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A SIMPLIFIED APPROACH TO MAPPING VULNERABILITY OF GROUNDWATER TO POLLUTION IN THE LAKE NAKURU BASIN, KENYA RIFT VALLEY: APPLICATION OF THE PROTECTIVE COVER AND INFILTRATION CONDITION (PI) METHOD

By:

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DECLARATION

I hereby declare that this dissertation is my original work and has not been presented for a degree in any other university and for any other award.

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ABSTRACT

Lake Nakuru Basin is situated along the Kenyan Rift valley, bounded by latitudes 0^0 10′ N to 0^0 45′ S and Longitudes 35^0 90′ E to 36^0 20′E and lies at the central part of the rift zone. Water supply in the study area is mainly from groundwater sources, whose quality is influenced by human activities which cause pollution at the land surface since most groundwater originates by recharge of rainwater. The unsaturated zone can help reduce the concentrations of some pollutants entering groundwater (especially micro-organisms), but it can also act as a store for significant quantities of pollutants such as nitrates, which may be released eventually to groundwater. Some contaminants enter groundwater directly from abandoned wells, and faults which may by-pass the unsaturated zone (overlying layers). Agricultural land use without environmental safeguards to prevent over application of agrochemicals is causing widespread deterioration of the soil/water ecosystem as well as underlying aquifers. Rapid population growth, urbanization and agricultural activities in the basin areas have also put enormous pressure on groundwater resources and catchment areas.

This study aimed at determining the spatial intrinsic variability of groundwater vulnerability to pollution in Lake Nakuru basin applying Protective cover and Infiltration condition (PI) method which is a GIS-based approach. Vulnerability was assessed firstly on the basis of the effectiveness of the protective cover which is a function of soil and lithological properties between the ground surface and the groundwater table, and secondly on infiltration conditions which indicates the degree to which the protective cover is bypassed by surface flow. This assessment took into account core properties such as land cover, slope and locations of fractures that allow surface water to rapidly enter the groundwater aquifer.

Though groundwater table in the study area occurs generally at depths of above 50 m, areas such as Bahati and Dundori are exceptionally characterized by shallow water table occurring at depths less than 2 m to4 m. The resulting vulnerability map indicates low vulnerability of groundwater to pollution in most parts of the study area due to high protection offered by the overlying layers and the depth of most of the groundwater aquifer. This is an exception in areas exhibiting faults where surface water can easily access groundwater if it channels itself through those open faults. In Dundori area, the accessibility of groundwater from shallow wells makes it more vulnerable to pollution due to low protection offered by the thin overlying layers.

From this study, the use of the PI method is demonstrated to be a more successful tool for vulnerability study than other existing techniques applied in the area. Decision makers can use this method as a tool to identify areas contributing to pollution risk in the area. The identified areas can then be prioritized for protection, rather than protecting larger areas which in most cases seem unrealistic due to the ever increasing growth in population.

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1 INTRODUCTION

1.1 Background Information

The Lake Nakuru Watershed is located in the East African Rift and is bounded by latitudes 0^0 10′ N to 0^0 45′ S and Longitudes 35^0 90′ E to 36^0 20′E (Figure 1.1). The watershed itself lies at the central part of the Rift zone which is occupied by the Kenya Dome (McCall, 1967) and within the Aberdare attachment. The East African rift basin is known to be generally asymmetric and is bounded by step border faults on either side.

Water has been the most exploited resource since man strode on earth. Rapid population growth, increasing living standards, human activities and industrialization have resulted in greater demand for good quality water.

The Rift Valley is a fractured system which is often characterized by thin soils, weathered and fractured lithology. Aquifers underlying such terrains coupled with flow concentrating in the intensively fractured layer and by point recharge via open faults are particularly vulnerable to contamination (Goldscheider, 2005). Contaminants can easily reach groundwater, where they may be transported rapidly in conduits over large distances. The residence time of contaminants are often short, and therefore its attenuation is normally not effective in such an environment. Aquifers in a fractured terrain need special protection mainly due to their heterogeneity and anisotropic nature as compared to homogenous aquifer systems.

Land-use plays an important role in groundwater quality protection. A major problem arises where catchment areas are usually in viable agricultural land and thus may be under intense settlement and farming. If good quality water were to be protected, then these catchments would be strongly protected against destruction by settlements and farming. However, such restrictions would mean protecting zones covering very large areas, which in some cases would be the entire catchment. Such measures might be unacceptable simply due to the ever increasing growth in population compared to the shrinking land resource. As a consequence, it is essential to protect at least those areas within the fractured system where contaminants can most easily reach the groundwater. This leads to the concept of groundwater vulnerability that is geared to identifying the most vulnerable areas and prioritizing to safeguard against contamination. A vulnerability map may thus help the decision makers to find a balance between groundwater protection and socio-economic aspects.

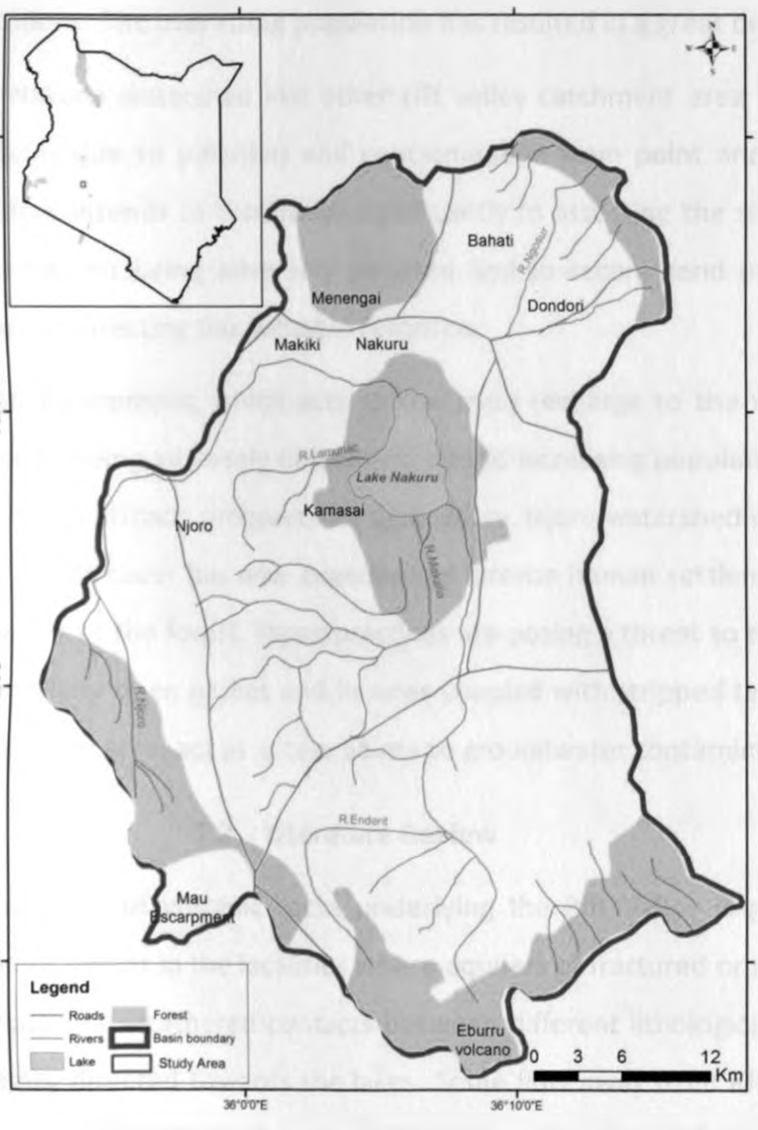


Figure 1.1 Location of Lake Nakuru Watershed

1.2 Scope

Lake Nakuru basin hosts Nakuru town which is the fourth largest in Kenya after Nairobi, Mombasa and Kisumu cities. The town is a vibrant commercial hub in the Great Rift Valley. Major economic activities in the study area include agriculture, tourism, commerce and industry. The town also has a military facility and several middle and higher learning institutions. The ever rising population has resulted in a great demand for good quality water.

Lake Nakuru watershed like other rift valley catchment area is facing growing water quality problems due to pollution and contamination from point and non-point sources. This study therefore intends to contribute significantly to assessing the sensitivity of ground water in the watershed to being adversely polluted and to recommend possible policies to put in place towards protecting this valuable resource.

Bahati Escarpment, which acts as the main recharge to the well fields in the study area, is currently being adversely deforested due to increasing population and the fertile nature of the land which attracts prospects for agriculture. Njoro watershed which until recently was under a large forest cover has now experienced intense human settlement and cultivation resulting to depletion of the forest. These practices are posing a threat to the groundwater resource in the basin. Many open gashes and fissures coupled with stripped terrain, which is actually the case in the study area, act as access points to groundwater contamination.

1.2 Literature Review

Permeability of volcanic rocks underlying the Rift Valley is generally low, but permeability becomes higher in the localities where aquifers of fractured or reworked volcanics exist, as well as along the weathered contacts between different lithological units. Groundwater flows are generally directed towards the lakes. Some flow away from Menengai and Bahati Escarpment area to the North-West towards the lower lying Lake Baringo, North East from the Mau Escarpment towards Lake Nakuru, South West from the Bahati escarpment and Northward from Eburru towards Lake Elementaita (Clarke et al., 1990). It is also probable that there is some southerly flow from Menengai towards Lake Nakuru. However at depth it is likely that flow occurs to the North East away from the Nakuru- Elementaita catchment towards the lower lying catchment around Lake Bogoria (Clarke, Op. Cit.).

The Lake Nakuru catchment is industrialized and therefore more likely to be impacted by human activity. This implies that groundwater aquifer in the area is also at risk. The death and migration of flamingoes from Lake Nakuru to other saline rift valley lakes has been attributed to pollution of the lake. According to Barua (1995) the increased quantities of heavy metals in the lakes Nakuru and Elementaita has greatly changed the limnological parameters of their waters due to increased disposal of waste into the lakes. These heavy metals are likely to find their way into the groundwater aquifers owing to the fractured nature of the terrain.

The concentrations of nitrate are generally higher in Nakuru which suggests effects of human activities. Dissolved organic carbon (DOC) is reported to have been detected at all wells in Nakuru. Its presence in water can affect the dissolved oxygen concentration, which in turn can affect the nutrients and trace elements present in the ground water. The source of the DOC may be organic matter in the aquifer or may be related to human activities such as the use of fertilizers.

Spatial variability of soil properties is naturally inherent due to geological and soil forming factors. Many studies on spatial variability of soil properties in the area have concentrated on the properties of agriculturally managed soils. However, soil properties in such soils may be greatly influenced by management practices like fertilizer applications (Mainuri, 2006; Iqbal et al., 2005). Variability of soil properties in the lake basin with the purpose of evaluating its potential to attenuate pollutants is still not addressed.

Degradation of watersheds generally diminishes soil capacity to provide critical ecosystem functions like recharging of groundwater. River Njoro watershed was once a forested area but has now been replaced by a fragmented landscape composed of remnant forest patches, advanced and emerging secondary vegetation (Odero and Peloso, 2000). The fragmentation resulted from decades of forest clearing for firewood and timber for construction, increased agricultural activities and overgrazing. Such practices may lead to hydrological modifications resulting in increased runoff and soil erosion in the watershed.

Contamination of freshwater supplies is a major problem in agricultural zones due to the increased dependence on agrichemicals. Fertilizers enriched in nitrates, phosphorus and potassium and non-fertilizers in form of pesticides, fungicides and herbicides are used to increase agricultural productivity to meet rising population demand at both domestic and industrial level. In addition, falling productivity in irrigated areas has led to increased use of agrichemicals with little attention given to aquifer contamination. In the study area, rivers draining the agricultural areas are found to be the highest nutrient transporters (Kulecho and Muhandiki, 2005). There is prevalent use of nitrogen and phosphate based fertilizers in the drainage area. The fertilizers can easily pollute groundwater if nutrient laden water gets its way to the aquifer through the numerous open faults in the area.

Kenyans depend on groundwater supply in their everyday lives, for applications ranging from drinking to irrigation purposes. These facts highlight the importance of protecting groundwater resources, a need which is compounded when the supply is used largely for drinking, as is the case in the Nakuru Municipality of Kenya Rift. In locations where land is being used intensely or is undergoing change, there exists an increased risk for groundwater contamination to occur. Hence there exists an absolute necessity for policy makers to have as many accurate and comprehensive resources at their disposal to enable them make informed decisions towards protecting this valuable resource. Vulnerability study of groundwater to pollution using PI method and Geographic Information System (GIS) are some of the important tools proposed by this study that can be used to gain such insights.

The PI Method which was first proposed in Europe was designed to be more physically based unlike other existing vulnerability mapping techniques. Although this method takes the specificity of the karstic environments into account it does not exclude its application to other geological conditions (Daly et al., 2002, Goldscheider et al., 2000). This approach is proposed for groundwater vulnerability mapping in the Lake Nakuru basin, Kenyan Rift valley whose terrain is heterogeneous and similar to the karst environments. Although the lithology for the two environments differs, the physical characteristics are comparable. The highly jointed lithology in the karst terrain and presence of swallow holes compares with the highly faulted lithology in the Kenyan rift floor with occasional open faults.

The DRASTIC method has been applied previously in mapping vulnerability of groundwater to pollution in the study area. This method is able to distinguish the degree of vulnerability at regional scales where lithology differs to a lesser extent (Vias et al., 2006). However, this method is less effective at assessing vulnerability in highly heterogeneous terrain at a local scale as they do not take into account its erratic settings. The large number of parameters included in DRASTIC method implies that data requirements are invariably difficult to meet. It can further be argued that the large number of variables factored into the final index number may mean that critical parameters may be subdued by other parameters having little or no bearing on vulnerability in that particular setting. Some DRASTIC parameters, such as aquifer and soil media and hydraulic conductivity, are not fully independent but correlated with each other.

The DRASTIC method was applied in the study area and indicated high vulnerability in most areas. Kemboi (2008) pointed out the shortcomings of the method being that it was developed in regions with compact geology unlike the rift that has experienced several episodes of faulting. This research therefore aims at mapping the vulnerability of groundwater using a more physically based approach where each parameter is rated on a vulnerability scale of lowest to highest and overlain using GIS to give an overall scenario of pollution vulnerability. In order to quantify the intrinsic vulnerability, two basic aspects will be considered, namely; the protective cover, which is the layers overlying the groundwater surface and the infiltration condition factor, which can occur in a diffuse way through the overlying layers.

1.3 Problem Statement

Nakuru town is Kenya's fourth largest town, a major industrial and agricultural center with significant tourism potential. Water supply source to the town is mainly from groundwater, which is now under great risk of pollution. Most aquifers in the rift valley floor are often in a fractured terrain. In this scenario, groundwater is extremely vulnerable to contamination because polluted water can flow rapidly through fissures and open gashes. The fractures provide direct entry points to groundwater, with little or no attenuation of contaminants. In certain areas, the covering layers are often thin or absent. Lake Nakuru basin aquifers, being in the Rift valley floor, face growing vulnerability due to pollution from point and non-point sources.

Rapid population growth, urbanization and agricultural activities in the basin areas have put enormous pressure on its water resources and catchment areas. Agricultural land use without environmental safeguards to prevent over application of agrochemicals is causing widespread deterioration of the soil/water ecosystem as well as underlying aquifers. This and the fractured nature of the rift terrain pose a risk to the quality of groundwater, which is the main source of water supply to the town. Therefore, there is need to protect this resource to ensure continuous supply of potable water to the town. Mapping groundwater vulnerability in the Lake Nakuru basin to zone those areas where groundwater is considered to be facing a threat from contamination will safeguard this valuable resource from deteriorating. The research therefore aims to identify those zones where groundwater is considered to be at a high risk of being polluted. This will enable decision makers to put up measures which will restrict any practices which negate protection of this valuable resource.

1.4 Aim and Objectives

This study aims at determining the spatial intrinsic variability of groundwater vulnerability to pollution based on the thickness and properties of the unsaturated zone, through application of the PI (Protective Cover and Infiltration Condition) method.

1.4.1 Objectives

1. To determine the basin specific protective function of the layers overlying groundwater (soil and lithology thickness and properties) and infiltration condition which is dependent on slope, land cover and presence of open faults.

2. To generate an intrinsic vulnerability to pollution map for the study area.

1.4.2 Significance

The natural attenuation capacity of contaminants varies widely according to geological and soil conditions. As earlier mentioned in sections 1.1 and 1.3, the study area lies in a highly fractured terrain, posing a great risk to the groundwater. In view of the importance of groundwater for potable supplies, it is expected that adequate protection to prevent groundwater quality deterioration should receive due attention. Assessing the spatial intrinsic vulnerability of groundwater to pollution based on the thickness and properties of the unsaturated zone will enable delineation of areas considered to be facing a high risk of being contaminated, instead of applying controls over extensive areas. This eventually will be more cost-effective and will provide less severe constraint to economic development if the degree of control is varied according to attenuation capacity. The protection of groundwater to pollution will be easily achieved because focused attention will be on those areas considered highly vulnerable.

2 DESCRIPTION OF THE STUDY AREA

2.1 Introduction

The study area is part of the classic East African Rift System which traverses through Kenya in a north-south direction. It forms a highly fractured volcanic zone where volcanism preceded or, in some cases, has been contemporary with major faulting (McCall, 1967).The East African Rift System in Kenya is divided into three tectonic terrains of contrasting age, size and type: the splay-faulted northern depression of Bogoria-Baringo-Turkana basin; the southern depression of Magadi-Natron basin; and the step faulted central basin of Nakuru-Elementaita-Naivasha basin, where this study is based. The three basins are separated by zones of cross-structures, multi-fractures and displacements; representing accommodation zones of complex wrench and oblique slip faults (Morley et al., 1990).

2.2 Location

Lake Nakuru basin is located in the central Rift Valley zone occupied by the Kenya dome and lies within the Aberdare Detachment. It is a closed drainage system of approximately 1800km^2.Menengai Crater (2272m a.s.l.) lies to the north, Bahati Highlands to the northeast, Mau Escarpment (3,000m a.s.l.) to the west, Eburru crater to the south, and gentle grasslands between the Lake Nakuru and Lake Elementaita basins lie to the east. The catchment basin drains to Lake Nakuru, which is one of the several shallow, alkaline-saline lakes lying in a closed hydrologic basin in the eastern African Rift Valley that stretches from northern Tanzania through Kenya to Ethiopia.

The basin is home to Nakuru Town, comprising a number of agro-based industries (horticulture, fertilizers, and dairy, among others), market towns and several institutions all of which depend heavily on groundwater. Nakuru Municipality, which forms the major part of the basin, comprises a dense population which swells annually. With the increasing population growth there is an increasing need for more water supplies in the town.

According to the 2009 population and housing census the population of Nakuru District stood at over 1.6 million persons, approximately 70% of whom are found within the Lake Nakuru Basin.

Nakuru District experienced a very high increase in population between 2002 and 2009. This increase is owed to both natural growth and immigration. The increasing human population in the catchment areas implies that more intensive agricultural activities have to be adopted to satisfy food requirements. The Bahati catchment area, which was earlier under forest cover, is now undergoing intense deforestation for agriculture and settlement.

2.3 Climate

There is considerable variation in climate within the lake Nakuru basin depending on altitude and topography. The climate ranges from cold and humid in areas around Bahati escarpment to arid and semi-arid in areas to the southern and southeastern part of the lake (Ronda area), typical characteristics of the Rift Valley floor. Mean annual rainfall varies from more than 500mm/year to under 200mm/year. The wet seasons occur in the months of November to December and April to May with the dry seasons falling in between (Nicholson, 2000). The rainfall is mainly convective and occurs in the afternoons as heavy storms that are quite erosive. Gully erosion is rampant in the northwestern part of the catchment. Areas undergoing serious erosion include newly opened forest zones (Odada et al., 2005).

2.4 Land Cover

The study area consists of both indigenous and man-made forests, as well as extensive tracks of crop plantations (both large and kitchen farms). The forested areas of the catchment basin consist of the Eastern Mau, Eburru and Bahati forests (Figure 2.1). The Eburru, composed of indigenous tree species, covers an area of 8,736 ha, while the Bahati forest covers an area of 6,956 ha (Odada et al., 2006). The Eastern Mau forest forms part of a national watershed (the Mau Complex), being the largest of these forest blocks and covering an area of 65,000ha. It is mainly composed of plantation and indigenous forests that have been progressively excised over the last decade to make way for human settlement (Odada et al., 2006). What forest remains now is restricted to the crest of the escarpment, and human settlements and plantations now occupy areas once covered by thick forest covers.

2.5 Land Use and Land Resources

The principal land-use is agricultural and dairy farming mainly in the region surrounding Nakuru Town. Both large and small-scale agricultural activities involving cultivation of such food crops as wheat, maize, potatoes and beans is practiced. Dairy farming involving rearing of grade cattle is practiced as well. The area around Lake Nakuru is utilized as a National Park, which offers one of the most diverse concentrations of wildlife in Kenya. Trade in both commercial and industrial merchandise is practiced in Nakuru Town and other adjacent smaller towns. In recent years, Nakuru Town has continued to grow as a major commercial and industrial centre in the area. Land-resources in the area include the valued groundwater, sand and blocks for construction.

2.6 Physiography and Drainage

Lake Nakuru is separated from Lake Elementaita by a low topographic divide and lies at the northern boundary of the study area (Figure 2.1). Menengai rises to the north of the lake and the high ground of the Mau and Eburru Forests lies to the south. The Naivasha catchment is separated from the Nakuru-Elementaita catchment mainly by the Eburru volcanic pile which is linked to the Mau Escarpment by a ridge at an altitude of around 2600m (McCall, 1967). Between Eburru and the Bahati Escarpment the surface drainage divide runs via Gilgil along a culmination of the Rift floor at an altitude of approximately 2000m. Lake Nakuru basin lies at 1756m a.s.l, is a shallow alkaline lake that supports variety of bird species.

The plains around Lake Nakuru show very low drainage density. The porous and permeable surface of volcanic ashes, pumiceous pyroclastic and faulted lava and tuff provides for percolation of runoff, leading to potentially high groundwater storage. Most of the drainage from the escarpments tapers off and disappears into pyroclastics and ashes covering the plains. The lake is alkaline and saline (sodium-bicarbonate) as a result of evaporation and is recharged by rainfall, surface runoff and groundwater (Clarke et al., 1990).The rivers in the area are structurally controlled evident particularly with Rivers Ngosur, Makalia and Nderit, which follow straight courses, though tributaries exhibit dendritic drainage pattern upstream.

2.7 Geology and Structures

The East African Rift System (EARS) is one the geologic processes where the earth's tectonic forces are presently trying to create new plates by splitting apart old ones (Wood and Guth, 2012). The rift is a fracture in the earth's surface that widens over time, more technically, it is an elongate basin bounded by opposed steeply dipping normal faults. The Rifting process (Figure 2.1) is well displayed in East Africa (Ethiopia-Kenya-Uganda-Tanzania) and the new Nubian Plate, which makes up most of Africa, and the smaller plate that is pulling away named the Somalian Plate (Wood and Guth, Op.Cit., p 21). These two plates are moving away from each other and also away from the Arabian plate to the north. The point where these three plates meet is the Afar region of Ethiopia forming a triple-junction. However, all the rifting in East Africa is not confined to the Horn of Africa, but there is also rifting activity further south as well, extending Tanzania and Great Lakes region of Africa.

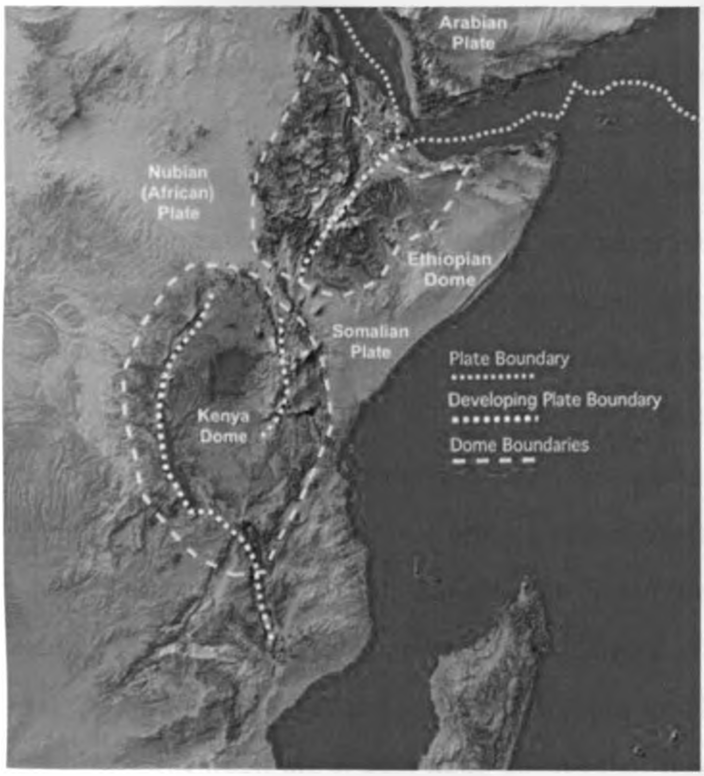


Figure 2.1 Digital Elevation Model showing tectonic plate boundaries of the East African Rift System outlining the elevation highs and lakes of East Africa (adapted from Wood and Guth, 2012)

The area under study lies within the Kenyan Dome, which is part of the greater Eastern Africa Rift System (Figure 2.2). This is a complex fault structure with a general north-south orientation, broken up by oblique structures and shorter fault trough that are normal to the main trend (Livingstone and Melack, 1984), of which the Gulf of Eden and Kavirondo Gulf are among the best examples. The Nakuru Basin is situated at the intersection of the Kavirondo Gulf and the main Rift Valley. At this junction a definite deflection in its course can be observed, resulting in more complex fault structures. The junction has also been the focus of intense volcanism, evidenced by four major volcanoes Londiani, Kilombe, Menengai and Eburru (McCall, 1967). Recent volcanism is observed to have occurred in Menengai, characterized by tongue-like lava flows of restricted extent, source and termination of these flows being easily determined when mapping in the field.

Nakuru sub-basin is covered by bedrock of spatially extensive volcanic rocks mainly faulted tuff and lava of varying compositions (Figure 2.2). The major faults in the detachment display large-scale structural domains with a consistent structural style, controlled by the geometry of the interaction among those fault displacements showing more than 1000m throw (Onywere, 1997). The fault flexures on the Mau escarpment have isostically uplifted footwalls giving monoclonal flexures. Basalts underlying the plateau trachyte of the rift floor are exposed at the Laikipia escarpment and, as suggested by Baker and Mitchell (1976), they were faulted before at least 1.4-0.8 Ma when the plateau trachytes were emplaced. These trachytes were subsequently faulted. The faults are arranged in *en echelon* patterns giving rise to individual fault blocks. In most parts of the rift floor, the earlier fault structures and lava flows are concealed by grey to white volcanic ashes and pyroclastics from the rift floor eruptive centers. The eruptive centers form an arc, defining the axis of the rift valley (Baker and Mitchell, 1976). Some of the rift floor volcanic ashes and pyroclastic are consolidated or welded to tuff, but others are incoherent ashes and pumice. At various localities in the pyroclastic and ash covered plains of the rift floor, are 5-10m deep gulleys that follow depressions defining the near N-S fault patterns. Along the depressions the runoff water quickly percolates or disappears into the ground through open fissures very similar to those of a karst terrain.

Sedimentary rocks in the area are mainly the volcano-sediments which consist of reworked tuffs and clays, intercalated in the older tuff formations of the Mau and Bahati Escarpments. These volcano-sediments form the aquifer media in the area. Lake sediments of the Pleistocene Lake of the Nakuru Basin are yellow-buff volcanic grits, reworked tuffs, clay and sometimes diatomite. Lateritic soils cover the larger areas of Lanet area towards Dundori though as one approaches the escarpments the lateritic nature fades and the soil turns black, rich with humus.

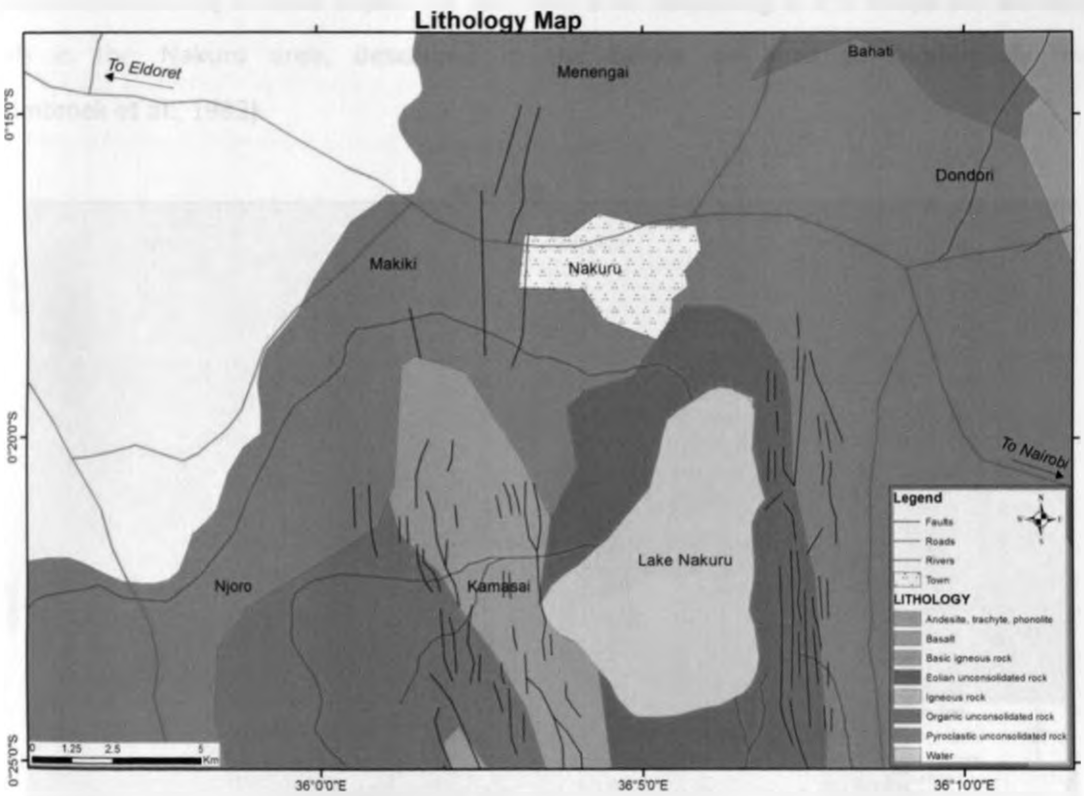


Figure 2.2 Geological map of the study area showing fault structures traversing the area

The geology and structure of the study area plays an important role with respect to the hydrogeology. The marginal rift faults and the system of grid faulting on the rift floor undoubtedly have substantial effect on the groundwater, as they act as access points for percolation of runoff, leading to potentially high groundwater storage.

2.8 Soils

The soils in the study area (Figure 2.3) can be grouped into soils developed on volcanic plain, those developed on the lacustrine plain, and soils developed in the hill land, considering the geo-pedological landscape units (Sombroek et al., 1982). The soils of the volcanic plain are formed mainly from weathered volcanic and pyroclastic deposits. These soils vary from depths of over 10 m, especially around Bahati and Dundori area, to moderate depths of around 5 m and sometimes very shallow depths of less than 2 m. According to the Kenya soil survey most soils in the Nakuru area, described in the below are well to moderately drained (Sombroek et al., 1982).

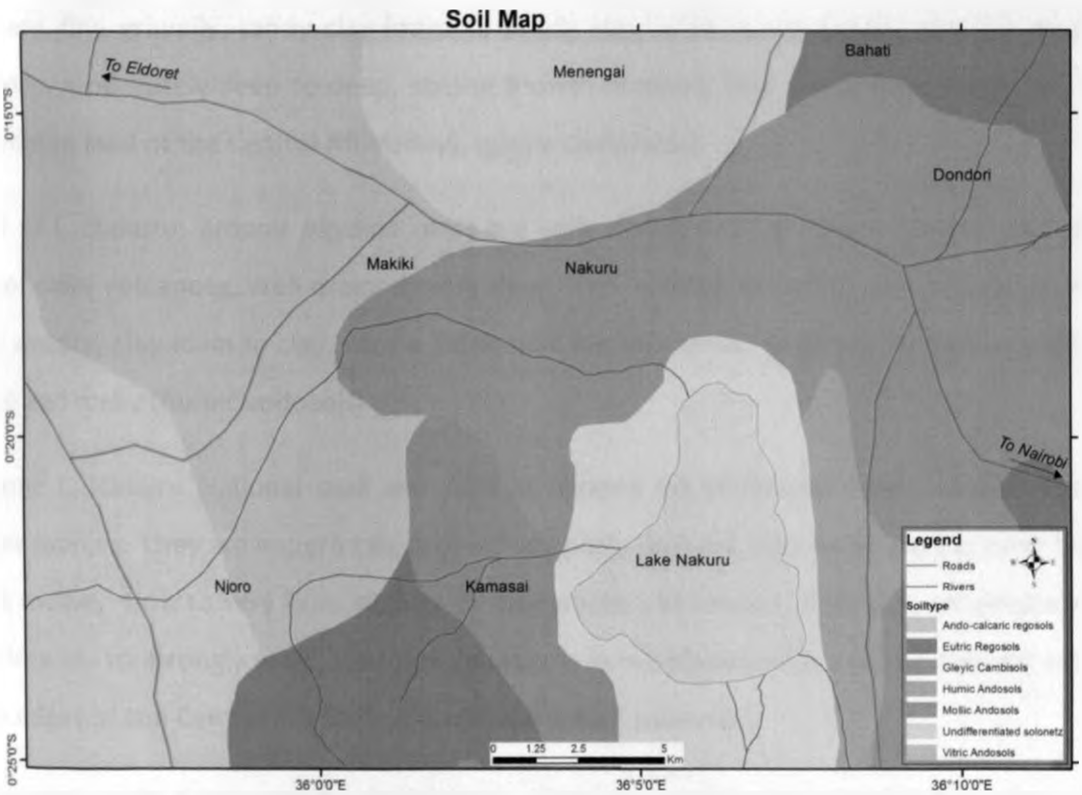


Figure 2.3 Lake Nakuru basin soil map (modified from Sombroek et al., 1982)

The area bordering and around Menengai Crater has soils developed on ashes and other pyroclastic rocks derived from recent volcanoes. They are somewhat excessively drained, shallow to moderately deep, brown to dark brown, firm and slightly smeary, strongly calcareous, stony to gravelly clay loam; in many places saline and /or sodic and with inclusions of lava fields (ando-calcaric regosols).

The area west of Menengai, around Makiki to Njoro are well drained, deep to very deep, dark reddish brown to dark brown, friable, slightly gravelly loam to clay loam, with humic topsoil (mollic andesols). East and north of Menengai, around Kabatini area and west of L. Nakuru are well drained, moderately deep to deep, brown to dark brown, very friable, loam to sandy clay loam (vitric andosols).

Area around Nakuru Municipality is soils developed on sediments mainly from volcanic ashes. They are complex of (a) well drained, moderately deep to deep, dark brown, friable and slightly smeary, fine gravelly, sandy clay loam to sandy clay, with humic topsoil and (b) imperfectly drained, moderately deep to deep, strong brown, mottled, firm and brittle, sandy clay to clay (Gamblian lake of the Central rift Valley), (gleyic cambisols).

East of L. Nakuru, around pipeline area are soils developed on olivine basalts and ashes of major older volcanoes. Well drained, very deep, dark reddish brown to dark brown, very friable and smeary, clay loam to clay, with a thick, acid humic topsoil; in places shallow to moderately deep and rocky (humic andosols)

Around L. Nakuru National park are soils developed on sediments from volcanic ashes and other sources. They are imperfectly drained to poorly drained, very deep, dark greyish brown to dark brown, firm to very firm, slightly to moderately calcareous, slightly to moderately saline, moderately to strongly sodic, silt loam to clay; in many places, with a humic topsoil; subrecent lake edges of the Central Rift Valley (undifferentiated solonetz).

In general, soils developed on the volcanic plain are well drained, moderately deep to very deep, dark brown to pale brown. On the other hand, soils developed on lacustrine deposits are moderately drained to well drained, very deep, very dark grayish brown to pale brown, silty clay to clay loam. In some places volcanic ashes and volcanic glasses are observable, and soils are very porous and drained, very deep, strongly calcerous, very friable, loam or sandy loam.

2.9 Surface and Groundwater Resources

Surface water

The catchment basin consists of five seasonal rivers (Makalia, Nderit, Naishi, Njoro and Larmuriac), which drain into the Lake Nakuru (Figure 2.1). Ngosur river, which is a permanent stream and several other minor streams coming from Bahati plain run westwards on remarkably straight courses across the plains before disappearing underground to recharge deep aquifers. In general the floor of the Rift valley around Nakuru is characterized by a very poor run off (Stuttard et al., 1995).

The Njoro, Larmuriac, Makalia and Nderit rivers drain down the Mau into Lake Nakuru. Rivers Njoro and Makalia recharge the lake though they become dry during dry seasons, whereas River Nderit disappears into a swampy area covered by acacia trees near the lake but recharges the lake directly during wet seasons. The Baharini springs also feeds the lake, where it is believed to be originating from Bahati catchment area through an underground stream. Baharini springs and other springs along the eastern shoreline (emanating from Lion's Hill ridge) are perennial and contribute about 0.6 m^3s^{-1} of the total lake's recharge (Raini, 1995). Lake Nakuru is mainly recharged by perennial rivers and ephemeral streams during the rainy seasons (Becht et al., 2005).

Groundwater Resources

The regional groundwater system is locally recharged by infiltration of rainwater through the extensive fault structures. Its spatial distribution is influenced by the ramps of faults and fractures. Faults are considered to have two effects on fluid flow; they may facilitate flow by providing channels of high permeability, or they may prove to be barriers to flow by offsetting zones of relatively high permeability.

The hydrogeology of central to southern portion of the rift valley is mainly controlled by the rift flanks faults, the grid faulting and the tectono-axis along the rift floor (Clark et al., 1990). Fluids are recharged laterally from the high rift flanks and axially along the rift floor southwards. A micro-seismic study by Allen et al. (1989) indicates that the grid faulting, unlike the escarpment faulting, is quite active suggesting the grid faults are open. Thus the faulting generally causes the ground water to flow from the escarpment to the center and then follow longer flow paths reaching greater depths.

McCall (1957, 1967) carried out studies on the geology and groundwater conditions in Nakuru area and geological survey of Nakuru-Thomson's Falls respectively. The author concludes that there are four types of aquifers found in the study area. These are aquifers found in fractured and fissured rocks, fractured and weathered volcanic rocks, weathered volcanic rocks and lacustrine deposits. It is important to mention that different rock contacts also form good aquifer media. The nature of soils, being volcanic, also facilitates percolation into the underlying aquifers. Percolation is further facilitated by the open faults and fissured zones which often act as groundwater conduits. These aquifers are often confined or semi-confined.

3 METHODOLOGY

3.1 Introduction

This section presents an overview of the method used in the study area and the various sources where data were obtained. It also presents the assessment criteria for the core factors of the PI method applied.

3.2 Overview of PI Concept

The concept of groundwater vulnerability is derived from the assumption that the physical environment may provide some degree of protection to groundwater against natural and human impacts, especially with regard to pollutants entering the subsurface environment. It assumes the Origin-Pathway-Target scenario (Figure 3.1). The term vulnerability of groundwater to contamination was introduced in France in the late 1960s by Alnibet and Margat in Chilton (2006). The general intention was to show that the protection provided by the natural environment varied from place to place. Vulnerability of groundwater can be either intrinsic or specific. Intrinsic vulnerability is vulnerability of groundwater to contaminants generated by human activities. It is purely as a function of hydrogeological factors as it takes into account the geological, hydrological characteristics of an area, but is independent of the nature of the human activities. The specific vulnerability defines the vulnerability of groundwater to a particular contaminant or group of contaminants. It takes into account the properties of a particular contaminant (or group of contaminants) and its relationship to the hydrogeological system. Therefore, vulnerability comprises the intrinsic properties of the strata separating a saturated aquifer from the land surface which determines the sensitivity of that aquifer to being adversely affected by pollution loads applied at the land surface (Paliwal, 2002).

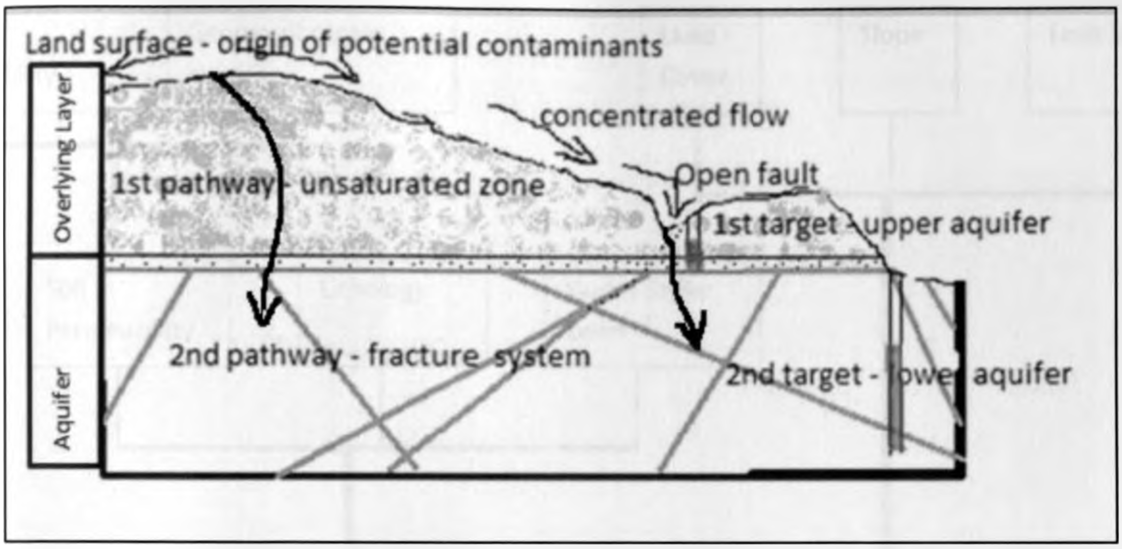


Figure 3.1 Schematic diagram of PI concept scenario (Modified from Goldscheider, 2005)

A simplified approach to mapping the intrinsic vulnerability of groundwater resources applying the PI method, synonyms for 'Protective cover and Infiltration condition' was carried out in the study area. It is an assessment technique which was introduced in Germany within the Framework of European Cooperation in the field of Scientific and Technical Research (COST) (Goldscheider, 2005), designed to handle any environment, though adopted mainly in Europe to assess vulnerability of groundwater to pollution in karst environments. This is because the method is found to be suitably applicable in heterogeneous and anisotropic settings. Since the situation existing in the East African Rift System is also heterogeneous and anisotropic, groundwater vulnerability in the Lake Nakuru basin was mapped using this method. The study area is characterized by features similar to karst environment; open gashes, faults, and sinking streams.

Vulnerability maps are an essential part of groundwater protection schemes and a valuable tool in environment management. The PI method was used to map the spatial intrinsic vulnerability of groundwater in the study area by considering the objectives of this study. The flow chart (Figure 3.2) below illustrates how key parameters were conceptualized and linked to arrive at the final vulnerability map.

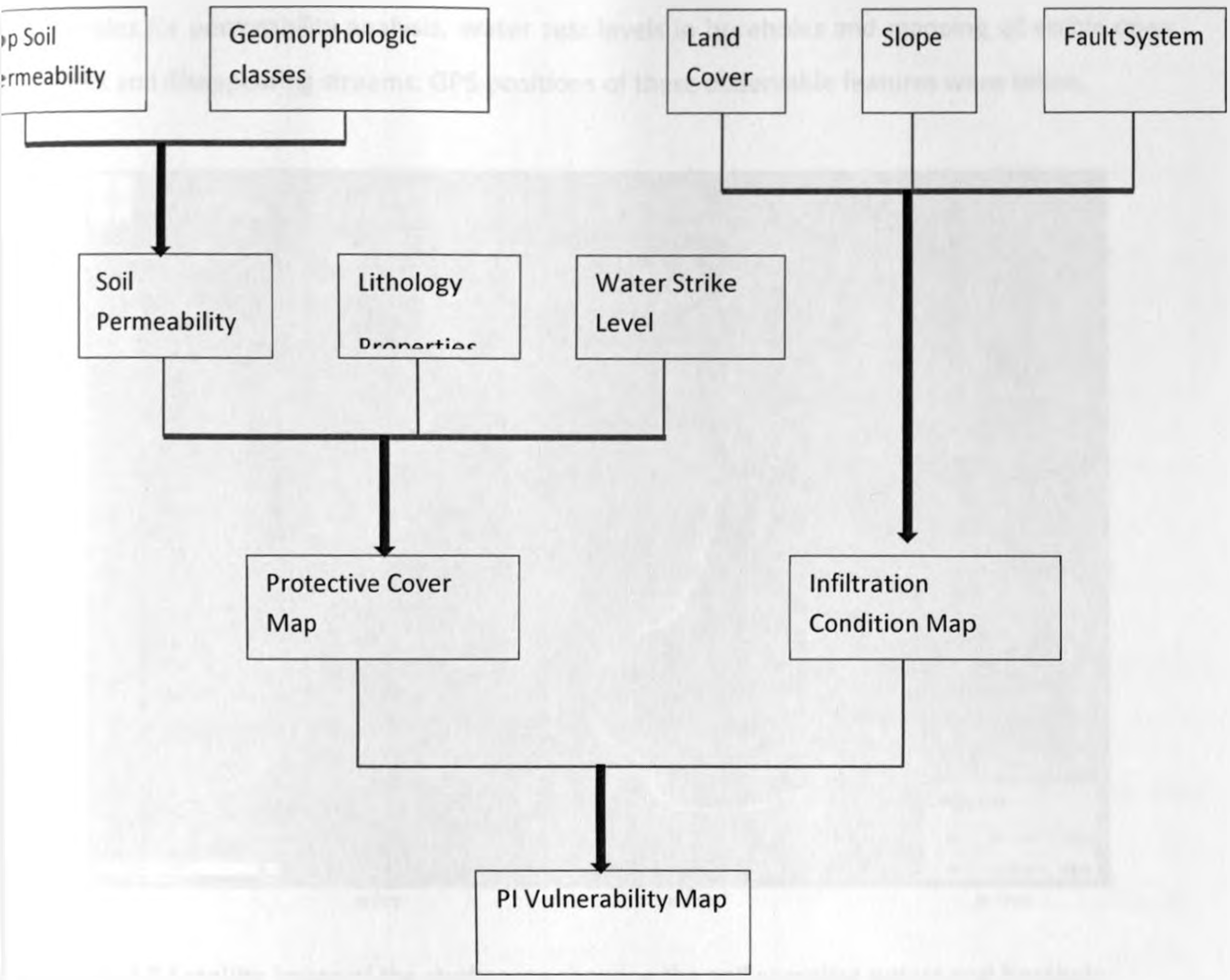


Figure 3.2. Conceptual chart for creating PI Vulnerability map

3.3 Data Gathering

3.3.1 Field Work

Fieldwork was conducted between 27th April and 10th May, 2007, in the Lake Nakuru basin. Soil samples were collected at various parts in the basin using simple tools, where a block of at least 10cm square was taken. Sampling points (Figure 3.3) were selected randomly at points where soils were observed to vary. Fieldwork was conducted with an objective of collecting soil samples for permeability analysis, water rest levels in boreholes and mapping of visible open faults and disappearing streams. GPS positions of these observable features were taken.

Figure 3.3 Satellite image of the study area showing the soil sampling points and borehole locations

3.3.2 Laboratory Analysis

Physical analyses of the soil samples were carried out in the laboratory to determine soil permeability. In 1856 the French engineer Henry Darcy successfully quantified several factors controlling ground water movement. These factors are expressed in an equation 1 commonly known as Darcy's Law.

$$Q = KA\left(\frac{dh}{dl}\right) \quad \text{Eqn 1}$$

Note:

- Q = Discharge (volume of water per unit time)
- K = Hydraulic conductivity (depend upon size and arrangement of pores, and fluid dynamics such as Viscosity, density and gravitational effects)
- A = cross- sectional area (at a right angle to ground water flow direction)
- dh/dl = Hydraulic gradient (this is the common notation for a change in head per unit distance)

By rearranging Darcy's Law and solving for K (hydraulic conductivity) gives;

$$K = \frac{Qdl}{Adh} \qquad \text{Eqn 2}$$

Hydraulic conductivity (*k*) or permeability is the property of soil which permits appreciable movement of water through it when saturated and actuated by hydrostatic pressure of the magnitude normally encountered in natural subsurface water (Singh, 1987). The commonly used physical unit for permeability is cm/s (Table 1). Soils may be rated as practically impervious when *k* is less than 10^{-7}cm/s, semi-pervious for *k* from 10^{-7}cm/s to 10^{-4} cm/s, and pervious for *k* greater than 10^{-4} cm/s (Singh, 1987).

Table 3.1 Ranges of common soil permeabilities (Modified from Singh, 1987)

Soil Type	**Permeability Coefficient, K (cm/S)**	**Relative Permeability**
Coarse Gravel	Exceeds 10^{-1}	High
Fine Sands	10^{-1} to 10^{-3}	Moderate
Silt Sands	10^{-3} to 10^{-5}	Low
Silts	10^{-5} to 10^{-7}	Very low
Clays	Less than 10^{-7}	Impervious

The falling head permeability test method was used to determine the different permeabilities of undisturbed soil samples collected from the field. It is a common laboratory testing method used to determine the permeability of medium to fine grained soils with intermediate and low permeability such as silts and clays. This method involves using an instrument such as a stand pipe in which water is passed through a soil sample and the hydraulic gradient measured.

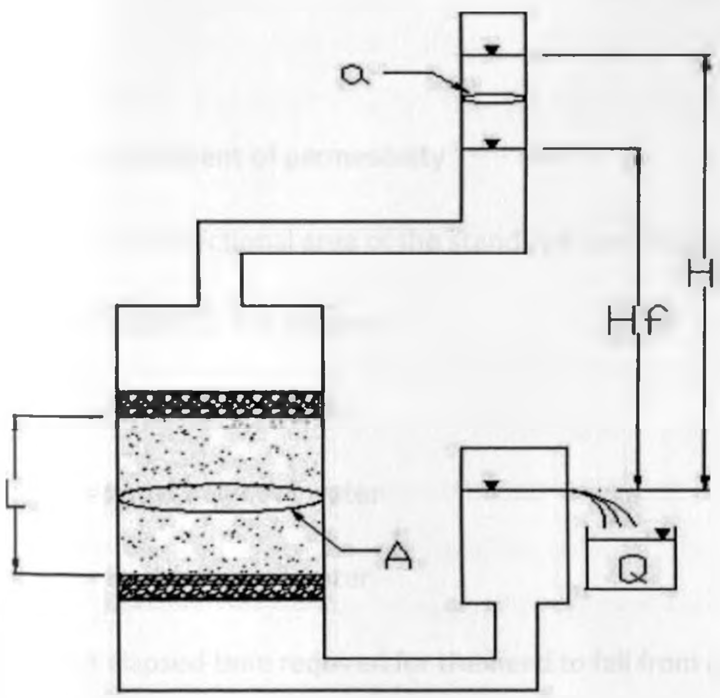


Figure 3.4 Falling head laboratory test set up (adapted from Messina, 2010)

The apparatus in figure 3.4 above shows a schematic of the falling head permeability apparatus. The sample of length (*L*) is placed in a vertical cylinder with a cross-sectional area (*A*). A standpipe of cross-sectional area (*a*) is attached to the test cylinder. Under steady state and fully saturated conditions, the change in head ($H_i - H_f$) with respect to time (*t*) is measured.

The test involves flow of water through the soil sample connected to a standpipe which provides the water head (Δh) and also allows measuring the volume of water passing through the sample. Before starting the flow measurements, the soil sample is saturated and the permeameter is filled with de-aired water to a given level. The test then starts by allowing water to flow through the sample until the water in the permeameter reaches a given lower limit. The time required for the water in the permeameter to drop from the upper to the lower level is recorded. Equation 3 below was used to compute permeability of the soil samples collected.

$$K = 2.3\frac{a.L}{At}ln\frac{H_i}{H_f} \quad \text{Eqn 3}$$

Where;

K = Coefficient of permeability

a = cross-sectional area of the standpipe (permeameter)

L = Length of soil column

A = Area of soil column

H_i = Initial height of water

H_f = Final height of water

t = elapsed time required for the head to fall from h_0 to h_1 to get head drop of (Δh)

Permeability test results for the collected soil samples from the study area are presented in chapter 4.

Additional data used for this study were gathered from various sources in the form of literature, data and maps from sources as follows;

- Soil type information was acquired from the Exploratory Soil Map and Agro-climatic zone Map of Kenya (E1) at a scale of 1:1,000,000, from the Kenya Soil Survey (Sombroek et al., 1982).

- Lithological types and properties i.e. whether the rock is fresh, weathered or highly weathered and water strike level were obtained from selected borehole logs obtained from Ministry of water, Nakuru.
- Land cover map (Figure 4.2) was generated using data obtained from ILRI (International Livestock Research Institute) database with modifications based on the field visit.
- Digital Elevation Model (DEM) was generated by digitizing the contour map of the study area using ArcGIS program.
- Faults and fissures distribution in the area was obtained from structural maps. They were digitized and modified based on ground truthing.

3.4 PI Core Factors Score Characterization

3.4.1 Introduction

As described in Goldscheider et al. (2000), the PI concept is based on an Origin-Pathway-Target scenario, described in section 3.1. The land surface was taken as the origin, the water table in the aquifer as the target, and the pathway includes all layers in between (overlying layers). The protective factor (P factor) describes the protective function of overlying layers that may be present between the ground surface and the groundwater table. The Infiltration factor (I factor) is a modifier of the P factor and represents the potential for recharge (run-off) channeling itself into an open fault, thereby bypassing the protection which should have been provided by the overlying layers. For the purpose of this study, a semi-quantitative risk characterization approach was used to provide an organized way of ranking the core factors according to their probability. This was achieved through a scoring system that allows mapping of the core factors into three categories. For the purpose of this study, low, moderate and high was utilized in ranking the parameters. In the case of the Protective factor, the value given to a parameter must reflect the protective capacity of the overlying layers. While for Infiltration factor, the value given to a parameter reflects the degree to which run-off infiltrates into the groundwater system. Rating was generated based on two or more parameters considered being characteristic for a certain area then grouped into classes.

3.4.2 Protective Factor (P Factor)

The parameters for quantification of the P factor are soil layer thicknesses, permeability values (obtained from soil samples), and also the nature of lithology - obtained from borehole logs; i.e. whether fresh or fractured and/or weathered.

Soil Filtering Capability

Soil properties such as depth and permeability help determine the rate of groundwater recharge, as well as protection from groundwater contamination. Land surface factors such as topography, geology and vegetation along with soil properties determine the potential for groundwater contamination. The soil acts as a natural filter by way of capturing solid particles. It also retains chemicals or dissolved substances on the soil particle surface, transforming chemicals through microbial biological processing, and retarding movement of substances.

Soil attenuation is the ability of soil to lessen the amount of or reduce the severity of groundwater contamination. During attenuation, the soil holds essential plant nutrients for uptake by agronomic crops, immobilizes metals or removes bacteria contained in animal or human wastes (Good and Madison, 1987)

However, the soil's ability to filter contaminants is limited. Contaminant attenuation in soils depends on water moving through the top two layers of soil (horizons A and B) at a rate that ensures maximum contact between the percolating water that contains contaminants and the soil particles. Deep, medium and fine-textured soils are the best, whereas coarse-textured materials are the worst in terms of contaminant removal. The soil permeability determined in the lab was rated based on permeability values obtained from secondary literature. It is important to note that all the soil samples collected in the study area fall in the moderate category of permeability except the soils around Lake Nakuru.

The Protective cover map describing the protective function of the overlying layers was developed by summing indexes of considered parameters. Indexes were assigned from low protection, rated 1 (one) in areas where overlying layer is absent and/or is perceived to be offering no protection to groundwater, while areas with thin soil layer was assigned to be moderate (2) and high protection, rated 3 (three) where the overlying layer is perceived to offer adequate protection to groundwater. An index associated with protection considering the above criteria was assigned as follows;

1 - Low protection

2 - Moderate protection

3 - High protection

Soil thickness and soil permeability were rated basing on the above criteria and summed up to give an overall protection factor index (Appendix II (a)).

3.4.3 Infiltration Factor (I Factor)

Infiltration was assessed from the presence of open fissures/faults which allow surface run-off to sink directly underground and slope and land cover which control runoff. Infiltration may occur normally through the overlying layers, without significant flow-concentration points at the land surface. On the other hand, surface water and possible contaminants can very quickly reach the groundwater by concentrated recharge via open fissures. Thus the protective function provided by the overlying layers is completely bypassed at these places. In the rift floor, which is characterised by faulting and fracturing, infiltration can occur in a diffuse way through the overlying layers or it can also concentrate by entering through open fractures and disappearing streams.

The I factor is a modifier of the overlying layers because it depends on the presence of open fractures or other places which concentrate flow and slope and vegetation parameters which control runoff.

Aspects of slope, vegetation cover and presence of open faults influences vulnerability of groundwater from the way in which recharge actually takes place. Although this process is very much different under different hydrogeological conditions, the location where recharge enters the geological system and the rate and intensity of recharge are important controls on the quality of groundwater.

If the infiltration occurs diffusely without significant concentration of flow, I factor is not an issue as the overlying layers are not bypassed. On the other hand, recharge can be concentrated and the overlying layers can be completely bypassed when the concentrated flow is channelled to an open fissure through which run-off and possible contaminants directly access groundwater. In such a case, I factor is a significant issue in determining vulnerability. Three classes of the degree to which run-off concentrate in different areas was generated. Where it is low infiltration, rated (0.1) on a horizontal, vegetated areas, where all recharge will occur in a diffuse way, i.e. by infiltration and subsequent percolation; rated 0.5, moderate infiltration and high infiltration (1.0) where surface run-off channels towards an open fault or an underground stream and in low vegetated areas.

Thus the I factor also ranges between high to low contribution to the degree of run-off infiltration, basing on the above criteria as follows;

1.0–high Infiltration

0.5- moderate Infiltration

0.1- low Infiltration

In this study, Land cover, slope and faults for each area were rated basing on the above criteria and summed up to give a final infiltration condition index (Appendix II(b)).

The final vulnerability map which is generated and presented in Chapter 4 shows the spatial distribution of the natural protection of groundwater, which was obtained by multiplying the P and I factors (Appendix III). The vulnerability map shows the natural protection of the groundwater in the uppermost aquifer.

4 RESULTS

4.1 Introduction

This section presents results generated from the methodology outlined in Chapter 3. The ArcGIS program was utilized in generating the Protective cover map and Infiltration condition map for the study area. The final vulnerability map was generated in ArcGIS after combining the resulting scores from the Protective cover and Infiltration condition map.

4.2 Protective Function of the Overlying Layers

4.2.1 Soils and Lithology

Generally, soils in the basin are mainly derivatives from volcanic rocks and pyroclastics with moderate permeability values (of top soil) ranging from 2.849 x 10^{-3} to 1.48 x 10^{-2}. For this study, in all areas, soil permeability parameter characterization was assigned moderate protection, which is therefore an index of 2.

Table 4.1 Permeability range for the top soils collected in the study area

Location	Position co-ordinates			Permeability (cm/s)
	Easting	Northing	Elevation (m)	
Agric	841724	9969538	1875	2.849 X 10^{-3}
EgertonBh 2	825490	9958912	2304	2.919 X 10^{-3}
EgertonBh 17	825448	9958558	2292	6.350 X 10^{-3}
EgertonBh 15	825297	9958576	2298	3.365 X 10^{-3}
Station 2	848942	9970879	1901	8.806 X 10^{-3}
Muhia's well	852634	9971027	1956	5.839 X 10^{-3}
R. Mereroni	854823	9968817	1970	1.480 X 10^{-2}
EGER 6A&B	825297	9958576	2308	9.335 X 10^{-3}
James Njoroge well	854290	9970076	1966	1.203 X 10^{-2}
Tabuga pry BH	853441	9971005	1992	5.841 X 10^{-3}
KPLC	849364	9966580	1881	5.841 X 10^{-3}
MenengaiFeedot	830008	9975572	2012	5.841 X 10^{-3}
Nyanjoro well	853977	9969648	1958	4.489 X 10^{-3}
R.Ngossur 1	851020	9973206	1953	6.061 X 10^{-3}
Njoro County Club	838452	9966320	1814	9.507 X 10^{-3}
Ingobor	836531	9963706	1940	8.921 X 10^{-3}
Wanyororo	854623	9971528	2010	6.774 X 10^{-3}
CDN	845286	9968778	1872	9.163 X 10^{-3}
Ann Wamuyo well	853441	9970807	1960	2.934 X 10^{-3}

Table 4.2 below presents a summary of soil layer thicknesses and water rest levels obtained from borehole logs from the considered sectors of the study area.

Table 4.2 Soil layer thicknesses and water rest levels from borehole logs in the study area

Location	Borehole Name	Easting	Northing	Elevation (m)	Total depth(m)	Water Strike Level (m)	Soil Layer thickness (m)
Makiki	Makiki BH	827723	9983408	1808	255.8	183.5	5.8
Kabatini	Kabatini BH 6	850876	9976733	2013	150	52-54	12
Njoro	Egerton Co-op	827716	9956418	2275	190	140	14
Nakuru Town	Elliots	834158	9968343	1833	150	92	1.8
Lanet	Chomu BH	854246	9961881	1900	160	144	10

Borehole logs (Appendix I) from the considered parts were used to obtain the typical lithology overlying the groundwater. Owing to the fractured nature of the rift floor, it is undoubted that the lithology is also fractured, though fresh rock cannot be ruled out at some localities. From this basis it is evident that the lithological unit overlying groundwater is highly weathered and/or fractured, which in some localities hosts the groundwater aquifer. For this study, the lithology overlying the groundwater in all areas was assumed to be both weathered and fractured. Furthermore, there was no precise way of rating the lithology overlying groundwater on the basis of its intensity of weathering and fracturing. This parameter was therefore not considered in coming up with the overall protection factor index in this study. Therefore protection factor (Appendix II (a)) was assessed largely as a function of soil thickness and permeability. Characterization of soil thickness is shown in Table 4.3 below;

Table 4.3 Soil thickness characterization

Soil thickness	Protection Characterization	P-factor value
> 5m	High protection	3
>2m ≤ 5m	Medium protection	2
< 2m	Low protection	1

Figure 4.1 below shows the protective cover map of the study area considering layers overlying groundwater which is basically soil thickness. Areas found to have thin soil cover is perceived to face a risk to groundwater pollution.

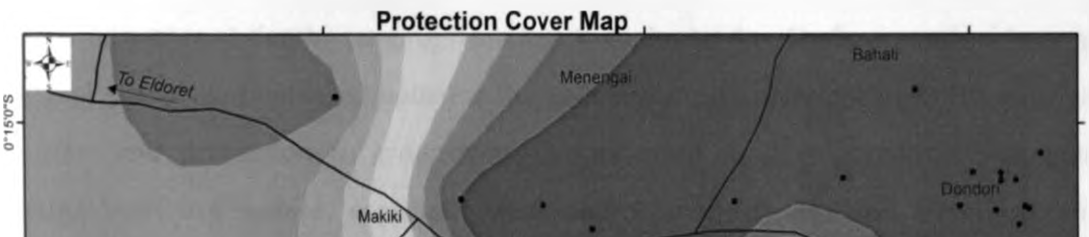


Figure 4.1 Spatial distribution of the protective cover in the study area

The area around Makiki consists of lateritic soils. They are well drained, deep to very deep, dark reddish brown to dark brown, friable, slightly gravelly loam to clay loam, with humic topsoil. Aquifers here occur at over 100m depth; therefore the thick soil cover attenuates any contaminants thus giving adequate protection. The lithology comprises weathered tuff which is known to be permeable. However greater than 5m overlying soil layer offers high protection to groundwater given an index of 3, thus perceived to have a low chance of being contaminated. Considering permeability and soil thickness, the protection factor for this area is therefore an index of 5.

Soils around Bahati are developed on volcanoclastics mainly from volcanic ashes and organic matter since it was initially forested. It covers most part of the basin. They are well drained, moderately deep to deep, dark brown, friable and slightly smeary, fine gravelly, with humic topsoil. The water table is shallow; therefore most residents have dug shallow wells encountering water at depths ranging from less than 2m to 4m. Shallow aquifers here are at a high risk of being contaminated because the soils are moderately drained. The overlying soil cover offer low protection to groundwater, thus rated 1. It is perceived that pollutants originating from the surface, especially wash-outs from pesticides and fertilisers can easily access groundwater with little being attenuated by the soil. With this view the protection factor offered by the overlying layers in the area results to an index of 3.

Soils around Dundori and Lanet areas are similar to those around Bahati developed mainly from volcanic ashes and organic matter. Residents dig shallow wells owing to the shallow water table around this area. Water from these shallow wells, which range from less than 2m to4m deep, are utilised for domestic use. It is apparent that contaminants can easily access groundwater with little being attenuated by the overlying thin soil layers thus offer low protection to the uppermost aquifer and therefore rated 1. The overall protection factor in the area is therefore an index of 3.

The area around Nakuru Municipality which incorporates the residential areas of the town consists of soils developed on sediments derived mainly from volcanic ashes. They are a complex of well drained to imperfectly drained soils which are moderately deep to shallow in some areas. Although soil cover varies from less than 1 m to more than 3m thick in some areas, the uppermost aquifer occurs above 50m depth. In view of the above the Protection factor of the overlying soil layer in the area is perceived to be moderate therefore assigned an index of 2. The overall protection for this area is therefore an index of 4.

Soils around Njoro and Egerton are developed on ashes and other pyroclastic rocks. They are well drained, deep to very deep, dark brown, friable and smeary, silty clay to clay, with humic topsoil. The soil thickness in a few localised areas is less than 1m, especially in hilly areas, which are unsettled. Most areas consist of deep dark loamy soils which vary in thickness from 5m and above. Pollutants originating from the land surface can be attenuated by the soils, which are perceived to offer high protection to groundwater and therefore rated 3. The resulting overall protection by overlying layers in the area is therefore an index of 5.

The area around L. Nakuru National park and Nderit to the south of the lake consists of soils developed on sediments from volcanic ashes and other sources. They are moderately drained to well drained, very deep, dark greyish brown to dark brown silt loam to clay; in many places with humic topsoil. The area immediately west and northwest of L. Nakuru, bordering the Park around Ingobor, consists of soils developed on undifferentiated Tertiary volcanic rocks (olivine basalts, rhyolites, andesites). They are a complex of well drained to moderately well drained, shallow to moderately deep, dark brown, firm, stony, clay loam to clay with humic topsoil. Generally groundwater in this area faces a lower risk of contamination due to the thick overlying soil layers which offers high protection to groundwater and therefore rated 3. The overall protection factor in the area is thus an index of 5.

4.3 Infiltration Factor (I Factor)

The Infiltration factor is a modifier of the Protective factor and represents the potential of runoff to bypass the protection provided by the overlying layers. The Infiltration factor represents the degree to which recharge at or near the aquifer is percolated and it was assessed using land cover, slope and faults parameters for each area.

4.3.1 Land cover

Generally, the study area is highly settled having converted from once big plantations to small parcels where small scale farming is practiced. This is an exception in Menengai area which is basically barren especially inside the caldera, with the surrounding areas covered by shrubs, and the area which is occupied by Nakuru National Park which is covered by dense woodland (Figure 4.2). All the remaining area is currently dotted with settlements with adjacent small farms and occasional large plantation. Heavy use of fertilizers and pesticides in the area is practiced in order to increase crop production for either subsistence or commercial use. Most of the study area therefore is considered to have low to moderate vegetation cover except the area around Nakuru National Park.

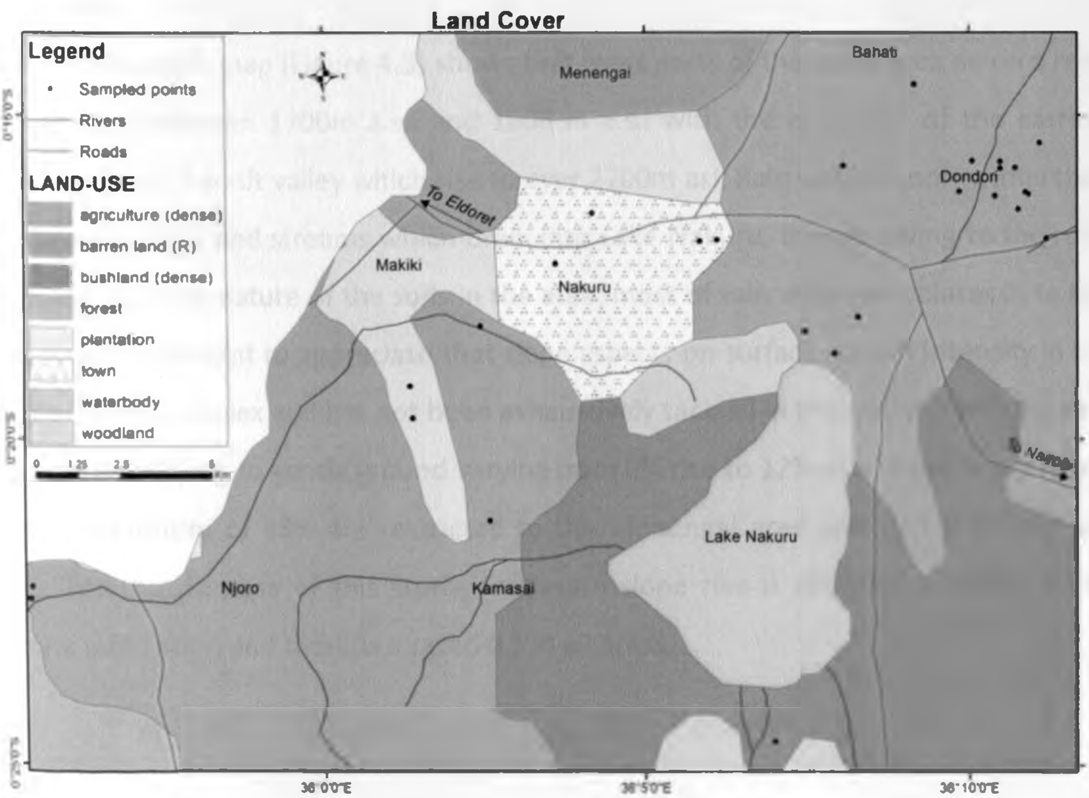


Figure 4.2 Typical Land cover features of the study area.

Vegetation creates more porous soils by both protecting the soil from pounding rainfall, which can close natural gaps between soil particles, and loosening soil through root action. Therefore, forested areas have the highest infiltration rates unlike open areas. With regards to vegetation cover on infiltration condition, the following characterization was adopted (Table 4.4).

Table 4.4 Land cover characterization

Land cover	Infiltration Condition	I-factor value
Forested areas	High Infiltration	1.0
Patchy shrubs	Medium Infiltration	0.5
Open land areas	Low Infiltration	0.1

4.3.2 Slope

The Digital elevation map (Figure 4.3) shows that most parts of the study area lie on a relatively gentle ground between 1700m a.s.l and 1900 m a.s.l with the exception of the eastern and western flanks of the rift valley which rise to over 2700m asl. Rain water runoff within the basin often follow gulleys and streams which drain into Lake Nakuru, though owing to the relatively flat ground, and the nature of the soils in the area, most of rain water percolates in to the soil. It is however important to appreciate that slope aspects on surface run-off intensity in relation to infiltration is complex and has not been exhaustively tackled in this study. The study area lies relatively on flat lying to gentle ground varying from 0% rise to 12% rise. Areas rising more than 12% to a maximum of 48% are restricted to the Menengai area and Lion Hill, west of Lake Nakuru. For the purpose of this study, moderate slope rise is adopted, meaning there is a moderate infiltration and therefore rated 0.5 in all areas.

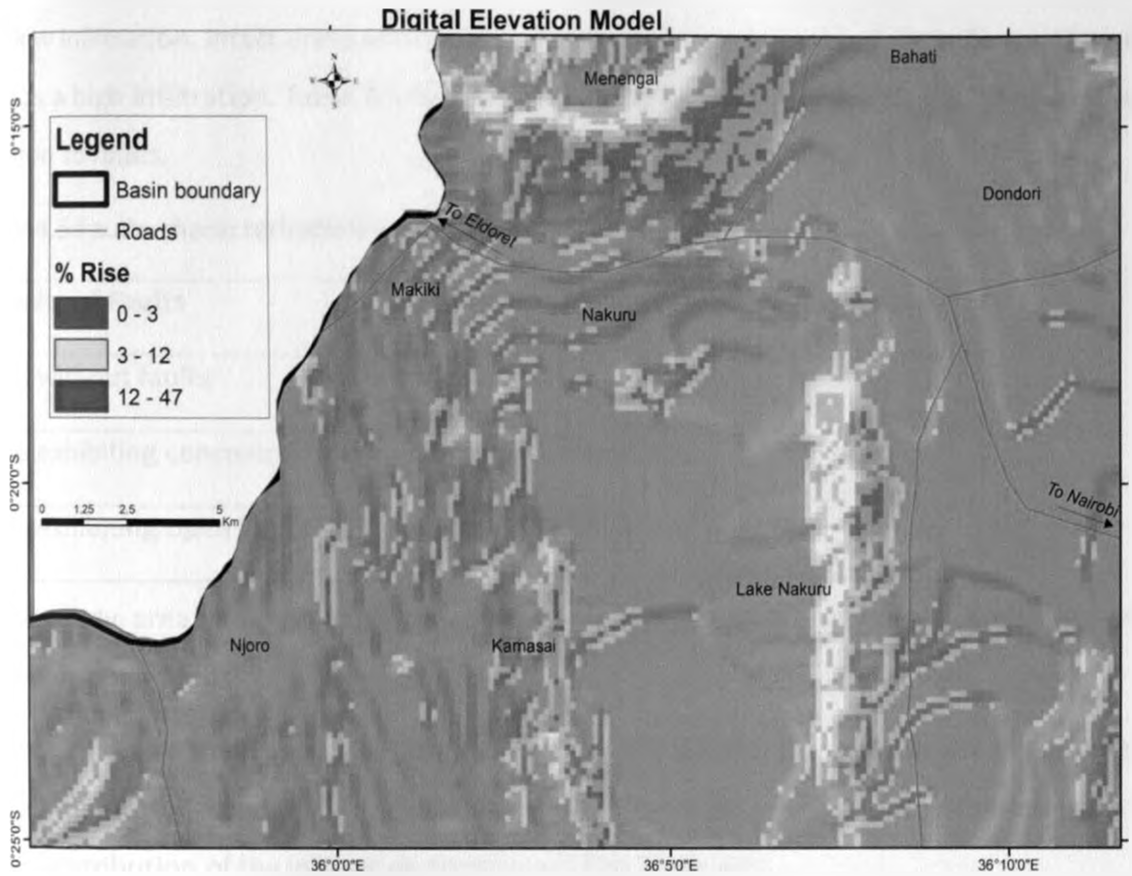


Figure 4.3 Digital elevation model of the study area

4.3.3 Fault Systems

The fault system in the study area is generally oriented north-south, although it is broken up into oblique structures and other shorter fault troughs normal to the main trend (Figure 2.3). These fractures and fissures are open but others are generally packed with rubble, thus cannot be easily noticed. The floor of the rift valley is known to be extensively fractured with grid faults which act as access points for groundwater percolation.

In fractured terrains, where presents of open faults characterizes the area, groundwater recharge mainly takes place via fractures and cavities so that the travel time of a drop of water from the land surface to the aquifer is often relatively short. This means that water laden with contaminants can easily introduce pollutants to the groundwater system. In the study area, intensity of faults was rated from high to low, meaning for high intensity faults, surface run-off has low infiltration. Intact areas with no observable faults was rated low, therefore surface run-off has a high infiltration. Table 4.5 below was used to characterize the degree of infiltration in relation to faults.

Table 4.5 Faults characterization and rating

Intensity of Faults	Infiltration Condition	I-factor value
Areas without faults	Low Infiltration	0.1
Areas exhibiting concealed faults	Medium Infiltration	0.5
Areas exhibiting open faults	High Infiltration	1.0

In the study area, only two categories were identified, i.e. areas without faults and areas exhibiting open faults.

Summing up the infiltration condition values for the parameters considered resulted to an overall infiltration condition for each area (Appendix II (b)). Figure 4.4 below presents the spatial distribution of the infiltration condition in the study area.

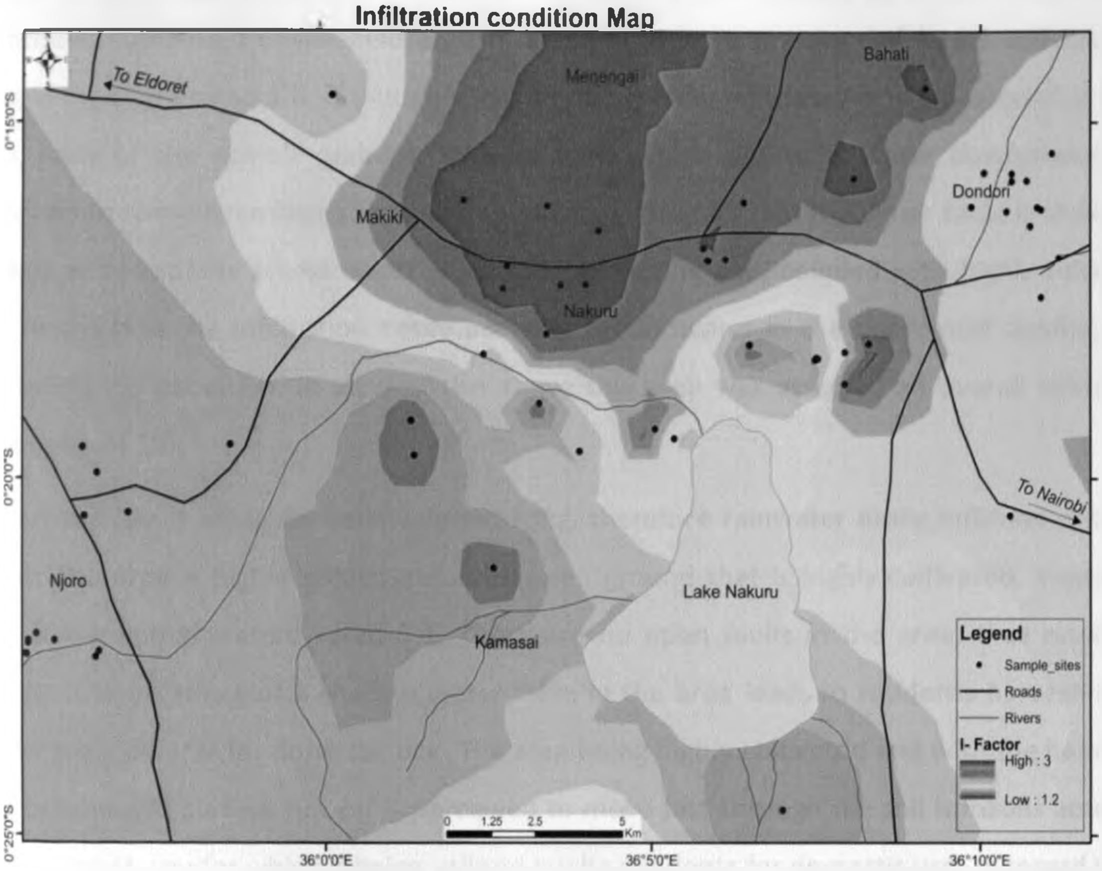


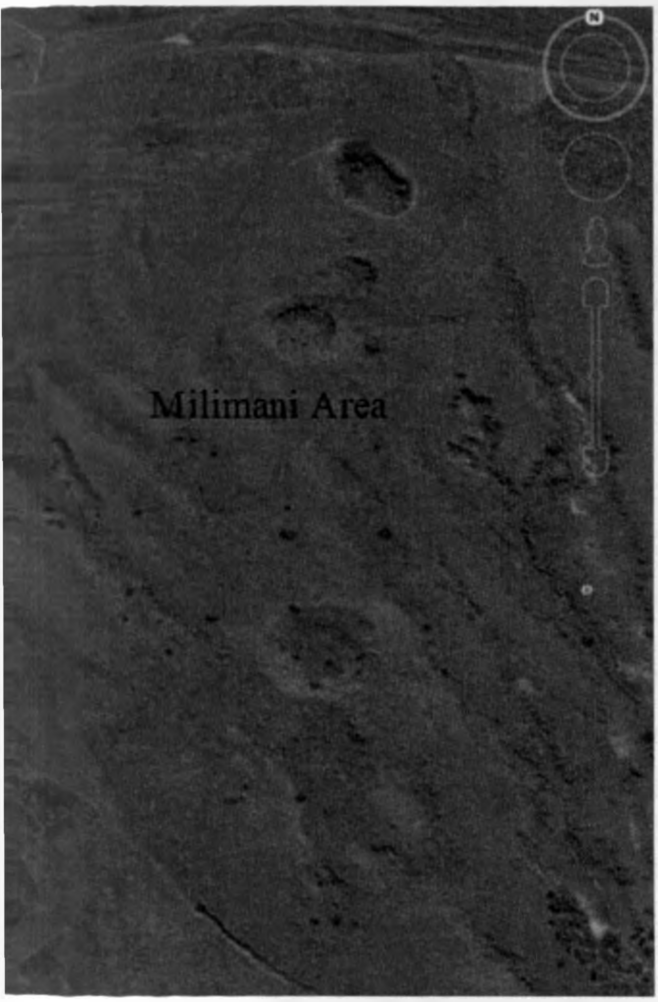
Figure 4.4. Spatial distribution of Infiltration condition in the study area.

With Regards to the Infiltration condition, Makiki area is relatively flat, with occasional bush lands intercalated with farm lands. The area was characterized to have moderate vegetation cover and therefore rated 0.5. There are no open faults in the area therefore surface run-off infiltrates in to the ground attenuating any potential contaminants. The Infiltration condition due to influence of faults is low, therefore rated 0.1. The area therefore was given an overall infiltration factor index of 1.1

Bahati area is situated on the slopes of Bahati escarpment, i.e. the area bordering Bahati highlands. Run-off therefore, move relatively fast compared to the low lying grounds around Dondori and Lanet. Vegetation cover varies from slightly forested areas which border the Bahati highlands to stripped and highly cultivated agricultural lands at the slopes. The area has a low vegetation cover and therefore rated 0.1. There are open faults in this area especially downstream towards the well field area of Kabatini. Due to presence of faults, infiltration is high and therefore rated 1.0. Although run-off undoubtedly infiltrates in to the ground in some areas, some of the run-off drains to Ngosur River which drains its water downstream and disappears to some open faults further downstream. The fact that the water table is shallow in the area and residents access water from shallow depths and, coupled with highly cultivated land, means that the Infiltration easily accesses groundwater in the uppermost aquifer, thus high infiltration condition. In view of the above this area was assigned an overall Infiltration factor index of 1.6.

Dondori and Lanet areas are relatively flat lying, therefore rainwater easily infiltrate in to the ground. The area is highly settled and with open ground that is highly cultivated. Vegetation cover is low and therefore rated 0.1. There are no open faults in the area, thus rated 0.1; however, the presence of a shallow water table in the area leads to residents harvesting the shallow groundwater for domestic use. The area being highly cultivated and with the heavy use of agrochemicals, surface run-off is perceived to move fast through the soil horizons accessing the uppermost aquifer which is being utilised by the residents for domestic use. In regard to the above, the overall infiltration condition indexed is therefore 0.7.

The area around Nakuru Town and its surroundings are known to frequently experience subsidence along the parallel fault zones during and after heavy rainfall (see Plate 4.1), where the overlying unconsolidated volcanoclastic sediments become oversaturated with water leading to subterranean erosion along faults. The unconsolidated sediments then collapse into the subsurface water channels which closely follow the fault zones usually governed by numerous N-S trending parallel faults leading to formation of “sinkholes” (Ngecu and Nyambok 2000).



late 4.1 A section around Milimani area showing subsidence associated with faulting (adapted

-om Google maps)

hese faults channel run-off water, results to high infiltration (1.0), posing a great risk to roundwater around these areas. The area is highly settled, thus low vegetation cover which is ated 0.1. During rainy seasons heavy storm water laden with pollutants from municipal waste nd wash-offs from paved grounds pose a risk to groundwater. This is further aggravated by the act that storm water easily collects due to dense settlements and roads. The existence of a umpsite in the vicinity of the town aggravates further the concentration of contaminants specially during rainy seasons when storm water carries a cocktail of contaminants from the dumpsite downstream. Considering the above factors, the overall infiltration condition in this area therefore is an index of 1.6.

Njoro area lies in a gentle terrain with some areas being relatively flat. Vegetation cover is patchy with most of the open grounds converted to farm lands and settlements, therefore moderated vegetation cover, rated 0.5. There are no open faults therefore runoff water is perceived to infiltrate in to the ground owing to the thick soil cover which easily attenuates any contaminants it carries. The infiltration condition in the area therefore results to an index of 1.1.

The area around the park lies on a relatively flat ground thus surface water easily percolates. Areas around Ingobor and Nderit, however, lie of gentle ground where run-off moves towards the low lying L. Nakuru. The park area is covered with dense woodland and shrubs but Ingobor and Nderit have less dense bush lands, thus high vegetation cover, rated 1.0. These areas also have low settlements. There are no open faults, therefore the risk of pollution due to the infiltration factors are low. The resulting infiltration condition in the area is an index of 1.6.

4.4 Groundwater PI Vulnerability Map of the Study area

The vulnerability map (combination of the overall Protection cover index and the overall Infiltration condition index) shows the natural protection of the groundwater in the uppermost aquifer (Figure 4.5). The map shows the spatial distribution of the natural protection of groundwater in the study area, which was obtained by multiplying the P and I factors (Appendix III). From the ratings of the P and I factors, the following combinations are possible;

6 x 3	6 x 2.5	6 x 2.1	6 x 2	6 x 1.5	6 x 1.1	6 x 2	6 x 0.7	6 x 0.3
5 x 3	5 x 2.5	6 x 2.1	5 x 2	5 x 1.5	5 x 1.1	5 x 2	5 x0.7	5 x 0.3
4 x 3	4 x 2.5	4 x 2.1	4 x 2	4 x 1.5	4 x 1.1	4 x 2	4 x 0.7	4 x 0.3
3 x 3	3 x 2.5	3 x 2.1	3 x 2	3 x 1.5	3 x 1.1	3 x 2	3 x 0.7	3 x 0.3
2 x 3	2 x 2.5	2 x 2.1	2 x 2	2 x 1.5	2 x 1.1	2 x 2	2 x 0.7	2 x 0.3

The natural protection factor therefore ranges between 0.6 and 18, with high values representing a high degree of natural protection and low vulnerability and vice versa with low values.

Table 4.6 PI vulnerability classes

PI Vulnerability Classes		
Description	**Range of PI Value**	**Degree of protection**
High Vulnerability	0 ≤ 6	Low Protection
Moderate Vulnerability	>6 ≤ 12	Moderate Protection
Low Vulnerability	>12 ≤ 18	High Protection

The sampled sites in this study area were assigned to one of the three classes, symbolized by colours red to blue representing high to low vulnerability of groundwater. It is evident from Figure 4.5 that groundwater in most parts in the study area is sufficiently protected by the overlying layers against pollution with the exception of those areas tapping their water from the shallow uppermost aquifers. Boreholes logs from different localities indicate most areas in the study area tap groundwater from deep aquifers with depths varying from around 50 m to as deep as 180 m. This clearly indicates groundwater is sufficiently protected by the overlying layers, which attenuates pollutants before reaching the water table. This, however, is an exception to those areas with thin soils, areas characterized by open faults and fissures and areas where groundwater is drawn from shallow wells. In such areas protection of groundwater by the overlying layers is insufficient thus it can be easily polluted. This is aggravated by intensive use of fertilizers and pesticides for crop production.

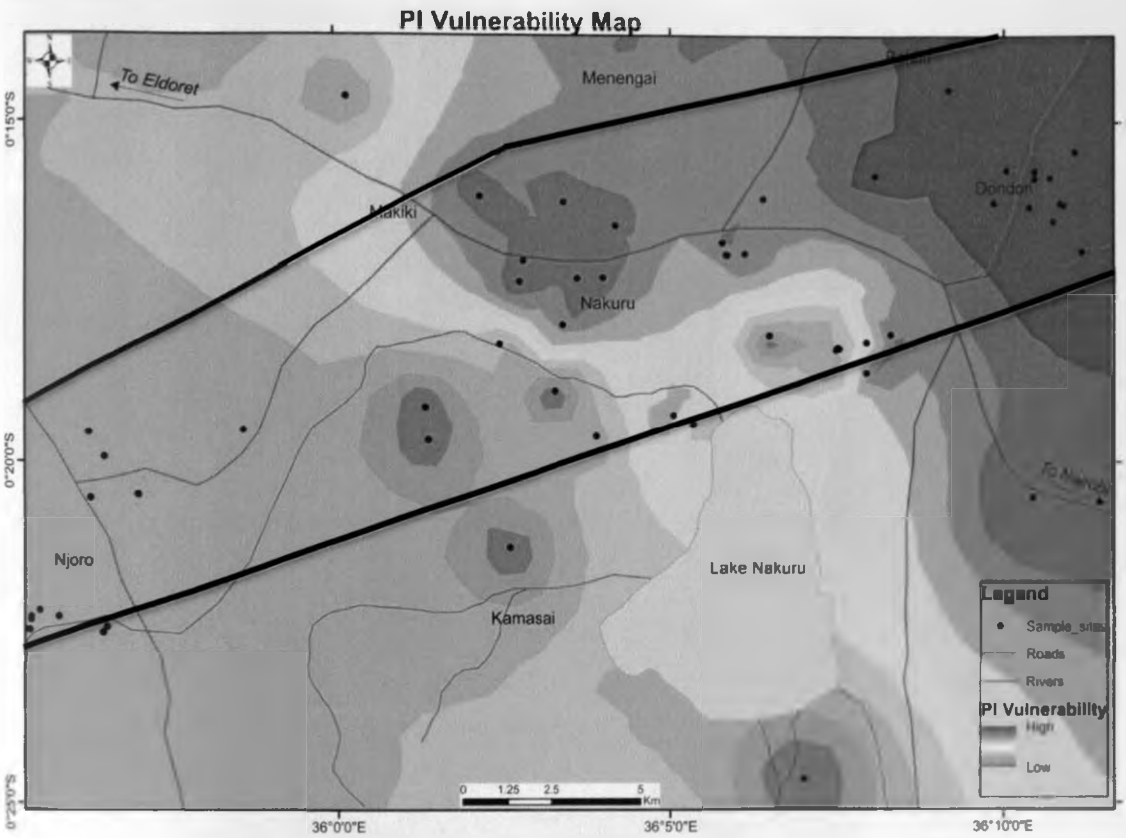


Figure 4.5 PI vulnerability map of the study area. The bold line presents area with good data coverage

Fairly deep and well drained to fairly drained soils covering the study area allow rain water to infiltrate in most areas of the study area, although infiltration will automatically be by-passed in areas with open faults.

Storm water from Nakuru Municipality and around Nakuru dumpsite undoubtedly carries with it pollutants which easily access groundwater when it channels itself through the open faults characterizing the area (Plate 4.2).

Plate 4.2. Nakuru dumpsite sitting right on a fault structure

5 DISCUSSION

The results of this study indicated that mapping groundwater vulnerability is an efficient tool significantly assisting in planning and decision making processes. Most of the area illustrated low vulnerability at a significant percentage of the examined coverage of approximately over 65% due to sufficient soil layer and the relatively flat terrain which enhance the unfavourable conditions for aquifer vulnerability. Most of the rainwater infiltrates naturally attenuating any possible contaminants in the thick soil layers, thus the class of vulnerability.

High vulnerability covers approximately 45% of the area of studied area. The area around Nakuru municipality presented high vulnerability even though the thick soil cover facilitates natural attenuation of pollutants and groundwater being harvested from deep aquifers. The high vulnerability class is attributed to the existence of open faults which traverse the area increasing the possibility of pollutants directly accessing groundwater through the numerous faults which can follow long paths and eventually contaminate groundwater in the area.

Bahati consist of numerous faults especially downstream which encourage runoff to disappear to these open faults; example is river Ngosur which disappears abruptly underground through these faults. However, the deep nature of the aquifers allows infiltrating water to attenuate any contaminates before assessing groundwater. High vulnerability is also seen in the area around Dundori and Lanet where owing to the shallow nature of the upper groundwater aquifer, contaminants can easily infiltrate into the shallow water table through the thin overlying soil layer. Intensive crop production by use of agrichemicals aggravates the situation more because most residents have dug shallow wells at the back yards of their homesteads where the kitchen farms sits. Therefore any runoff from these farms directly enters the wells. Natural infiltration can easily assess the shallow water table due to the overlying thin soil cover. It is important to mention here that although the shallow uppermost aquifer can be easily polluted, groundwater harvested from deep aquifer in the area is adequately protected from pollution by overlying layers.

The findings from this study clearly show that simplifying aquifers system in the rift floor as homogenous and isotropic should be traded with care, because it can lead to simplification of models of groundwater. Those models which are applicable in compact geological settings should be avoided in faulted terrain and instead adopt such kind of models which are applicable in karst terrains where the effects of faults/open fissures in movement of groundwater is carefully considered. Authors who have worked in the study have indicated presence of significant coliforms in groundwater harvested from deep aquifers in the area. This means that, although the thick overlying layers are present, the long and complex paths followed by faults in the area may be contributing to these kinds of pollutants getting their way to the deep aquifers, further emphasizing the need to carefully consider the effects of faults in regards to movement of groundwater.

Despite the considerable insights learnt/gained from this study, the method has never been applied in the study area, or any other faulted terrain known to the author, other than the Karst terrains. This study has therefore come with some limitations which should be adequately tackled before the method is quality assured. First, in order to develop a consistent approach to considering and applying this method in assessing vulnerability of groundwater in any faulted terrain, a clear method of quantifying/categorising factors should be developed. In addition a concise way of combining and weighting the different factors with respect to the underlying physical processes in faulted terrain such as attenuation processes should be defined. Secondly, applying the proposed method to various test sites which have different hydrogeological conditions, but within similar faulted terrain, allows data of varying quality to be used in individual cases. This will enable estimation of how good the assessment of groundwater vulnerability applying PI is, based on the quality of the data input. Finally revising the approach based on the results from the test sites in comparison with other vulnerability maps will eventually result to quality assurance.

6 CONCLUSION AND RECOMMENDATIONS

The results of this study indicated that mapping groundwater vulnerability is an efficient tool significantly assisting in planning and decision making processes. Most of the area illustrated low vulnerability at a significant percentage of the examined coverage of approximately over 65% due to sufficient soil layer and the relatively flat terrain which enhance the unfavourable conditions for aquifer vulnerability. Most of the rainwater infiltrates naturally attenuating any possible contaminants in the thick soil layers, thus the class of vulnerability.

High vulnerability covers approximately 35% of the area of study. The area around Nakuru municipality presented high vulnerability even though the thick soil cover facilitates natural attenuation of pollutants and groundwater being harvested from deep aquifers. The high vulnerability class is attributed to the existence of open faults which traverse the area increasing the possibility of pollutants directly accessing groundwater through the numerous faults which can follow long paths and eventually contaminate groundwater in the area.

Bahati consist of numerous faults especially downstream which encourage runoff to disappear to these open faults; example is river Ngosur which disappears abruptly underground through these faults. However, the deep nature of the aquifers allows infiltrating water to attenuate any contaminates before assessing groundwater. High vulnerability is also seen in the area around Dundori and Lanet where owing to the shallow nature of the upper groundwater aquifer, contaminants can easily infiltrate into the shallow water table through the thin overlying soil layer. Intensive crop production by use of agrichemicals aggravates the situation more because most residents have dug shallow wells at the back yards of their homesteads where the kitchen farms sits. Therefore any runoff from these farms directly enters the wells. Natural infiltration can easily assess the shallow water table due to the overlying thin soil cover. It is important to mention here that although the shallow uppermost aquifer can be easily polluted, groundwater harvested from deep aquifer in the area is adequately protected from pollution by overlying layers.

The findings from this study clearly show that simplifying aquifers system in the rift floor as homogenous and isotropic should be traded with care, because it can lead to simplification of models of groundwater. Those models which are applicable in compact geological settings should be avoided in faulted terrain and instead adopt such kind of models which are applicable in karst terrains where the effects of faults/open fissures in movement of groundwater is carefully considered. Authors who have worked in the study have indicated presence of significant coliforms in groundwater harvested from deep aquifers in the area. This means that, although the thick overlying layers are present, the long and complex paths followed by faults in the area may be contributing to these kinds of pollutants getting their way to the deep aquifers, further emphasizing the need to carefully consider the effects of faults in regards to movement of groundwater.

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APPENDIX I

ım5 boreholes created using WinLog program

C-10704	**X: 827716.40**
e: Egerton co-op	**Y: 9956417.58**
o	**Altitude:**
	Map S/No.: 118/4
	Log Sheet No.: 1 of 1

ologic nbol	Lithologic Description	Elevation (m)	Well Completion Details	General Description
	Ground Surface			
	Sediments Coarse			
	Tuffs Alternating weathered and less weathered tuffs			Water Rest Level
				Water Strike Level
	Trachyte Weathered			
	Sediments Coarse			

's: 2	**Aquifer Material: Weathered trachyte & Coars**
	Borehole Completion Date: 31-08-1993

Borehole No.: C-10764

Borehole Name: M.H.M.N.T

Location: Lanet

Owner:

Area: Nakuru

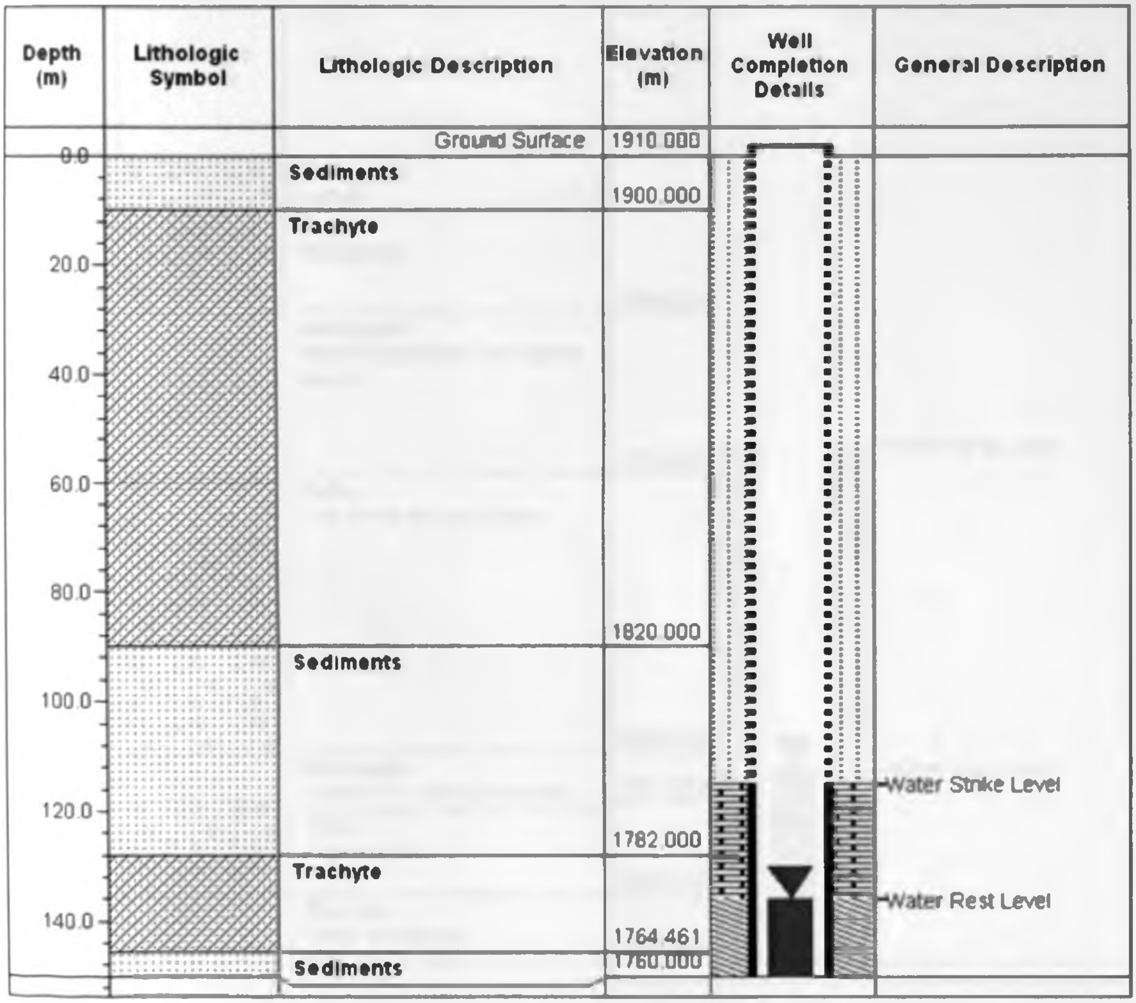
X: 848582.16

Y: 9965587.81

Altitude: 1910m

Map S No.: 119/3

Log Sheet No.: 1 of 1



No. of Aquifers: 2

Contractors:

Aquifer Material: Fine volcano sediments

Borehole Completion Date: 20-03-1994

Borehole No.: C-9943

Borehole Name: Kabarak one

Location: Kabarak

Owner:

Area: Kabarak

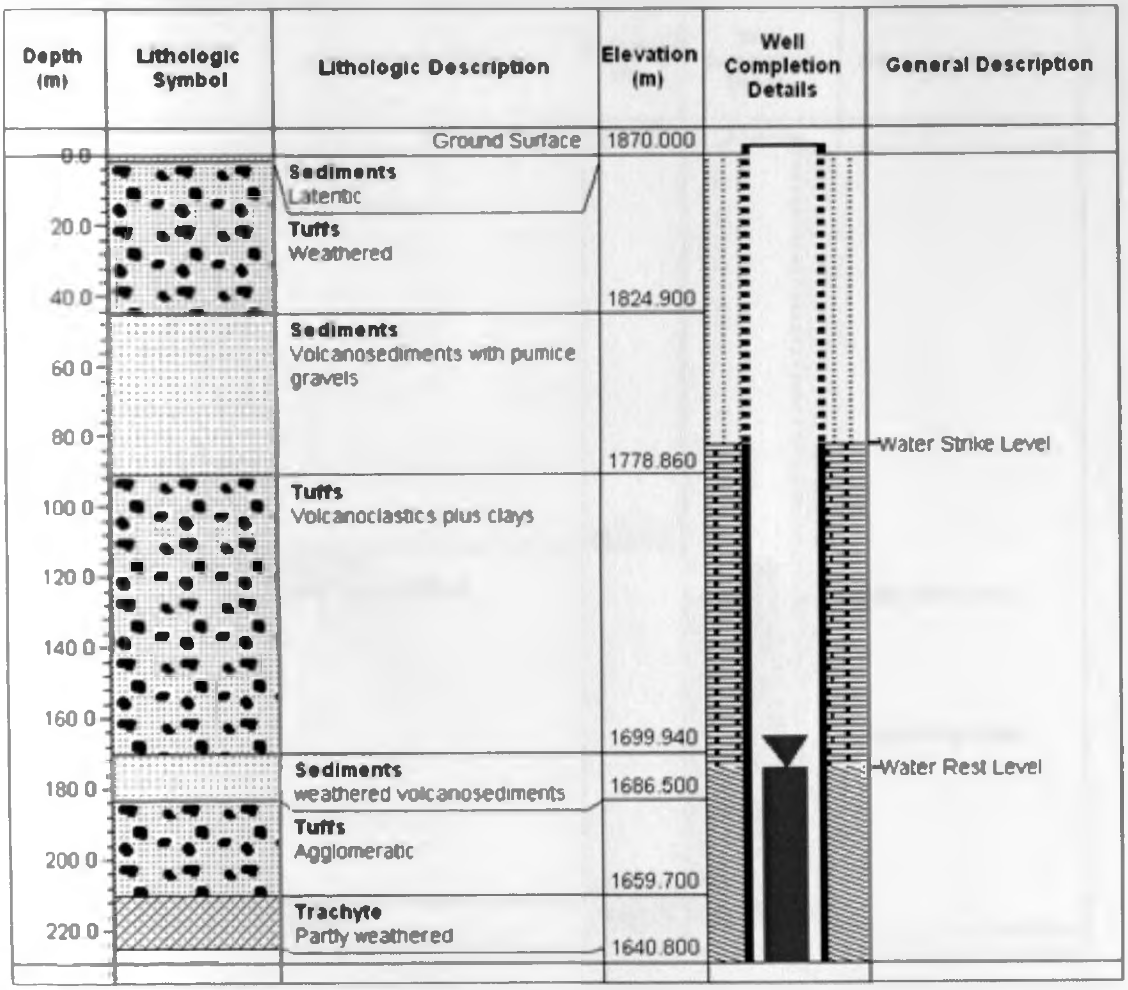
X: 827722.98

Y: 9983408.07

Altitude: 1870m

Map S No.: 118 2

Log Sheet No.: 1 of 1



No. of Aquifers: 2

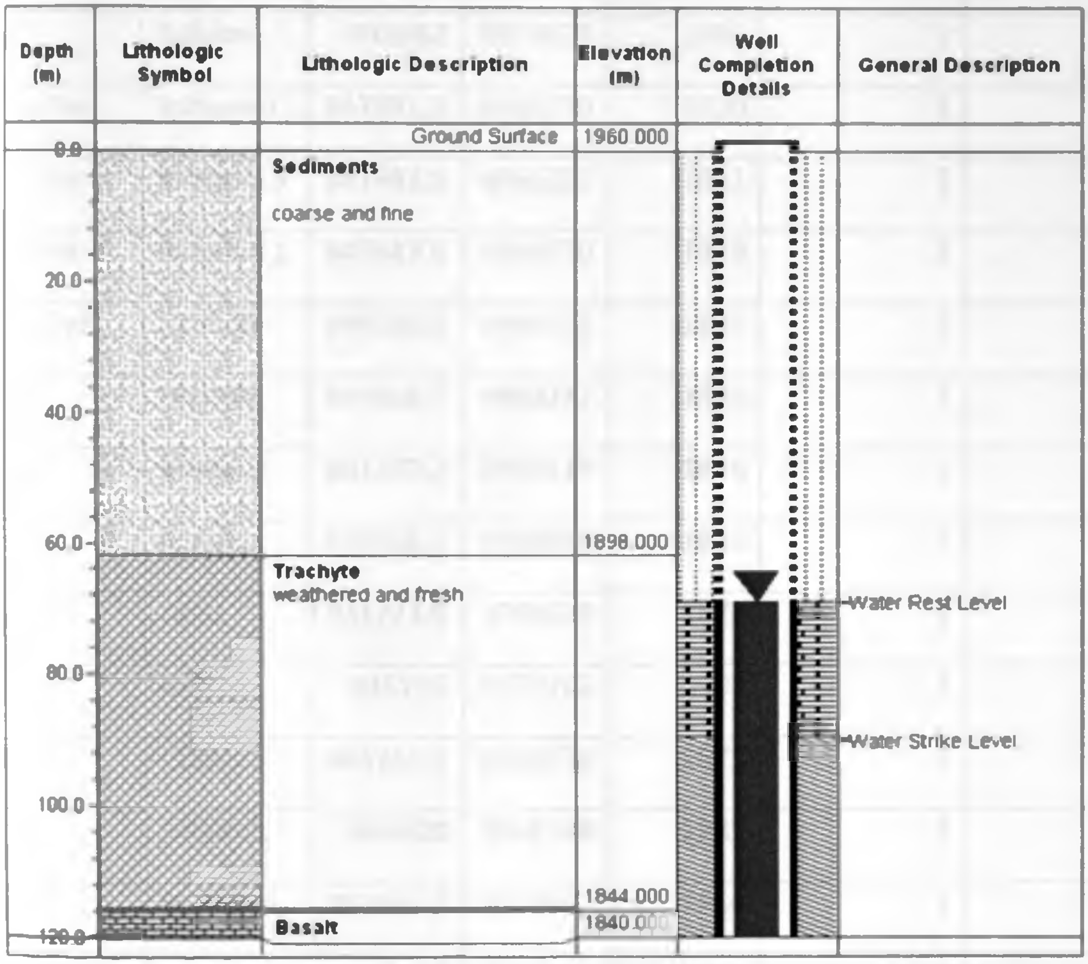
Contractors:

Aquifer Material: Tuff

Borehole Completion Date: 22-08-1991

Borehole No.: C-8441
Borehole Name: Bahati
Location: Bahati
Owner:
Area: Bahati

X: 82777.83
Y: 99771002.46
Altitude: 1960m
Map S No.: 119/1
Log Sheet No.: 1 of 1



No. of Aquifers: 3
Contractors:

Aquifer Material: Fissured trachyte & Gravel.
Borehole Completion Date: 3-12-1990

APPENDIX II

(a) P factor values score characterization for the sample sites

Location	Site	Easting	Northing	Elevation (m)	Protective factor Rating		
					Soil Thickness	Soil Permeability	P Factor Index
Bahati	Kabatni	848942	9970879	1901	1	2	3
Nakuru Park	Baharini7	847891.3	9966220	1830	3	2	5
Nakuru Park	Baharini 9	847942.1	9966202	1831	3	2	5
Nakuru Park	Baharini 1	847847.6	9966170	1828	3	2	5
Nakuru Park	NrbRd6	844780.2	9968751	1885	3	2	5
Nakuru	NrbRd4	844806.7	9968737	1885	2	2	4
Nakuru	Bontana	841369.2	9968114	1846	2	2	4
Nakuru	Londra	840666.1	9968098	1858	2	2	4
Nakuru	AGRI	841723.9	9969538	1875	2	2	4
Nakuru	KITI	845795	9970262	1908	2	2	4
Nakuru	CDN	845286.1	9968778	1872	2	2	4
Nakuru	NRBRd5	844809	9968748	1885	2	2	4
Dundori	Wamuyu	853441.2	9970807	1960	1	2	3
Dundori	Tabuga	853441.3	9971005	1992	1	2	3
Dundori	Njogu	853877.4	9970822	1972	1	2	3
Dundori	Njoroge	854290.1	9970076	1966	1	2	3
Dundori	Munui	854175.1	9970130	1970	1	2	3
Dundori	Nyanjor	853976.8	9969648	1958	1	2	3
Dundori	Nyoike	853287.8	9970026	1950	1	2	3

cation	Site	Easting	Northing	Elevation (m)	Protective factor Rating Continued		
					Soil Thickness	Soil Permeability	P Factor Index
ındori	C.C.O	852276.5	9970147	1935	1	2	3
oro	Egert6a	825297	9958576	2308	3	2	5
oro	Egert6b	825297	9958576	2308	3	2	5
oro	Egert11	825297	9958576	2298	3	2	5
oro	Egert17	825448	9958558	2292	3	2	5
oro	Egert3	825490	9958912	2304	3	2	5
oro	Egert2	825742	9959088	2278	3	2	5
oro	Egert12	827508	9958494	2250	3	2	5
oro	Egert15	824478	9959678	2274	3	2	5
joro	Egert1	826284	9958922	2267	3	2	5
joro	NjorCDF	827152	9963910	2210	3	2	5
joro	Njoro CC	827197	9962132	2160	3	2	5
ahati	Ngosur	851019.6	9973206	1953	1	2	3
undori	Wany'ro	854622.9	9971528	2010	1	2	3
joro	Njoro4	838451.9	9966320	1814	3	2	5
ljoro	NjoroB	825488	9958840	2219	3	2	5
ljoro	Njoro3	831312	9963989	2139	3	2	5
Jakuru Park	Ingobr	836531.3	9963706	1940	3	2	5
Jakuru Park	Mogon	836456.8	9964607	1941	3	2	5
Jakuru Park	Kamasai	838718.6	9960797	1861	3	2	5

Location	Site	Easting	Northing	Elevation (m)	Protective factor Rating Continued		
					Soil Thickness	Soil Permeability	P Factor Index
Nakuru	NjoroBr	843340.4	9964386	1767	2	2	4
Njoro	NjoroLk	843882.3	9964138	1777	3	2	5
Nakuru Park	Makalia	842972.3	9945556	1775	3	2	5
Nakuru Park	Nderit	846924.4	9954526	1767	3	2	5
Nakuru Park	Baharin	845958.1	9966558	1959	3	2	5
Dundori	Merern1	854287	9967785	1951	1	2	3
Dundori	Grenstd	853394.4	9962140	1926	1	2	3
Makiki	Mfeedot	830008	9975572	2012	3	2	5
Makiki	Makiki1	831007	9976072	2012	3	2	5
Makiki	Makiki2	834299.1	9973014	2032	3	2	5
Nakuru	Oliveln	837910	9970320	1936	2	2	4
Nakuru	Lion HG	848693.1	9965544	1886	2	2	4
Nakuru	KPLC	849363.8	9966580	1881	2	2	4
Nakuru	Rasul	848695.8	9966368	1882	2	2	4
Bahati	BahtiHC	847851.4	9980794	2078	1	2	3
Nakuru	NkrTunn	840258.5	9966838	1812	2	2	4
Nakuru	Ngayoyi	843005.6	9945387	1852	2	2	4
Nakuru	BIDCO	839126.1	9968588	1875	2	2	4
Nakuru	Windml	841864.9	9950316	2442	2	2	4
Nakuru	Evrydy	839005.2	9968010	1875	2	2	4

Location	Site	Easting	Northing	Elevation (m)	Protective factor Rating		
					Soil Thickness	Soil Permeability	P Factor Index
Bahati	Ngorik	859990.3	9966205	2251	1	2	3
Nakuru	Pyrthrm	840293.5	9970170	1875	2	2	4
Nakuru Park	Ronda	840029.2	9965047	1811	3	2	5
Njoro	NjorBSc	827563.9	9963245	2174	3	2	5
Nakuru	NkrBSc	844676.2	9969076	2174	2	2	4
Bahati	Ngorika	862658.4	9965485	1999	1	2	3
Nakuru	Deflord	857734.9	9911307	1919	2	2	4
Njoro	Njoro	825488	9958840	2296	3	2	5
Njoro	Egert.	824839	9958696	2265	3	2	5
Njoro	SewDis	827608.5	9958643	2287	3	2	5
Njoro	KARI	841185.7	9963812	2296	3	2	5

(b) I factor values score characterization for the sample sites

Location	Site	Easting	Northing	Elevation (m)	Infiltration Condition Rating			
					Land cover	Slope	Faults	I Factor Index
Bahati	Kabatni	848942	9970879	1901	0.1	0.5	1	1.6
Nakuru Park	Baharini7	847891	9966220	1830	1	0.5	0.1	1.6
Nakuru Park	Baharini 9	847942	9966202	1831	1	0.5	0.1	1.6
Nakuru Park	Baharini 1	847848	9966170	1828	1	0.5	0.1	1.6

Location	Site	Easting	Northing	Elevation (m)	Infiltration Condition Rating Continued			
					Land cover	Slope	Faults	I Factor Index
Nakuru	NrbRd4	844807	9968737	1885	0.1	0.5	1	1.6
Nakuru	Bontana	841369	9968114	1846	0.1	0.5	1	1.6
Nakuru	Londra	840666	9968098	1858	0.1	0.5	1	1.6
Nakuru	AGRI	841724	9969538	1875	0.1	0.5	1	1.6
Nakuru	KITI	845795	9970262	1908	0.1	0.5	1	1.6
Nakuru	CDN	845286	9968778	1872	0.1	0.5	1	1.6
Nakuru	NRBRd5	844809	9968748	1885	0.1	0.5	1	1.6
Dundori	Wamuyu	853441	9970807	1960	0.1	0.5	0.1	0.7
Dundori	Tabuga	853441	9971005	1992	0.1	0.5	0.1	0.7
Dundori	Njogu	853877	9970822	1972	0.1	0.5	0.1	0.7
Dundori	Njoroge	854290	9970076	1966	0.1	0.5	0.1	0.7
Dundori	Munui	854175	9970130	1970	0.1	0.5	0.1	0.7
Dundori	Nyanjor	853977	9969648	1958	0.1	0.5	0.1	0.7
Dundori	Nyoike	853288	9970026	1950	0.1	0.5	0.1	0.7
Dundori	Muhia's	852634	9971027	1956	0.1	0.5	0.1	0.7
Dundori	C.C.O	852277	9970147	1935	0.1	0.5	0.1	0.7
Njoro	Egert6a	825297	9958576	2308	0.5	0.5	0.1	1.1
Njoro	Egert6b	825297	9958576	2308	0.5	0.5	0.1	1.1
Njoro	Egert11	825297	9958576	2298	0.5	0.5	0.1	1.1
Njoro	Egert17	825448	9958558	2292	0.5	0.5	0.1	1.1

	Site	Easting	Northing	Elevation (m)	Infiltration Condition Rating Continued			
					Land cover	Slope	Faults	I Factor Index
	Egert3	825490	9958912	2304	0.5	0.5	0.1	1.1
	Egert2	825742	9959088	2278	0.5	0.5	0.1	1.1
	Egert12	827508	9958494	2250	0.5	0.5	0.1	1.1
	Egert15	824478	9959678	2274	0.5	0.5	0.1	1.1
	Egert1	826284	9958922	2267	0.5	0.5	0.1	1.1
	NjorCDF	827152	9963910	2210	0.5	0.5	0.1	1.1
	NjoroCC	827197	9962132	2160	0.5	0.5	0.1	1.1
	Ngosur	851020	9973206	1953	0.1	0.5	1	1.6
	Njoro1	824839	9958696	2307	0.5	0.5	0.1	1.1
	Njoro4	838452	9966320	1814	0.5	0.5	0.1	1.1
	NjoroB	825488	9958840	2219	0.5	0.5	0.1	1.1
	Njoro3	831312	9963989	2139	0.5	0.5	0.1	1.1
rk	Ingobr	836531	9963706	1940	1	0.5	0.1	1.6
rk	Mogon	836457	9964607	1941	1	0.5	0.1	1.6
rk	Kamasai	838719	9960797	1861	1	0.5	0.1	1.6
	NjoroBr	843340	9964386	1767	0.1	0.5	1	1.6
	NjoroLk	843882	9964138	1777	0.5	0.5	0.1	1.1
rk	Makalia	842972	9945556	1775	1	0.5	0.1	1.6
rk	Nderit	846924	9954526	1767	1	0.5	0.1	1.6
rk	Baharin	845958	9966558	1959	1	0.5	0.1	1.6
	Grenstd	853394	9962140	1926	0.1	0.5	0.1	0.7

Location	Site	Easting	Northing	Elevation (m)	Infiltration Condition Rating Continued			
					Land cover	Slope	Faults	I Factor Index
Makiki	Mfeedot	830008	9975572	2012	0.5	0.5	0.1	1.1
Makiki	Makiki1	831007	9976072	2012	0.5	0.5	0.1	1.1
Makiki	Makiki2	834299	9973014	2032	0.5	0.5	0.1	1.1
Nakuru	OliveIn	837910	9970320	1936	0.1	0.5	1	1.6
Nakuru	Lion HG	848693	9965544	1886	0.1	0.5	1	1.6
Nakuru	KPLC	849364	9966580	1881	0.1	0.5	1	1.6
Nakuru	Rasul	848696	9966368	1882	0.1	0.5	1	1.6
Bahati	BahtiHC	847851	9980794	2078	0.1	0.5	1	1.6
Nakuru	NkrTunn	840259	9966838	1812	0.1	0.5	1	1.6
Nakuru	Ngayoyi	843006	9945387	1852	0.1	0.5	1	1.6
Nakuru	BIDCO	839126	9968588	1875	0.1	0.5	1	1.6
Nakuru	Windml	841865	9950316	2442	0.1	0.5	1	1.6
Nakuru	Evrydy	839005	9968010	1875	0.1	0.5	1	1.6
Nakuru	Pyrthrm	840294	9970170	1875	0.1	0.5	1	1.6
Nakuru Park	Ronda	840029	9965047	1811	1	0.5	0.1	1.6
Nakuru Park	Ronda2	840029	9965047	1811	1	0.5	0.1	1.6
Bahati	Ngorik	859990	9966205	2251	0.1	0.5	1	1.6
Njoro	NjorBSc	827564	9963245	2174	0.5	0.5	0.1	1.1
Nakuru	NkrBSc	844676	9969076	2174	0.1	0.5	1	1.6
Bahati	Ngorika	862658	9965485	1999	0.1	0.5	1	1.6
Nakuru	Deflord	857735	9911307	1919	0.1	0.5	1	1.6
Njoro	Njoro	825488	9958840	2296	0.5	0.5	0.1	1.1
Njoro	Egert.	824839	9958696	2265	0.5	0.5	0.1	1.1

APPENDIX III

PI score characterization for the sample sites

Location	Site	Easting	Northing	Elevation (m)	P-Factor Value	I-factor Value	PI Score
Bahati	Kabatni	848942	9970879	1901	3	1.6	4.8
Nakuru Park	Baharini7	847891	9966220	1830	5	1.6	8
Nakuru Park	Baharini 9	847942	9966202	1831	5	1.6	8
Nakuru Park	Baharini 1	847848	9966170	1828	5	1.6	8
Nakuru Park	NrbRd6	844780	9968751	1885	5	0.7	3.5
Nakuru	NrbRd4	844807	9968737	1885	4	1.6	6.4
Nakuru	Bontana	841369	9968114	1846	4	1.6	6.4
Nakuru	Londra	840666	9968098	1858	4	1.6	6.4
Nakuru	AGRI	841724	9969538	1875	4	1.6	6.4
Nakuru	KITI	845795	9970262	1908	4	1.6	6.4
Nakuru	CDN	845286	9968778	1872	4	1.6	6.4
Nakuru	NRBRd5	844809	9968748	1885	4	1.6	6.4
Dundori	Wamuyu	853441	9970807	1960	3	0.7	2.1
Dundori	Tabuga	853441	9971005	1992	3	0.7	2.1
Dundori	Njogu	853877	9970822	1972	3	0.7	2.1
Dundori	Njoroge	854290	9970076	1966	3	0.7	2.1
Dundori	Munui	854175	9970130	1970	3	0.7	2.1
Dundori	Nyanjor	853977	9969648	1958	3	0.7	2.1
Dundori	Nyoike	853288	9970026	1950	3	0.7	2.1

Location	Site	Easting	Northing	Elevation (m)	P-Factor Value	I-factor Value	PI Score
Dundori	Muhia's	852634	9971027	1956	3	0.7	2.1
Dundori	C.C.O	852277	9970147	1935	3	0.7	2.1
Njoro	Egert6a	825297	9958576	2308	5	1.1	5.5
Njoro	Egert6b	825297	9958576	2308	5	1.1	5.5
Njoro	Egert11	825297	9958576	2298	5	1.1	5.5
Njoro	Egert17	825448	9958558	2292	5	1.1	5.5
Njoro	Egert3	825490	9958912	2304	5	1.1	5.5
Njoro	Egert2	825742	9959088	2278	5	1.1	5.5
Njoro	Egert12	827508	9958494	2250	5	1.1	5.5
Njoro	Egert15	824478	9959678	2274	5	1.1	5.5
Njoro	Egert1	826284	9958922	2267	5	1.1	5.5
Njoro	NjorCDF	827152	9963910	2210	5	1.1	5.5
Njoro	NjoroCC	827197	9962132	2160	5	1.1	5.5
Bahati	Ngosur	851020	9973206	1953	3	1.6	4.8
Dundori	Wany'ro	854623	9971528	2010	3	0.7	2.1
Dundori	Merern2	854823	9968817	1970	3	0.7	2.1
Bahati	Ngosur	853066	9977869	2100	3	1.6	4.8
Njoro	Njoro1	824839	9958696	2307	5	1.1	5.5
Njoro	Njoro4	838452	9966320	1814	5	1.1	5.5
Njoro	NjoroB	825488	9958840	2219	5	1.1	5.5
Njoro	Njoro3	831312	9963989	2139	5	1.1	5.5

Location	Site	Easting	Northing	Elevation (m)	P-Factor Value	I-factor Value	PI Score
Nakuru Park	Ingobr	836531	9963706	1940	5	1.6	8
Nakuru Park	Mogon	836457	9964607	1941	5	1.6	8
Nakuru Park	Kamasai	838719	9960797	1861	5	1.6	8
Nakuru	NjoroBr	843340	9964386	1767	4	1.6	6.4
Njoro	NjoroLk	843882	9964138	1777	5	1.1	5.5
Nakuru Park	Makalia	842972	9945556	1775	5	1.6	8
Nakuru Park	Nderit	846924	9954526	1767	5	1.6	8
Nakuru Park	Baharin	845958	9966558	1959	5	1.6	8
Dundori	Merern1	854287	9967785	1951	3	0.7	2.1
Dundori	Grenstd	853394	9962140	1926	3	0.7	2.1
Makiki	Mfeedot	830008	9975572	2012	5	1.1	5.5
Makiki	Makiki1	831007	9976072	2012	5	1.1	5.5
Makiki	Makiki2	834299	9973014	2032	5	1.1	5.5
Nakuru	Oliveln	837910	9970320	1936	4	1.6	6.4
Nakuru	Lion HG	848693	9965544	1886	4	1.6	6.4
Nakuru	KPLC	849364	9966580	1881	4	1.6	6.4
Nakuru	Rasul	848696	9966368	1882	4	1.6	6.4
Bahati	BahtiHC	847851	9980794	2078	3	1.6	4.8
Nakuru	NkrTunn	840259	9966838	1812	4	1.6	6.4
Nakuru	Ngayoyi	843006	9945387	1852	4	1.6	6.4
Nakuru	BIDCO	839126	9968588	1875	4	1.6	6.4

Location	Site	Easting	Northing	Elevation (m)	P-Factor Value	I-factor Value	PI Score
Nakuru	Windml	841865	9950316	2442	4	1.6	6.4
Nakuru	Evrydy	839005	9968010	1875	4	1.6	6.4
Nakuru	Pyrthrm	840294	9970170	1875	4	1.6	6.4
Nakuru Park	Ronda	840029	9965047	1811	5	1.6	8
Nakuru Park	Ronda2	840029	9965047	1811	5	1.6	8
Bahati	Ngorik	859990	9966205	2251	3	1.6	4.8
Njoro	NjorBSc	827564	9963245	2174	5	1.1	5.5