

A1: Interview Guide

General Details

Date & Time	
Location	
Name of Interviewer	
Name of Respondent	
Organization	
Role of Respondent	
Years of Experience in the Department	
Phone	
Email	
Postal Address	

Organization Details

Role of the department as pertains to Nairobi County	
Number of employees	

Key Discussions Points

What are some of the recent or emergent trends in groundwater practice in Nairobi County?
What data does WRMA collect on groundwater and how is it managed?
What are some of the main challenges WRMA faces in executing its mandate on groundwater?
How would you rate the level of compliance with regulations?
What are the key challenges/issues faced in groundwater management in Nairobi?

Which factors cause and drive these challenges/issues?	
Are these challenges/issues particular to certain locations in Nairobi? If so which areas can be considered of most concern?	
Target Datasets for the Study	
Borehole Water Quality Borehole Location (Map) Borehole Type Pumping Depth Borehole Depth Drilling Method Borehole Structure	Pumping Regime Pump Type NAS Map Aquifer Details (Type, Porosity, Transmissivity, Storativity, Conductivity, Yield) Maps of Catchment Areas

APPENDIX B: MAPS

B1: Decadal Spatial Temporal Maps 1900-2013

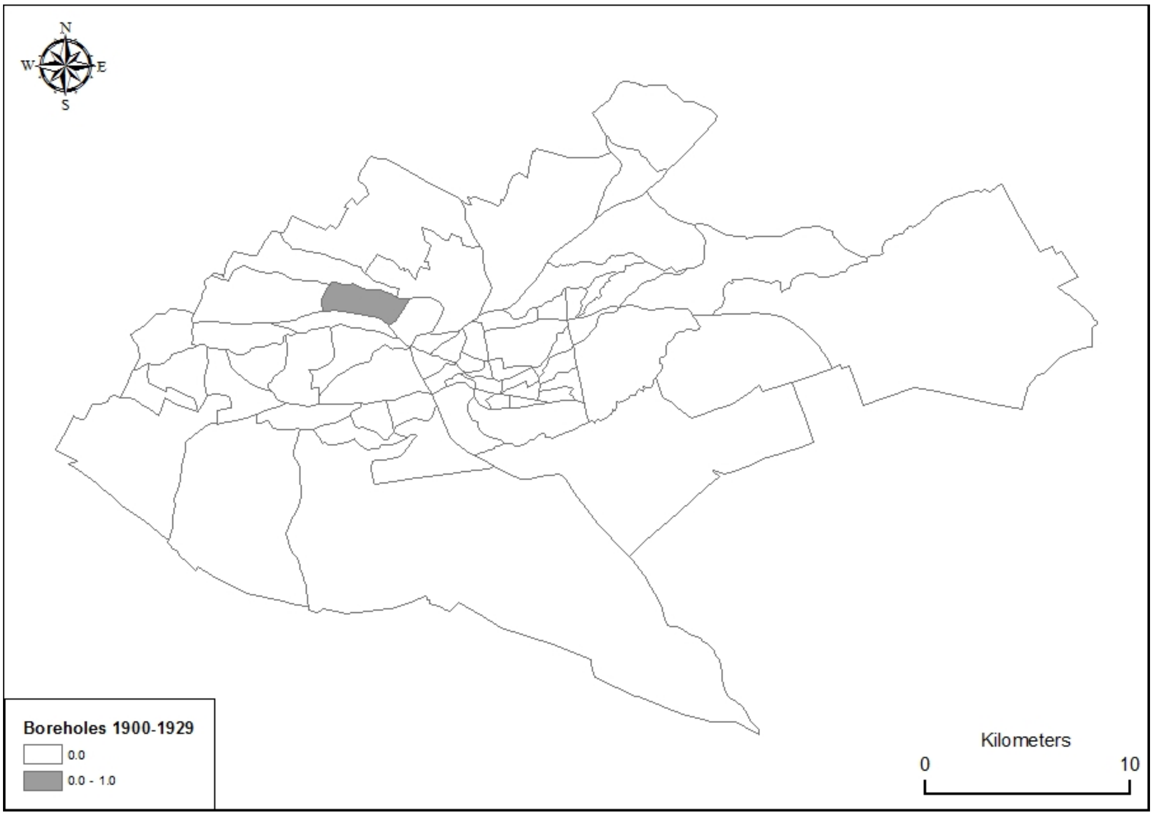


Figure B1-1: Decadal Spatial Temporal Map 1900-1929

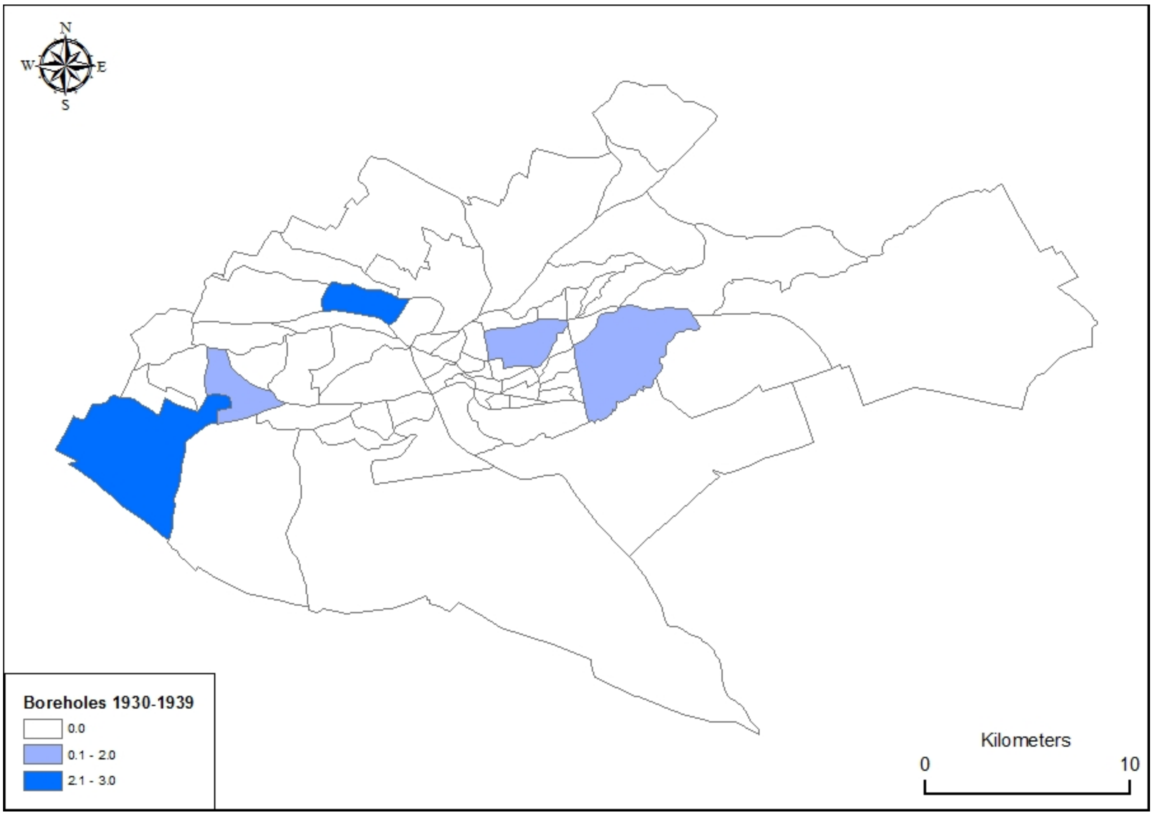


Figure B1-2: Decadal Spatial Temporal Map 1930-1939

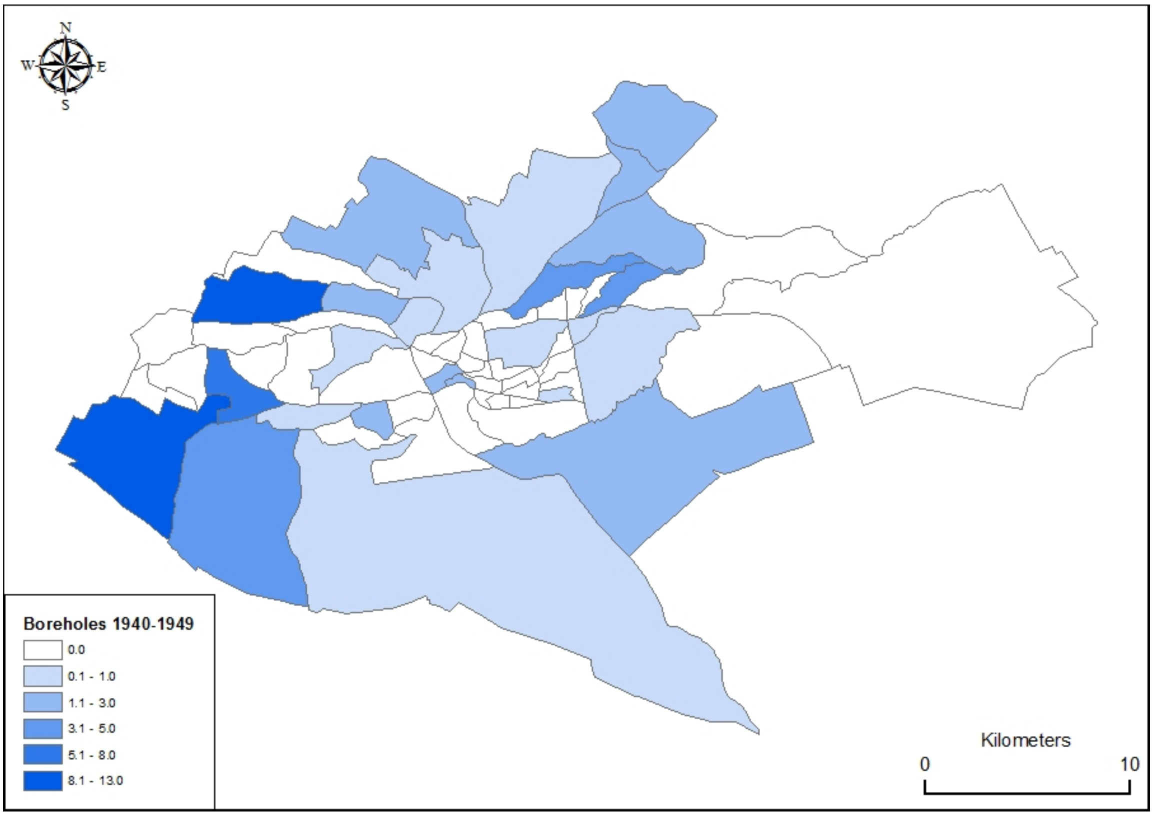


Figure B1-3: Decadal Spatial Temporal Map 1940-1949

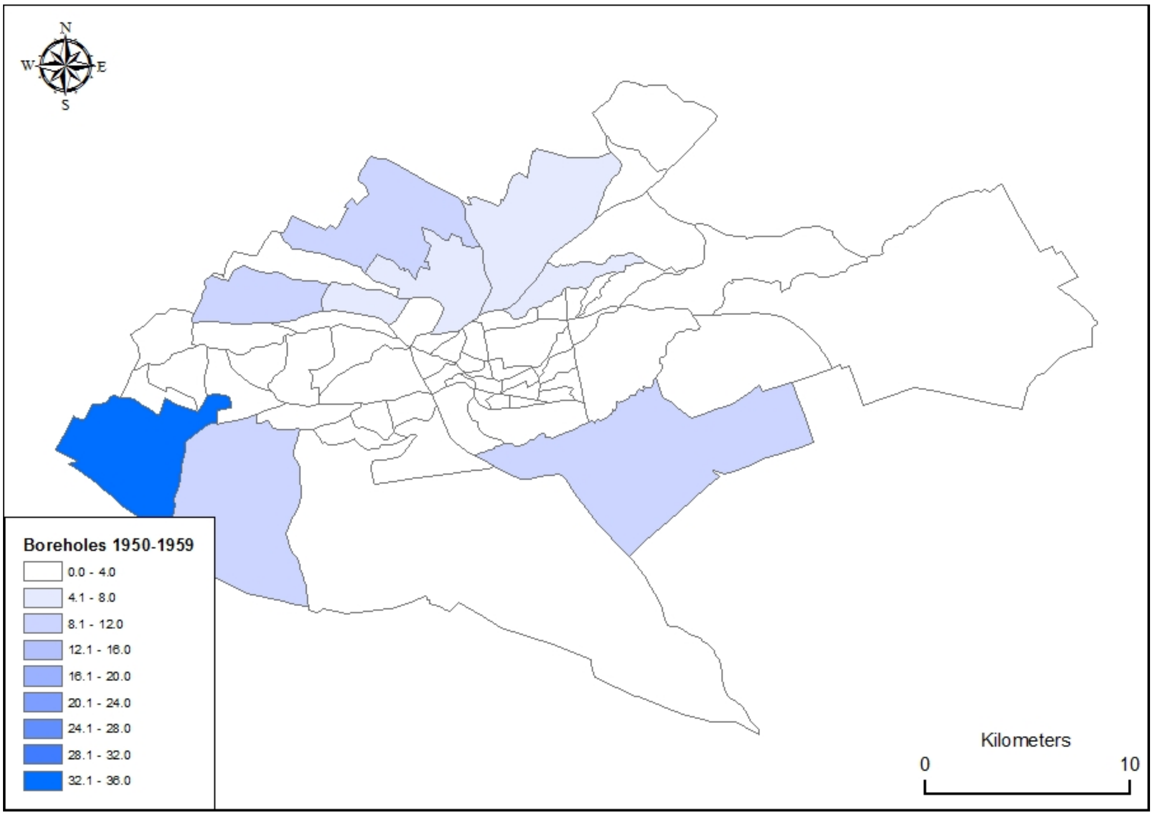


Figure B1-4: Decadal Spatial Temporal Map 1950-1959

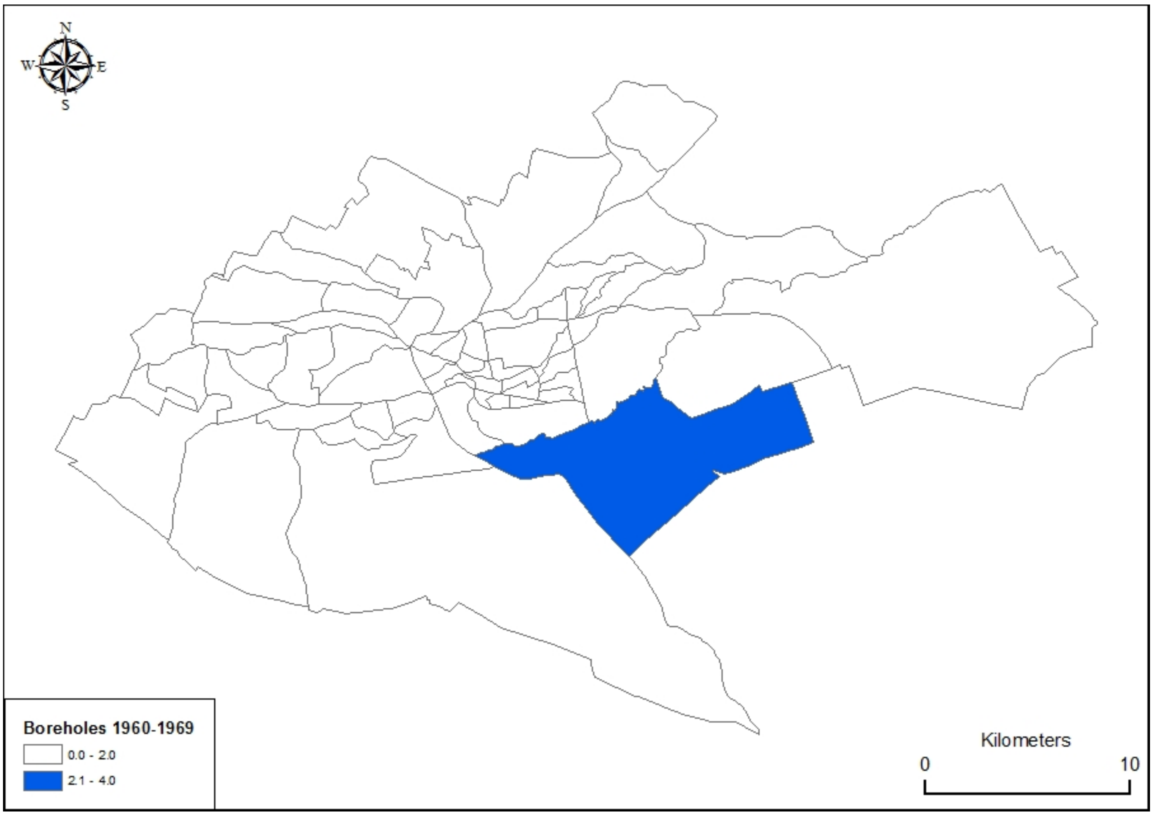


Figure B1-5: Decadal Spatial Temporal Map 1960-1969

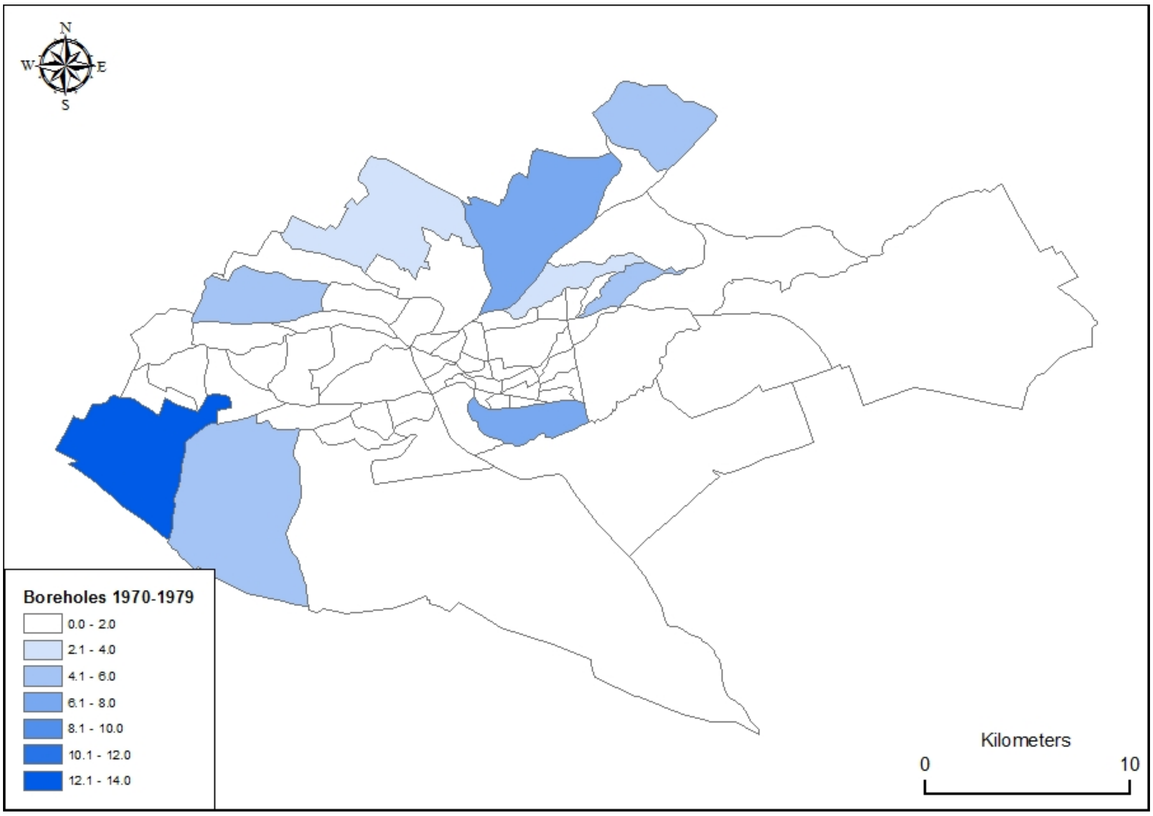


Figure B1-6: Decadal Spatial Temporal Map 1970-1979

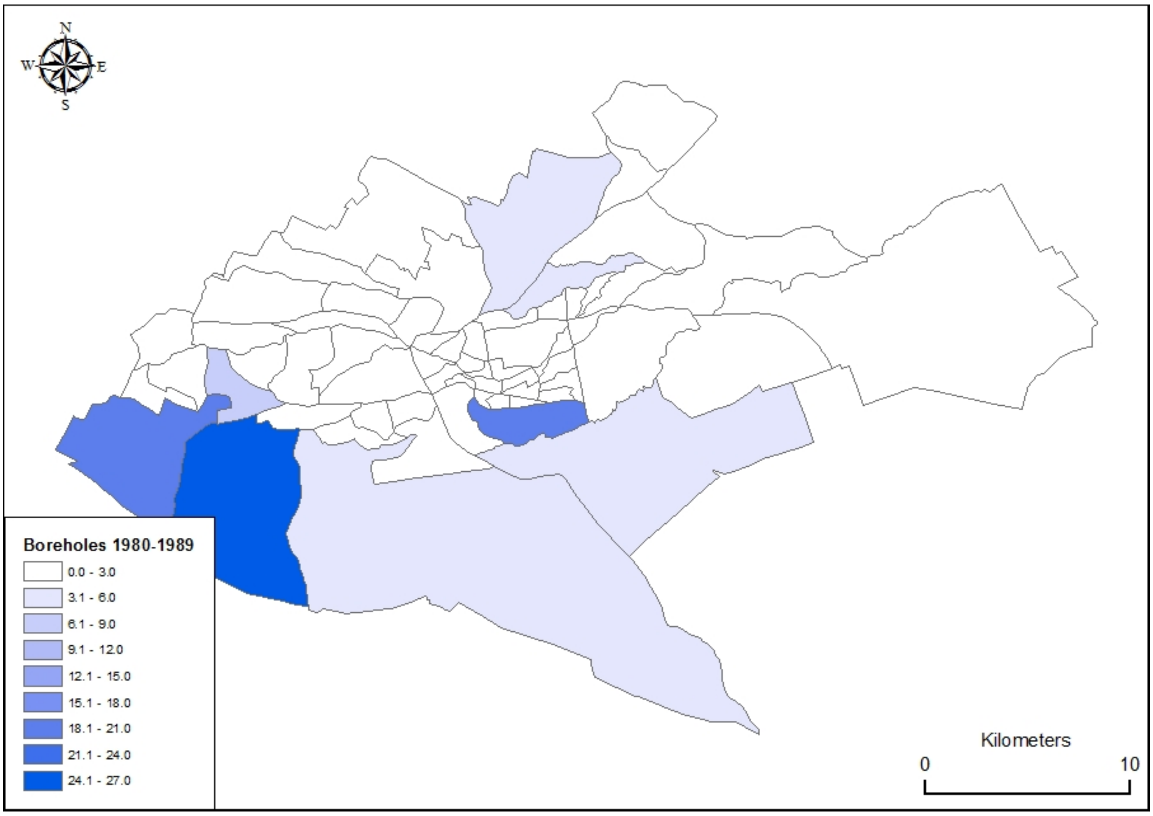


Figure B1-7: Decadal Spatial Temporal Map 1980-1989

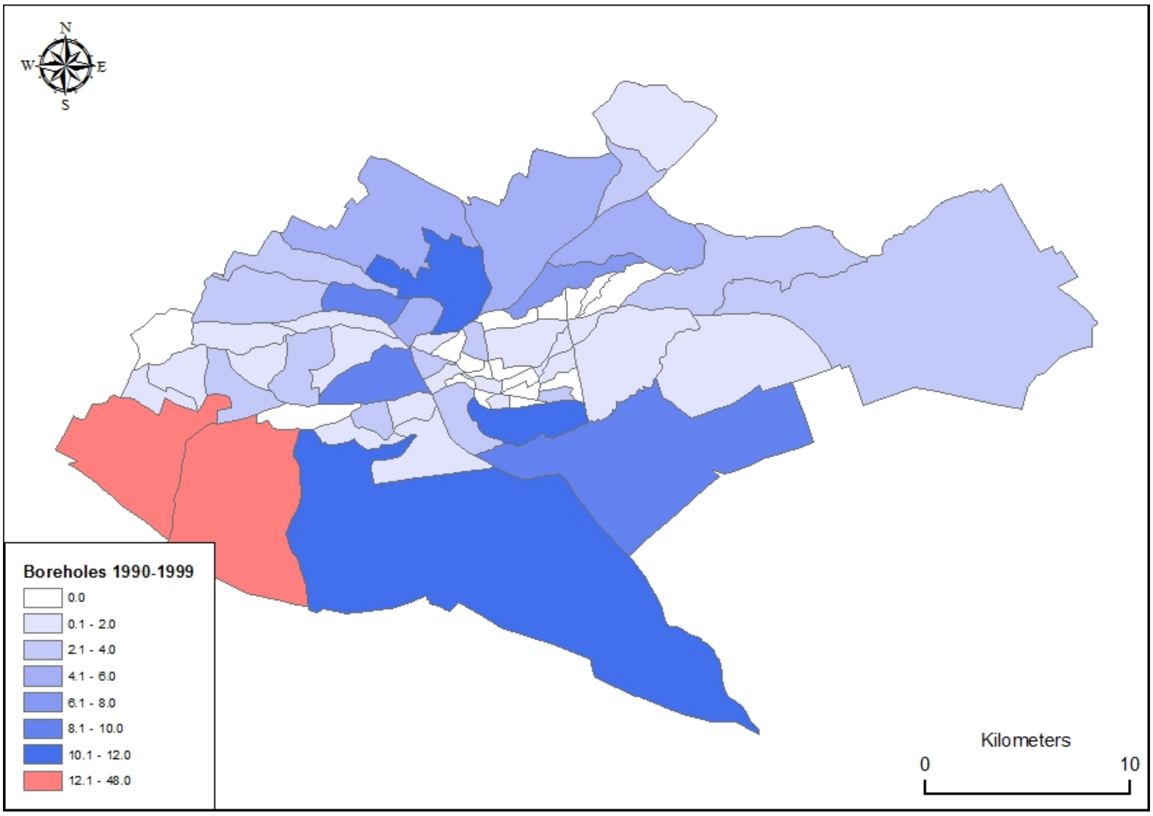


Figure B1-8: Decadal Spatial Temporal Map 1990-1999

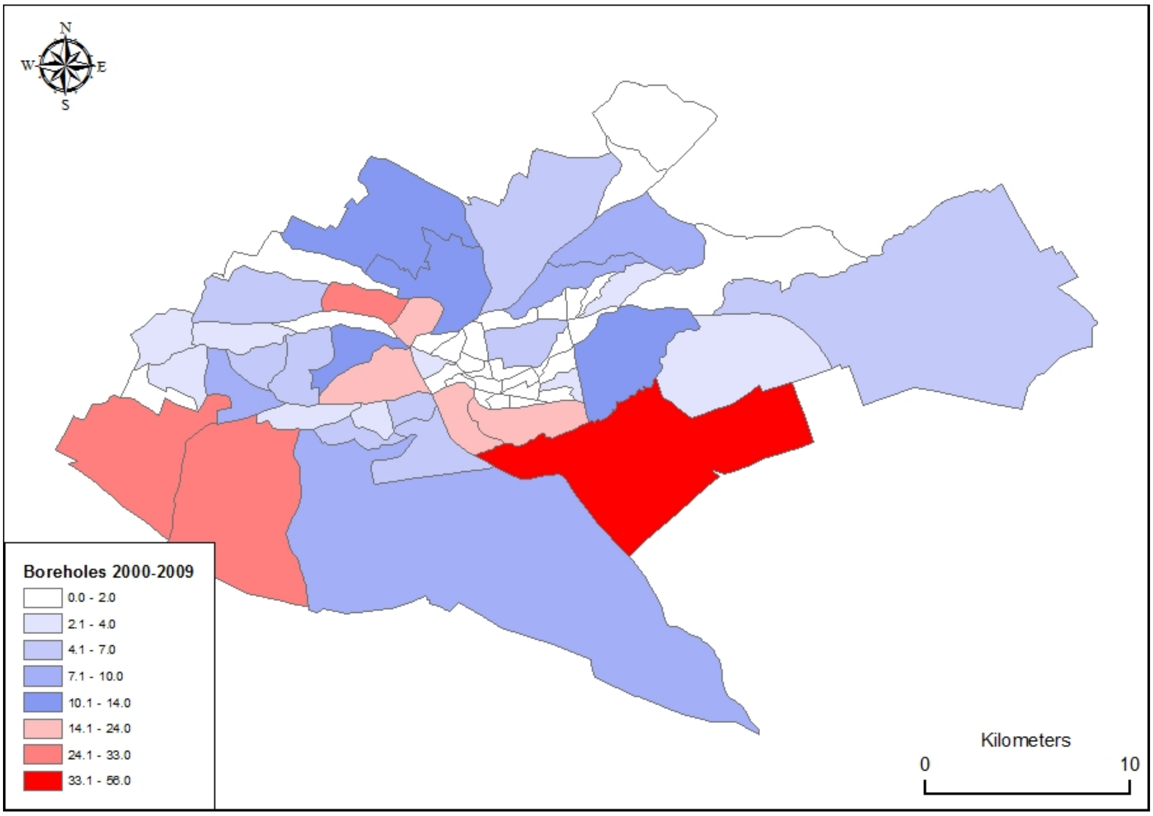


Figure B1-9: Decadal Spatial Temporal Map 2000-2009

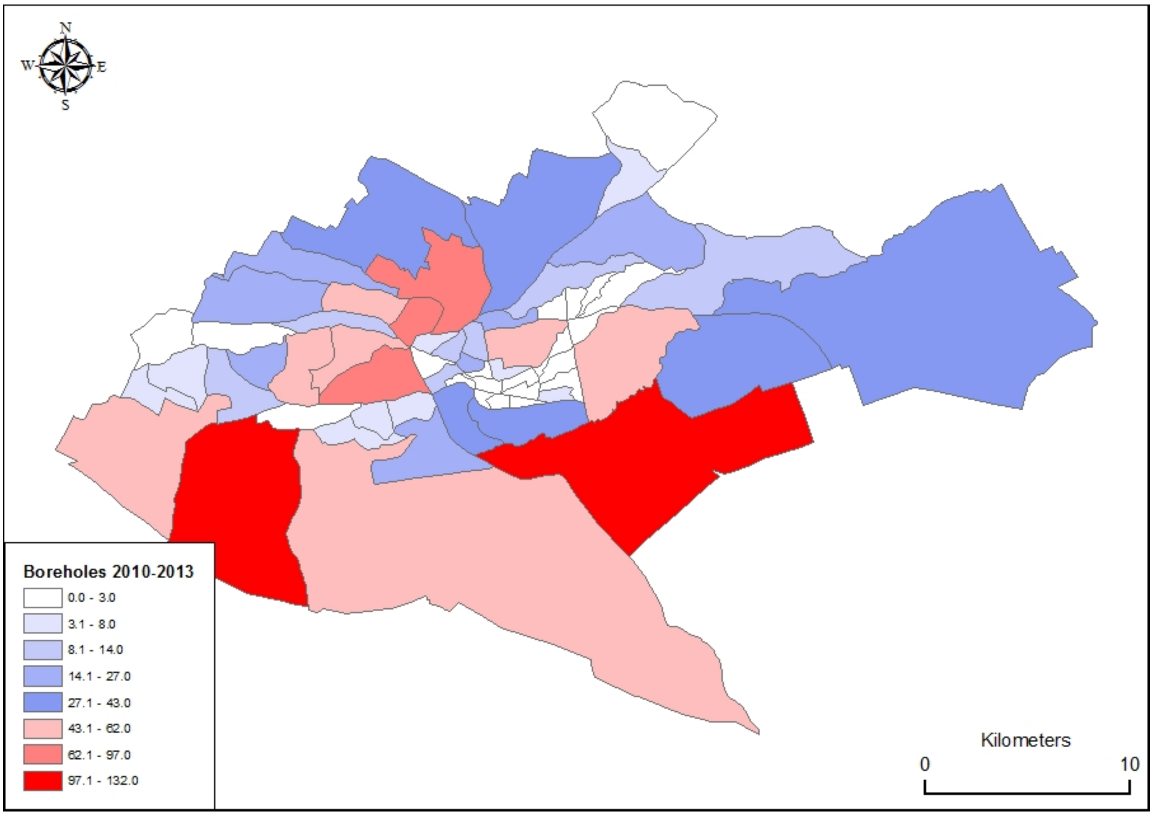


Figure B1-10: Decadal Spatial Temporal Map 2010-2013