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Project on Assessment of Pollution Status and Vulnerability of Water Supply Aquifers in African Cities

Vulnerability and Pollution of Groundwater in the Kisauni Area, Mombasa, Kenya

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Executive Summary

The growing population along the coastal region as a result of natural population growth and in-migration is exerting increasing pressure on coastal resources. It is realised that the development of facilities and public services has failed to keep pace with the growing population and demand. This state of affairs prevails in the Mombasa District in general, and the Kisauni area in particular. The Kisauni area experiences inadequacies in the infrastructure and public services, notably water supply and waste management infrastructure. The largely unplanned high-density settlements and slums in Kisauni are among the most poorly served areas. This is manifested in the shortage of clean drinking water, leaving the inhabitants with groundwater to supplement their supply, or in most cases as the sole option.

An assessment of the intrinsic aquifer vulnerability using the DRASTIC model employing GIS analytical tools (ESRI's ArcView 3.2 and Spatial Analyst 2.0) indicated that the northern and south-eastern parts of Kisauni and the south-western part of the Mombasa Island are the most vulnerable to pollution. The groundwater stream flow in the Kisauni area, assessed using the modelling tool Modflow with Pmpath (Chiang & Kinzelbach, 1993), indicated that the dominant groundwater flow direction is towards the Mtwapa creek along the northern boundary and Tudor creek along the southern boundary of the study site and relatively less intense flow towards the Indian Ocean.

Monitoring data on physico-chemical characteristics showed that water obtained from abstraction facilities located in the limestone geological zone is brackish and unsuitable for drinking. Whereas, within the sand geological zone, groundwater of acceptable potable standard is obtainable. It was, however, realised that groundwater in particularly the high population density Kisauni areas has raised concentrations of nitrates, which was attributed to contamination from on-site waste disposal systems, dominated by pit latrines and septic tank / soak pit systems as the mode of sewage disposal. Other sources of groundwater contamination in the area are uncollected municipal refuse. Generally, nitrate/nitrite concentrations were elevated with concentrations of NO_3^{-1}/NO_2^{-1}-N varying from 0.4 to 44.4 mg l^{-1}. Relatively higher concentrations of nitrate/nitrite were recorded during the long rain season in June/July. The nitrate concentration levels, however, have not exceeded the 50 mg l^{-1} level set by WHO for potable water.

The Kisauni area is indicated as experiencing a high degree of groundwater contamination by microbial contaminants, especially in the high-density housing settlements, attributed to on-site sewage disposal methods dominated by pit latrines and septic tank / soak pit systems. The contamination levels are more severe during the rain season when aquifer recharge is enhanced. Direct intervention by the Mombasa City local authority in conjunction with the Ministry of Water & Irrigation to alleviate the situation has consisted of supplying chlorinating agents free of charge which helps to control outbreaks of water borne diseases such as cholera and typhoid.

INTRODUCTION

The rapid growth in population and urbanization in Mombasa City has exerted relentless pressure on resources and services such as, housing, water supply and sanitation, education and health facilities. The delivery of essential services in the city has failed to keep pace with the increased demand. The increased demand in housing has resulted in the mushrooming of unplanned settlements and slums most often in marginal areas of the district, with inadequate or lack of supply of water and sanitary services. Consequently, the inhabitants have had to increasingly rely on groundwater to supplement or as their sole source of potable water supply in most parts of Mombasa. However, groundwater in the area is under threat of pollution due to the utilization of on-site sewage management practices, dominated by pit latrines and septic tank-soak pit systems. The presence of mounds of uncollected domestic refuse is testimony to inadequate solid waste collection and disposal services, which pose a potential source of groundwater contamination through aquifer recharge during precipitation. The increasing abstraction of groundwater exacerbates the threat of deterioration of the water quality through saline water intrusion.

Waste management practices in Mombasa have been attributed with adverse impacts on public health. Incidences of water-borne diseases, especially cholera, dysentery, typhoid, diarrhoea, intestinal worms and skin and eye infections, have been associated with the use of groundwater contaminated as a result of inadequate sewage treatment and/or utilization of on-site sewage disposal methods. Thus, Mwaguni (2002) correlated the morbidity of water borne diseases with inadequate sewage treatment and disposal. This raises the need to address the problem of groundwater contamination with a view of monitoring the situation and formulating possible mitigation measures.

The Study Area

Mombasa District lies between latitudes 3° 80’ and 4° 10’ S and longitudes 39° 60’ and 39° 80’ E, with a total land mass of 229.6 km^2 and inshore waters covering 65 km^2. The administrative boundaries comprise the Island Division, Changamwe in the west, Kisauni in the north and Likoni Division in the south. The Island Division is the smallest and the most developed, while the three other sub-urban divisions are predominantly rural. The thrust of this study was the Kisauni area or Mombasa north mainland (Fig 1).

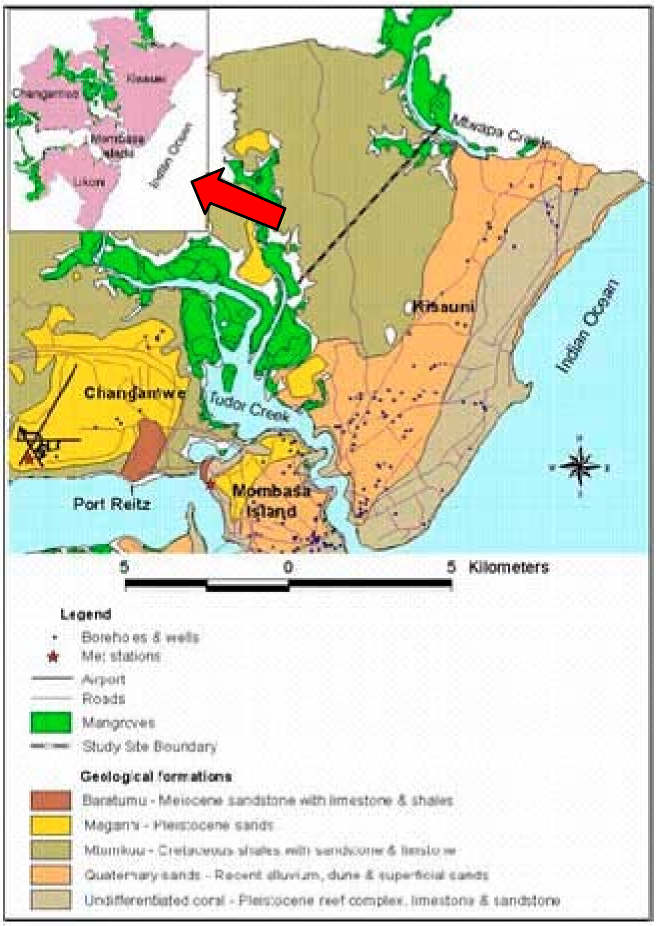

Figure 1: Map of Mombasa District showing the study area

Climate

Climatic condition variations in the district are attributed to SE Monsoon winds (blowing between April and September) and the NE Monsoons (October to March) and oceanic influence. The rains occur during the inter-monsoonal period, with the long rains starting from March to June, while the short rains occur from October to November/December. The mean annual rainfall within the period was 956 mm, peaking in May and October. The monthly mean rainfall and temperatures in the Mombasa district for the period 1999 – 2004 are presented in Fig. 2.

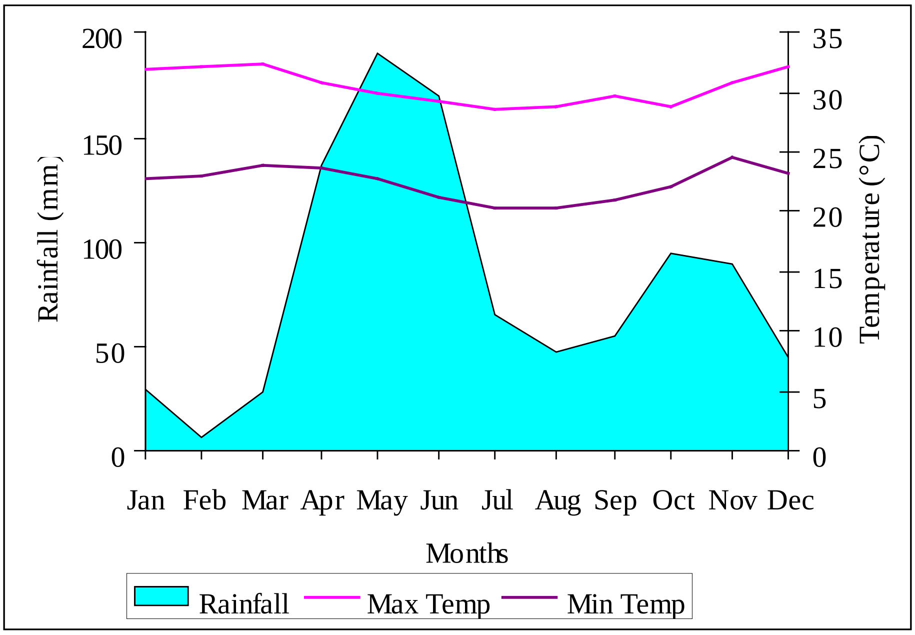

Figure 2: Average Rainfall, Maximum and Minimum Temperatures (1999 - 2004)

Topography and Geology

The Mombasa District is situated in coastal lowland with extensive flat areas rising gently from 8 meters above sea level to 100 meters above sea level in the west. It can be divided into three main physiographic belts, namely, the flat coastal plain, which is 6 kilometres wide, and includes the Island division, Kisauni on the north mainland and Mtongwe to the south. Next, are found the broken, severely dissected and eroded belt that consists of Jurassic shale overlain in places by residual sandy plateau found in Changamwe division. Finally, there is the undulating plateau of sandstone that is divided from the Jurassic belt by a scarp fault.

Nearer the sea, the land is composed of coral reef of Pleistocene Age that offers excellent drainage. The coral limestone and lagoonal deposit reach a thickness of 100 meters. Along the coastline are to be found beautiful beaches, which together with a variety of coastal resources and a rich biodiversity, has attracted tourists making Mombasa a favourite tourist destination.

Mombasa district has no permanent rivers, but due to the favourable geology of some parts of the district, the water table is high and the sinking of boreholes and wells has led to the increased supply of water to supplement the reticulated supply (Fig. 1).

Soil and Agroecology

The soil types are broadly associated with the geological formations along the physiographic zones in the district, as detailed by GOK Ministry of Agriculture (1988). Along the coastal lowlands, four soil types predominate.

1. On the raised reefs along the shore well-drained, shallow (< 10 cm) to moderately deep, loamy to sandy soils predominate.
2. On unconsolidated deposits in the quaternary sands zone (also referred to as Kilindini sands) are well drained moderately deep to deep, sandy clay loam to sandy clay, underlying 20 to 40 cm loamy medium sand.
3. On the Kilindini sands are also found areas with very deep soils of varying drainage conditions and colour, variable consistency, texture and salinity.
4. Also found on the Kilindini sands are well-drained very deep, dark red to strong brown, firm, sandy clay loam to sandy clay, underlying 30 to 60 cm medium sand to loamy sand soils.

On the coastal uplands, composed of the raised areas in Changamwe and western parts of Kisauni, 2 soil types are dominant

1. Soils developed on unconsolidated sandy deposits in the Magarini formation, composed of sandy to loamy soils. These are well drained, very deep, sandy clay loam to sandy clay, with a topsoil of fine sand to sandy loam.
2. Soils developed on shales composed of heavy textured soils constitute the relatively high agricultural potential area in the district. The soils are dominated by well drained to imperfectly drained, shallow to moderately deep, firm to very firm clay, and imperfectly drained deep, very firm clay, with a humic topsoil and a sodic deeper subsoil.

Most of the agricultural activities in the district occur in the mainland areas, i.e. Kisauni (north mainland), Likoni (south mainland) and Changamwe (west mainland). The low lying areas are dominated by the coconut-cassava (zone L3) and cashewnut-cassava (zone L4) agroecological zones (GOK Ministry of Agriculture 1988). Most of the Mombasa island area and parts of Kisauni and Likoni fall under the coconut-cassava zone. This zone is characterised by a medium to long cropping season and intermediate rains. The rest of the low lying areas in Kisauni and Likoni fall under the cashewnut-cassava zone, which is characterised by medium cropping season, followed by intermediate rains. Most of the raised Changamwe area falls under the cashewnut-cassava zone. The raised areas in Kisauni and parts of Changamwe, that mainly include the shale areas, fall under the lowland livestock-millet zone (zone L5). This zone is characterised by a short to medium cropping season and a second season with intermediate cropping.

Demography

According to the 1999 Population and Housing Census (GOK, 1999) the population of Mombasa District stood at 665,000 persons distributed in the four divisions of the District as indicated in Table 1.

Table 1: Population distribution in the Mombasa District

Administrative Division	Size: Area km^2	Population			% Population increase since last Census	Population density/ km^2 1999
		1979	1989	1999		
Island	14.1	136,140	127,720	146,334	14.57	10,379
Kisauni	109.7	79,995	153,324	249,861	63.00	2,278
Likoni	51.3	39,665	67,240	94,883	41.11	1,850
Changamwe	54.5	81,348	113,469	173,930	53.28	3,191
TOTAL	229.6	336,148	461,753	665,018	44.02	2,896

Source: GOK (1999, 1989 & 1979).

Mombasa district experienced a 44% increase in population between the census years of 1989 and 1999. The Kisauni area population grew by 63% in the same period. The high increase in population was attributed to natural growth and in-migration, mostly of the labour force from other parts of the country. The high population has proved to be a serious challenge in the provision of housing and essential services such as water, sanitation and health care.

Land use

A land use classification study (UNEP/FAO/PAP/CDA, 1999) indicated that only 31.2% of the total land area in Mombasa district was under residential settlements (Fig. 3). The direction of growth in human settlements is northwards, concentrated in Kisauni Division. This has entailed the crowding of many people in small areas with serious social implications. These unplanned crowded human settlements have the poorest sanitation and generally poor infrastructural facilities, resulting in a myriad of environmental problems

(Gatabaki-Kamau et al., 2000). In the period between 1978 and 1998, the land area for residential purposes increased by almost two and half times. Whereas, land area claimed for tourism activities increased threefold, land for commercial purposes doubled in the same period (UNEP/FAO/PAP/CDA, 1999).

The Kisauni Division has other significant socio-economic activities that occupy large parcels of land. For example, large beef and dairy farms, tourist hotels, Shimo La Tewa School and Prison and Bamburi Cement Factory, occupy large tracts of land. On the ground, this entails the crowding of many people in small land areas. This is manifested in the sprawling low cost, high density settlements of Kisauni Estate, Mlaleo, Barsheba, Mwandoni, Bakarani, Magogoni, Mishomoroni, Mtopanga, Shanzu and the squatter areas of Ziwa la Ngombe, Kisimani and the Bombolulu slums. Other informal settlements and slum areas include Matopeni (Kengeleni), Mnazi Mmoja, Kisumu Ndogo (Kongowea), Maweni (Kongowea), VOK, Mafisini, Kilimanjaro, Makobeni (Mtopanga), Mwembe Legeza, Utange Giriama, and Majaoni (Fig. 3).

Figure 3: Distribution of informal settlements in Mombasa District in 1997
(Source: Mwaguni 2002)

Industrial and Commercial Activities

The Bamburi Cement remains the single largest industry in the area and continues with its programs of rehabilitation of the abandoned coral limestone quarries. The rehabilitated areas have since been converted into nature parks doing businesses in eco-tourism and fish farming.

Another landmark feature for the economy of the area remains the Kongowea wholesale market, trading in all types of foodstuffs. Presently, the sale of second-hand shoes and clothes in the market peripheries has emerged to be a large business attracting a large population into the area. Despite the diversification of the businesses and therefore increase in human traffic, sewage management systems have not been upgraded to cope with the rising demand since the market was built. Presently, unpleasant odours at the market area are quite common due to uncollected putrefying garbage and poor sanitation. Therefore, sanitation remains a major issue of concern at the market.

Water Supply and Waste Management Practices

The Mombasa District heavily depends on water sources from outside the district for its potable needs. Its main sources of water supply are the Mzima Spring located about 200 km west, Baricho Water works located about 150 km north and Marere boreholes found about 40 km south of Mombasa mainly supplying the Likoni area. Generally, the whole Mombasa district has a daily water demand of 200,000 cubic meters of water against the available 130,000 cubic meters. There is therefore a water shortfall of 70, 000 cubic meters, about 35 % of the demand, which is met by tapping the groundwater sources (NWCPC, 2000). In fact, 13,286 out of the 183,540 households in the district are almost permanently dependant on groundwater. These are distributed as follows: - wells- 6,245 households, boreholes- 6,941 households (GOK, 1999). Thus, a significant proportion of the population relies on groundwater for their potable water needs.

The shortage of water in the Mombasa district and lack of funds to undertake capital investment projects has delayed extensions of water borne sewerage, forcing the residents to rely on on-site systems for sewage management. About 17% of the households in Mombasa, as well as hotels and most public buildings, have septic tank and soakage pit systems. Of the

13,000 septic tanks that are in use in Mombasa, most of them are found in high-income residential areas. A great majority of households in Mombasa, (about 70%) use pits latrines. Of the 34,000 latrines found in the district, 55% of them are found in Kisauni division where the study area is located. It is an officially sanctioned practice to dig pit latrines to reach the water table so that they do not fill-up in a short time. One housing estate in Kisauni discharges sewage and wastewater into an open area which has evolved into a wetland with poor capacity to treat the waste (Fig. 4). The lack of adequate services for solid waste collection and disposal has resulted in the building up of mounds of refuse in the high density housing settlements of Kisauni, posing a threat to public health (Fig. 5). On-site disposal of both solid and liquid waste and the lack of appropriate sewage treatment are major sources of pollution of groundwater due to human waste through aquifer recharge (Fig. 6).

Figure 4: Uncontrolled sewage disposal into a wetland in Kisauni

Figure 5: Uncollected refuse in a high-density unplanned housing settlement in Kisauni

Figure 6: A case of on-site waste management and groundwater abstraction in Kisauni – contamination of groundwater

Aims and Objectives

The aim of this study was to establish the pollution status of the water supply aquifer in Mombasa District, focusing on the Kisauni area, north mainland, with the following specific objectives.

- Analysis of the hydrogeological set-up of the area and preparation of a pollution vulnerability map.
- Preparation of a hydrographic model of the aquifer.
- Assessment of the pollution status of groundwater in Kisauni.

METHODOLOGY

Aquifer Vulnerability and Groundwater Flow

The intrinsic vulnerability to pollution of the water supply aquifer in, particularly, Kisauni was assessed using the DRASTIC model employing GIS analytical tools (ESRI's ArcView 3.2 and Spatial Analyst 2.0). The groundwater stream flow in the Kisauni area was assessed using the modelling tool Modflow with Pmpath (Chiang & Kinzelbach 1993).

Water Quality

The study area covers Kisauni from the northern boundary of Mombasa District along Mtwapa Creek to the Tudor creek in the south (Fig. 7). The predominant geological formations in the area comprise the pleistocene corals and limestone zone along the shorefront, the quaternary sands and cretaceous shales further west. Population settlements and housing developments are mostly concentrated in the coral and sand zones which form the primary water supply aquifer.

Most groundwater abstraction facilities in the area are wells, with some of the older facilities found in the coral zone being partially protected. Three transects were constructed arbitrarily, with Transects 1 and 2 approximately perpendicular to the shoreline and Transect 3 parallel to the shoreline (Fig. 7). Eventually, a total of 24 sampling points were identified composed of 4 boreholes and 20 wells as indicted in the figure.

Water samples were collected on 16 and 29 June, 13 July 2004 and 9-10 and 17 November 2004. The samples were stored in a cool-box with ice before analysis within 24 hours of sampling. Samples were analysed for physical and chemical parameters, namely pH, electrical conductivity (EC), salinity, total dissolved solids (TDS), total alkalinity, sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), chloride (Cl^-), total hardness, ammonia, nitrates and phosphates. Using the colorimetric methods described by Parsons *et al* (1984), the samples were analysed for Nitrite + Nitrate {(NO_2^- + NO_3^-)-N} and orthophosphate (PO_4^{3-}-P). All chemicals used in these analyses were of analytical grade and glassware acid-washed.

As indicators of microbial contamination of water, faecal coliforms and *E. coli* were enumerated in samples by the multiple tube method of the most probable number (MPN). The 5-tube 3-dilution technique was used for water samples (FAO 1979, UNEP/WHO/IAEA 1985). MacConkey broth was used to enumerate total coliforms at 37 ^oC incubation. Tubes found positive for total coliforms were used for inoculation of fresh tubes of MacConkey broth and incubated at 44 - 45^oC for faecal coliforms estimation. *E. coli* was biochemically determined by indole production using Kovacs reagent.

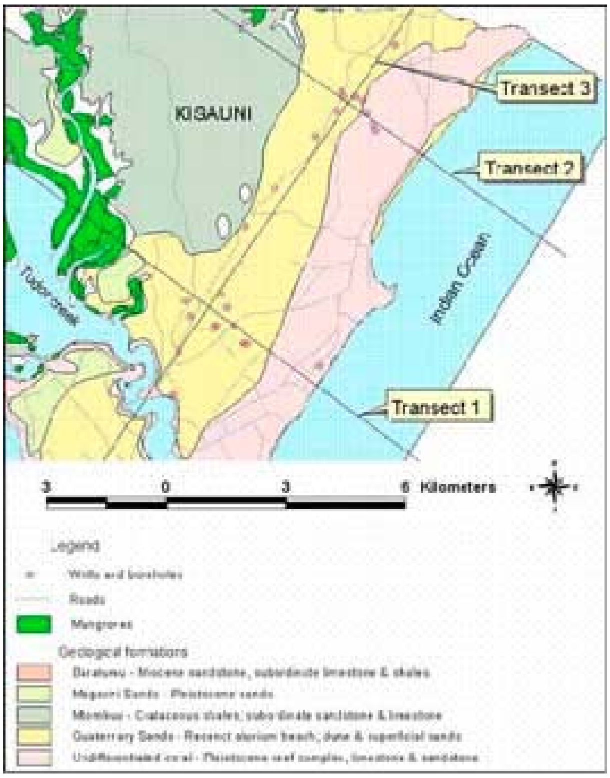

Figure 7: Transects of sampling points in Kisauni – Mombasa North Mainland

The scheme for the analytical procedure is presented in the flow diagram (Fig. 8).

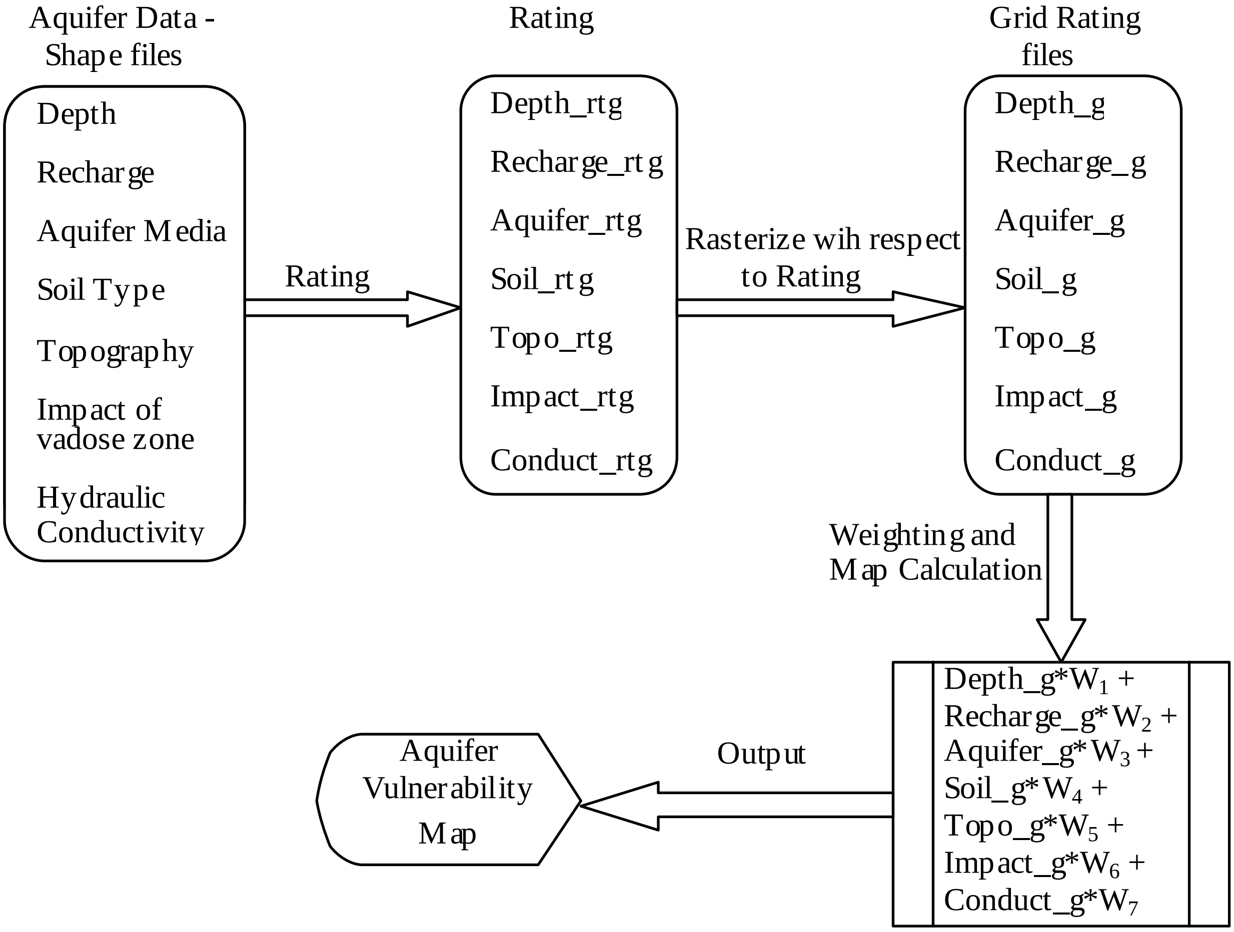

Figure 8: Schematic presentation of the analytical procedure

Depth to the Water Table

The piezometric data covered Kisauni and the Mombasa island area (Njue et al., 1994). The depth to the groundwater level ranged from 11.0 to 27.0 m. The interpolated depth to the aquifer indicates that the water table is shallowest in the south-eastern and towards the north of Kisauni and the south-western side of the island. This is reflected in the rating of the relative vulnerability of the aquifer due to depth (Table 2). These shallow areas are indicated as the most vulnerable to pollution originating from the surface and sub-surface with respect to the depth to the aquifer (Fig. 9).

Table 2: Rating of depth to the water table to aquifer vulnerability

Depth range (m)	Rating
11 -15	5
15 - 19	4
19 - 23	3
23 – 27	2

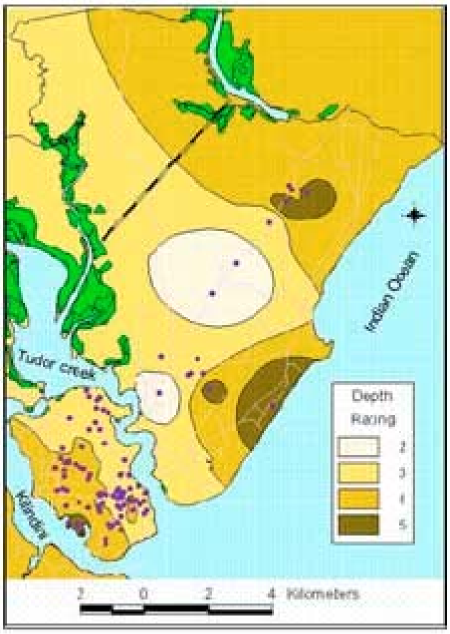

Figure 9: Rating of depth to the water table to aquifer vulnerability

Recharge of the Aquifer

The aquifer recharge was assessed by considering the mean annual rainfall distribution in the district and the relative permeability of the underlying geological formations. The following recharge rates were adopted for the 5 geological formations in the region (Table 3).

Table 3: Water recharge rates and geological formations in Mombasa

Geological Formations		Recharge Rate (%)
Name	Formation	
Baratumu	Miocene Sandstone with subordinate limestone and shales	3
Magarini sands	Pleistocene sands	8
Mtomkuu	Cretaceous shales with subordinate sandstones and limestone	2
Quaternary sands	Recent alluvium beach sands, dune sands and superficial sands	10
Undifferentiated corals	Pleistocene reef complex, limestone and sandstone	6

It is realised that the highest aquifer recharge occurs in the permeable quaternary sands zone, followed by the Magarini sands and coral / limestone zones (Fig. 4). The least recharge is experienced in the relatively impermeable Mtomkuu shales formation zone. The higher the recharge rate the more vulnerable the underlying aquifer. The intrinsic aquifer vulnerability due to recharge is indicated by the relative ratings as presented in Table 4 and displayed in Fig. 10.

Table 4: Rating of recharge to aquifer vulnerability

Recharge range (mm)	Rating
0 – 50	1
50 – 75	2
75 – 100	3

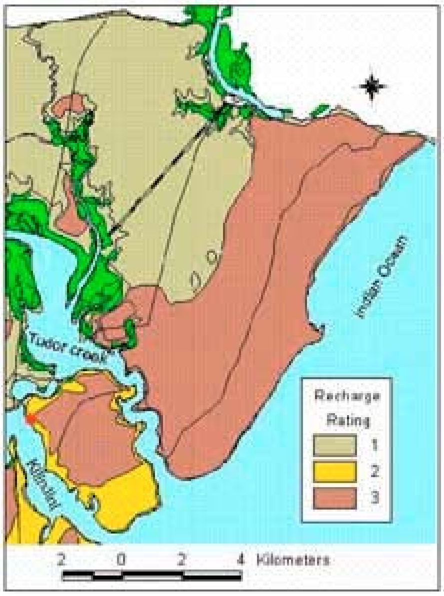

Figure 10: Rating for recharge to aquifer vulnerability in Mombasa

Aquifer Media

The aquifer media determines the attenuation capacity of the aquifer to introduced contaminants. This is influenced by among other factors, the grain and pore sizes of rock material. In the saturated zone contaminant attenuation is largely determined by dilution and natural die-off (in the case of microbial contamination). In the Mombasa District the aquifer media is broadly determined by the geological formations. In particular, in the coastal lowlands, the geological formations are reported to extend to depths of 100 m whereas the depth to the water level is as shallow as 11 m in Kisauni. The dominant aquifer media in the district include limestone, sandstone and shale. The ratings of the aquifer media to pollution vulnerability in the district is presented in Table 5 and Fig. 11. The results indicate that the unconfined aquifer on the island and in the low-lying areas in Kisauni are the most vulnerable.

Table 5: Rating of aquifer media to aquifer vulnerability

Aquifer media	Rating
Shale	2
Bedded sandstone, limestone and shell	6
Massive sandstone	6
Massive limestone	6
Sand and gravel	8
Karst limestone	10

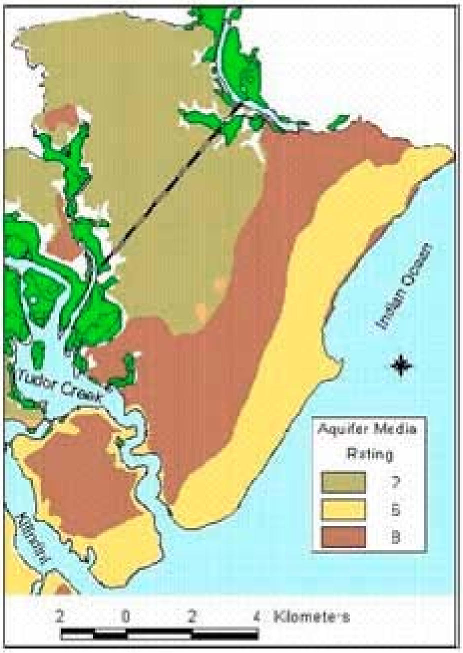

Figure 11: Ratings of aquifer media to aquifer vulnerability

Soil Media

The soil is the most biologically active layer and the first line of defence against contamination of groundwater, and contributes significantly to the attenuation of contaminants introduced on the surface. Such contaminants include nitrates and microbial organisms. The soil type, grain size and thickness play a limiting role in attenuation processes of contaminants, namely filtration, biodegradation, sorption and volatilisation. The rating of the soil media on aquifer vulnerability is presented in Table 6 and Fig. 12. It is evident that the limestone zones with thin soils are the most vulnerable to pollution of the aquifer.

Table 6: Rating of soil media to aquifer vulnerability

Soil media	Rating
Thin or absent	10
Sand	9
Sandy loam	6
Loam	5
Clay loam	3
Non-shrinking or non-agregated clay	1

Figure 12: Rating of soil media to aquifer vulnerability in Mombasa

Topography

The low-lying coastal zone is characterised by an even terrain, with cliffs sloping to the shoreline at certain places. Steep slopes are found in the raised areas towards the western part of Kisauni, especially along the *Nguu Tatu* ridge with peaks rising over 120 m. The slope influences run-off. The steeper the slope the faster the runoff and reduced potential for contamination of groundwater. The rating of the slope to vulnerability of the aquifer is presented in Table 7 and Fig. 13.

Table 7: Rating of the topography to aquifer vulnerability

Topography range (%)	Rating
< 2	10
2 – 6	9
6 – 12	5
12 – 18	3
18 – 90	1

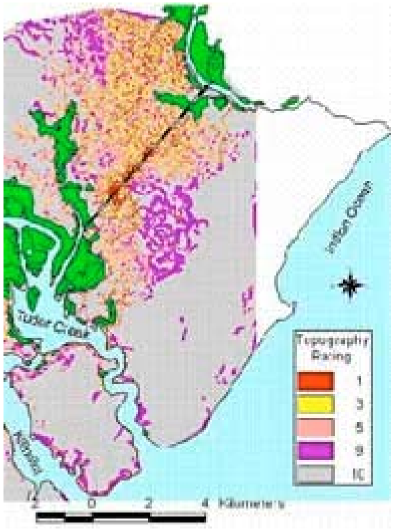

Figure 13: Rating of slope to aquifer vulnerability in Mombasa

Impact of the Vadose Zone

The unsaturated layer or vadose zone has an impact on the attenuation of the contaminants in the aquifer. The material in the vadose zone in the unconfined aquifer in the district is closely related to the geological formations. Thus the vadose zone is dominated by the limestone, sandstone, sand and shale. The ratings adopted for the vadose zone material to vulnerability of the aquifer is presented in Table 8 and Fig. 14.

Table 8: Rating for the impact of the vadose zone on aquifer vulnerability

Vadose zone media	Rating
Shale	3
Limestone	6
Sandstone	6
Bedded limestone, sandstone, shale	6
Karst limestone	10

Figure 14: Rating of impact of the vadose zone to aquifer vulnerability

Hydraulic Conductivity

The hydraulic conductivity determines the rate at which a contaminant moves, which depends on the inter-connectivity of voids within the aquifer. The higher the conductivity, the higher the vulnerability of the aquifer to pollution. The hydraulic conductivity of the aquifer in the district was estimated with reference to literature, because of the paucity of data from pumping tests. The ratings for hydraulic conductivity are presented in Table 10 and a spatial display in Fig. 15.

Table 9: Rating of the hydraulic conductivity to aquifer vulnerability

Range (m day^{-1})	Rating
< 4	1
4 – 12	2
12 – 29	4
29 – 41	6

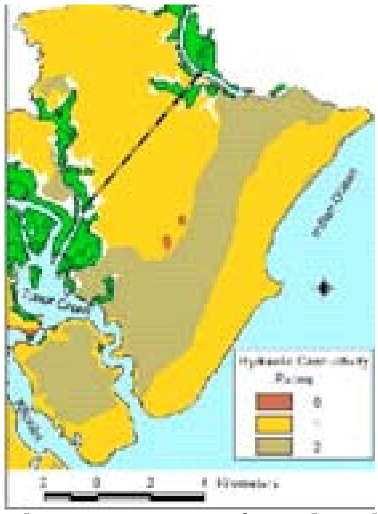

Figure 15: Rating of hydraulic conductivity on aquifer vulnerability in Mombasa

Aquifer Vulnerability

The DRASTIC model factors namely depth, recharge, aquifer media, soil media, topography, impact of the vadose zone and hydraulic conductivity, were weighted (Table 10) and added. The resultant aquifer vulnerability map primarily for Kisauni and the Mombasa Island is presented in Fig. 16.

Table 10: Weights for DRASTIC factors

Factor	Weight
Depth to water table	5
Aquifer Recharge	4
Aquifer media	3
Soil media	2
Topography	1
Impact of vadose zone	5
Hydraulic Conductivity	3

Figure 16: Vulnerability to pollution of water supply aquifer

The results of the assessment of the vulnerability of the water supply aquifers indicate that the northern and south-eastern parts of Kisauni and the south-western part of the Mombasa Island are the most vulnerable to pollution.

Groundwater Flow

The groundwater stream flow in the Kisauni area was assessed using the modelling tool Modflow with Pmpath (Chiang & Kinzelbach, 1993). The model boundaries were determined by considering physiological and hydrogeological features in the area. The model was bounded in the east by the Indian Ocean, in the north and south by the Mtwapa creek and Tudor Creek, respectively, and in the west by the topographic features composed of a ridge approximately running north-south and westwards with three peaks rising to about 120 m being prominent, locally known as *Nguu Tatu*. Beyond the ridge the land drops landscaping into undulating hills and valleys rising gently westwards. Thus, the ridge was considered to form a natural boundary in the west of the low-lying coastal area towards the ocean (Fig. 17). It is the coastal lowland which holds the water supply aquifers in the quaternary sands and Pleistocene coral reefs where housing settlements are concentrated in and massive abstraction of groundwater being carried out.

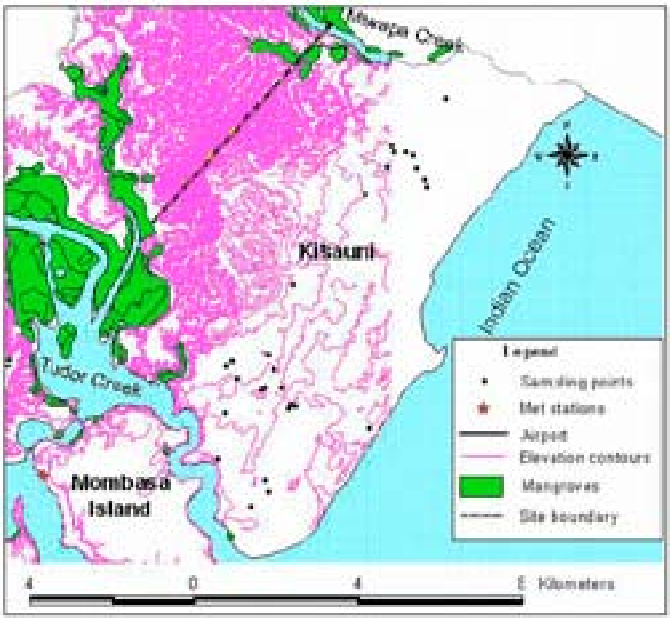

Figure 17: Map of the Kisauni study site

The model was developed under steady state conditions with the relevant parameters inputted into the model consisting of the following

- Initial hydraulic head – actual heads for specific wells under dynamic conditions were inputted with the rest of the area remaining at zero.
- Aquifer topography – the top of the aquifer was kept at 30 m and bottom topography kept at -100 m.
- Horizontal hydraulic conductivity was kept at 2.31E-5 m s^{-1} (Fig. 15)
- Porosity was kept at 0.25
- Aquifer recharge flux – there were two recharge zones in the area with quaternary sand zone bearing the highest recharge rate at 6.7E-09 m s^{-1} and the coral reefs and shale areas in the west with 7.93E-10 m s^{-1}(Fig. 10).

The output of the Modflow with Pmpath is as presented in Fig. 18.

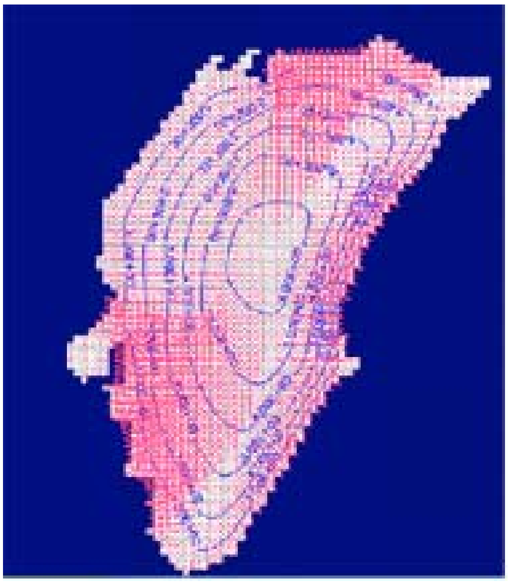

Figure 18: Groundwater flow model in Kisauni by Modflow

The model indicates that in the Kisauni area the dominant groundwater flow direction is towards the Mtwapa creek along the northern boundary and Tudor creek along the southern boundary of the study site and relatively less intense flow towards the Indian Ocean (Fig. 10) It is noted that the sources of freshwater to the Mtwapa and Tudor mangrove fringed creeks consist of small rivers or seasonal streams discharging at the top of the creeks. Thus groundwater flow contributes significantly in maintaining the mangrove habitats especially during the dry season when surface discharges are low.

GROUNDWATER QUALITY

Physical and Chemical Parameters

Presented in Fig. 19 are the variations of EC, salinity, TDS, total alkalinity and pH in groundwater along the 3 transects. The results generally show an increase in EC and corresponding salinity and TDS along Transects 1 and 2 as the sampling points approach the sea. Thus the highest value of EC was indicated in samples from the eastern most sampling point along Transect 1 in the coral and limestone geological zone. Along Transect 3 an elevation of EC, salinity and TDS was indicated in sampling points approaching the Tudor creek in the southern and Mtwapa creek in the northern boundary of the study area.

Variations of the major ions Na, K, Mg, Ca and chloride and total hardness in groundwater are shown in Fig. 20. Chloride content showed an increase towards the sea as indicated in Transects 1 and 2. This is reflected by the general increase of Na ions as sampling points approach the sea. Along Transect 1, relatively high concentrations of Mg and Ca ions (compared to Na) result in raised levels of water hardness. Along Transect 3 a rise in chloride ions is indicated in the northern most sampling point (towards Mtwapa creek). A peak in hardness is indicated at point 8, which is in the vicinity of point 2 along Transect 1.

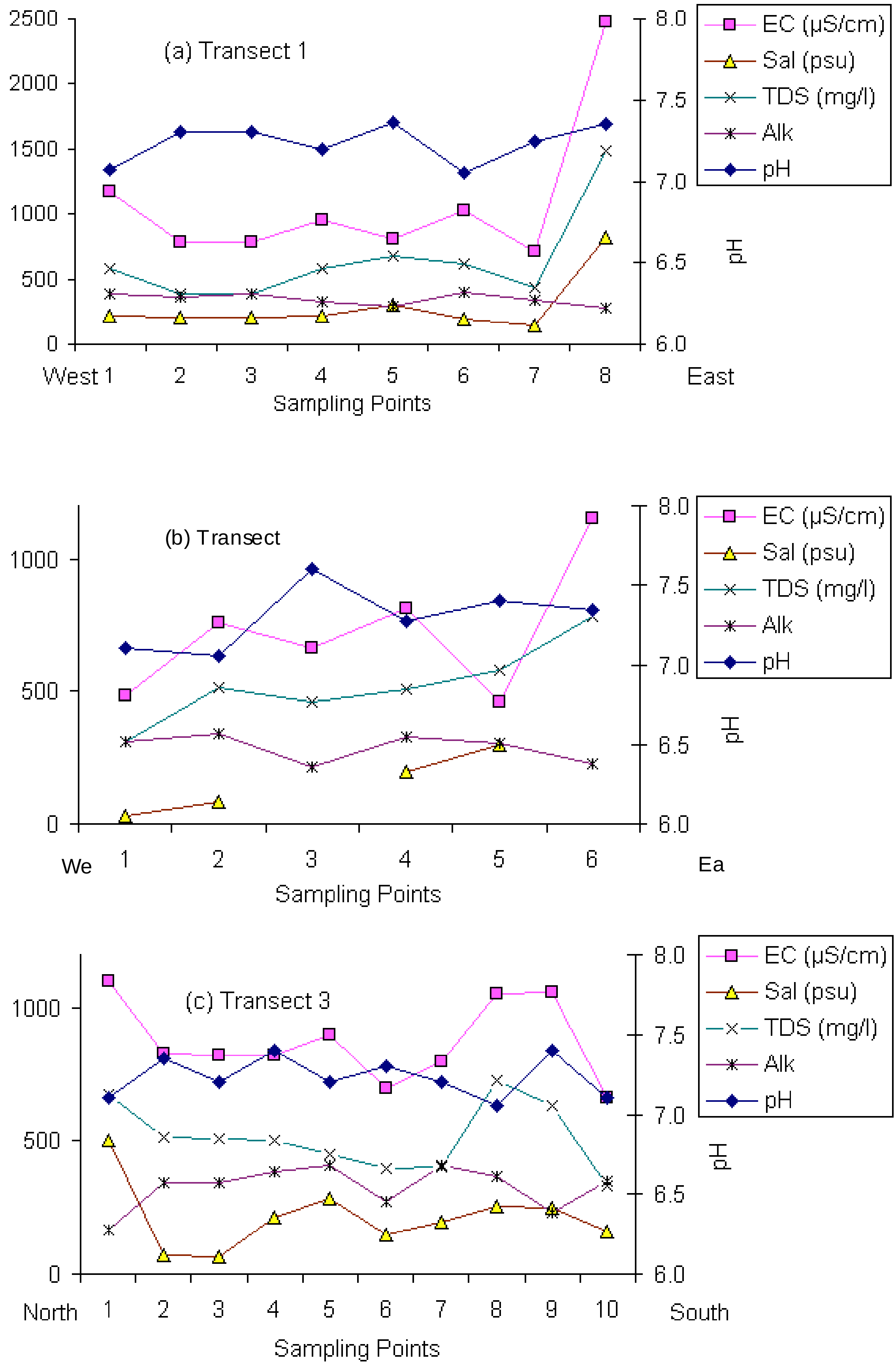

Fig. 2: Variations of Physiochemical Parameters in Groundwater in Kisauni Mombasa in June 2004 along (a) Transect 1 (b) Transect 2 (c) Transect 3

Figure 19: Variations of physiochemical parameters in groundwater in Kisauni Mombasa in June 2004 along (a) Transect 1 (b) Transect 2 (c) Transect 3

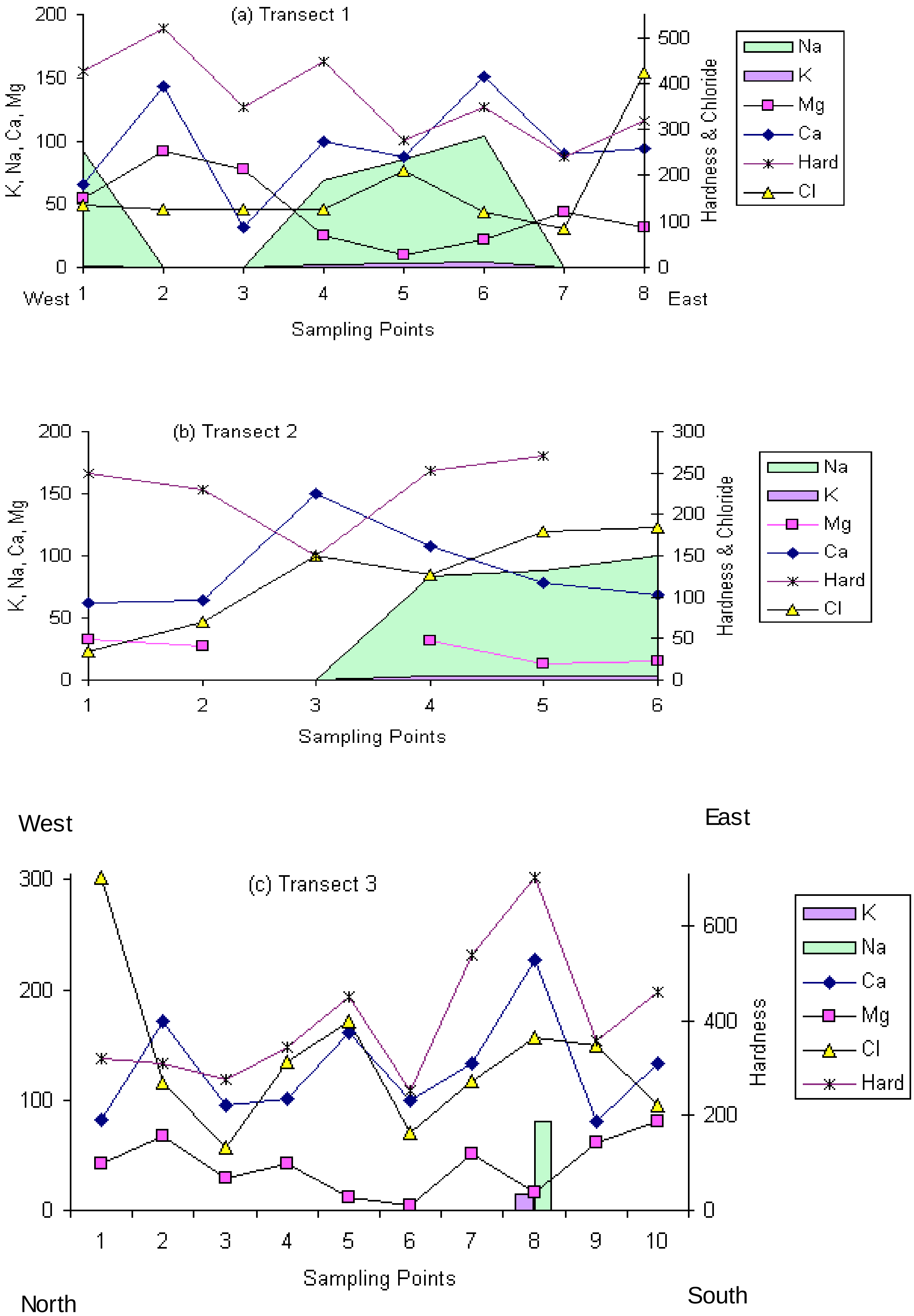

Fig. 3: Variations of K, Na, Ca, Mg, chloride and hardness in Groundwater in Kisauni Mombasa - (a) Transect 1 (b) Transect 2 (c) Transect 3 (Concentrations in mg l^{-1})

Figure 20: Variations of K, Na, Ca, Mg, chloride and hardness in groundwater in Kisauni Mombasa (a) Transect 1 (b) Transect 2 (c) Transect 3

Concentrations in $\mu g\ l^{-1}$

The distribution of nitrates+nitrites in groundwater in the Kisauni area during the long-rains season in June/July and the short-rains in November are presented by simple surface models in Fig. 21 and 22. Generally, nitrate/nitrite concentrations were elevated in groundwater from all the sampling points. Concentrations of NO_3^{-1}/NO_2^{-1}-N varied from 0.4 to 44.4 mg l^{-1}. Relatively higher concentrations of nitrate/nitrite were recorded in June/July ranging from 2.1 to 44.4 mg l^{-1} (Fig. 21). The concentrations of the nutrients were lower in November ranging from 0.4 to 19.6 mg l^{-1} (Fig. 22).

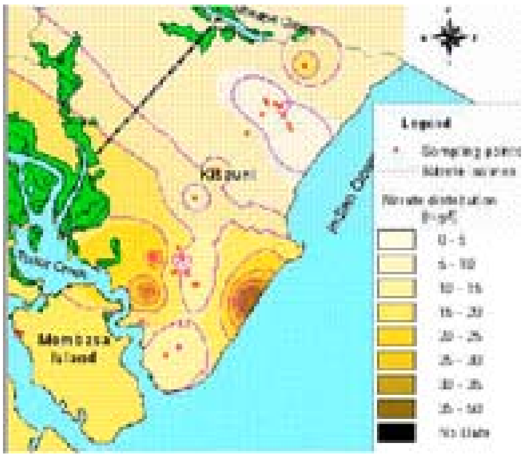

Figure 21: Nitrate concentrations in Kisauni in June/July 2004

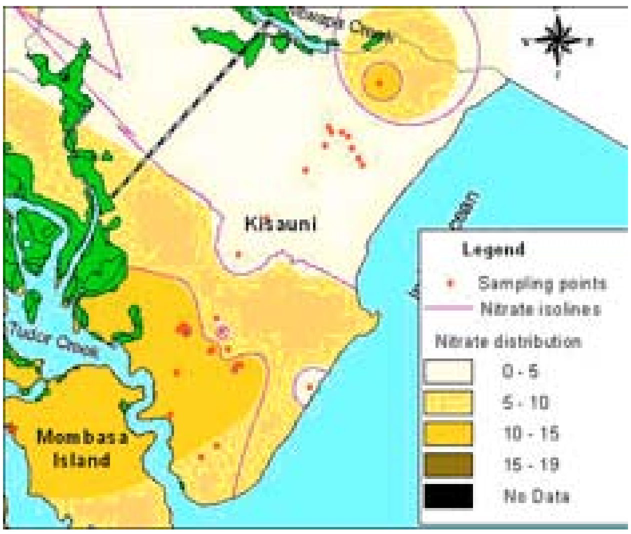

Figure 22: Groundwater nitrate concentrations in Kisauni in November 2004

The results indicated relatively higher nitrate/nitrite concentrations occurring in the southern parts of Kisauni towards the Tudor creek and along the Indian Ocean. The area towards the Tudor creek is occupied by high density housing settlements, mostly unplanned, where the majority of the inhabitants use pit latrines for sewage management and disposal. Towards the Indian Ocean shores tourist beach hotels and low density housing estates dominate which mostly use septic tanks and soakage pits for sewage management. On the other hand the northern parts with relatively low nitrate/nitrite concentrations have less dense housing settlements. However, a hot spot exists adjacent to the Mtwapa creek in the north representing the Shimo la Tewa Prison. The distribution of the nutrients is approximately reflected by the groundwater flow model (Fig. 17). Thus the contamination tends to move and concentrate towards the Tudor and Mtwapa creeks and the Indian Ocean. However, the concentrations of nitrate/nitrite encountered were generally within the WHO recommended potability limit of 50 mg l^{-1} (Lawrence et al. 2001).

Microbial Contamination

An indication of the contamination of groundwater with potentially harmful microbial organisms is given in Fig. 23. Out of 12 facilities sampled (5 boreholes and 7 wells) only 2 wells and 1 borehole produced water of acceptable potable quality in June 2004. Analysis of the water quality in July gave an indication of an improved situation. Thus all 3 wells and 2 boreholes sampled produced water of acceptable potability. It is noted that June was a relatively wet period, whereas July was essentially dry. Thus, the dry conditions in July probably lowered the extent of contamination of the groundwater through recharge. In addition, it was noted that in some wells, chlorine balls had been suspended into the water to effect disinfection, which could have contributed to the drastic reduction in potentially harmful microorganisms. The water quality situation was worse in November, as all 25 boreholes and wells sampled were contaminated with unacceptable levels of Faecal coliform and *E. coli* (Fig. 24). The presence of *E. coli* indicated that the primary source of contamination is human waste as a result of-site disposal of domestic sewage. These findings are comparable to data obtained from the Government of Kenya Ministry of Water Resources Development and Management (MWRDM) including measurements carried out in July 2003 in the present study which indicated that most of the wells and boreholes examined produced poor quality water with levels of microbial contamination exceeding the acceptable standards. Thus only one out of 16 wells sampled gave water of acceptable quality, and none of the 5 boreholes samples met the standards. In comparison Mwaguni (2002) found less than 10 % of the groundwater facilities examined produced water of acceptable standard.

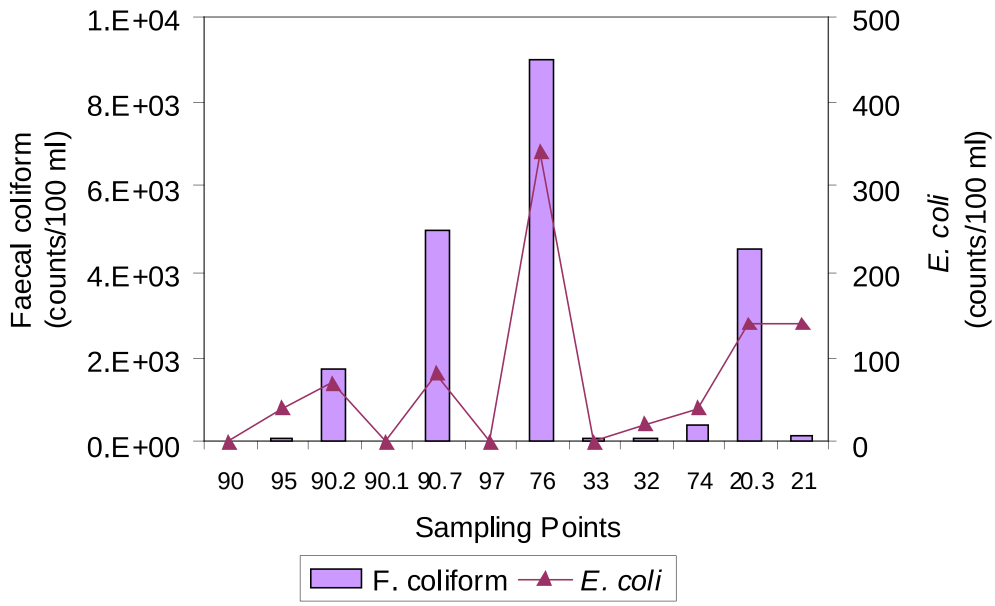

Figure 23: Microbial contamination in Kisauni groundwater – June 2004

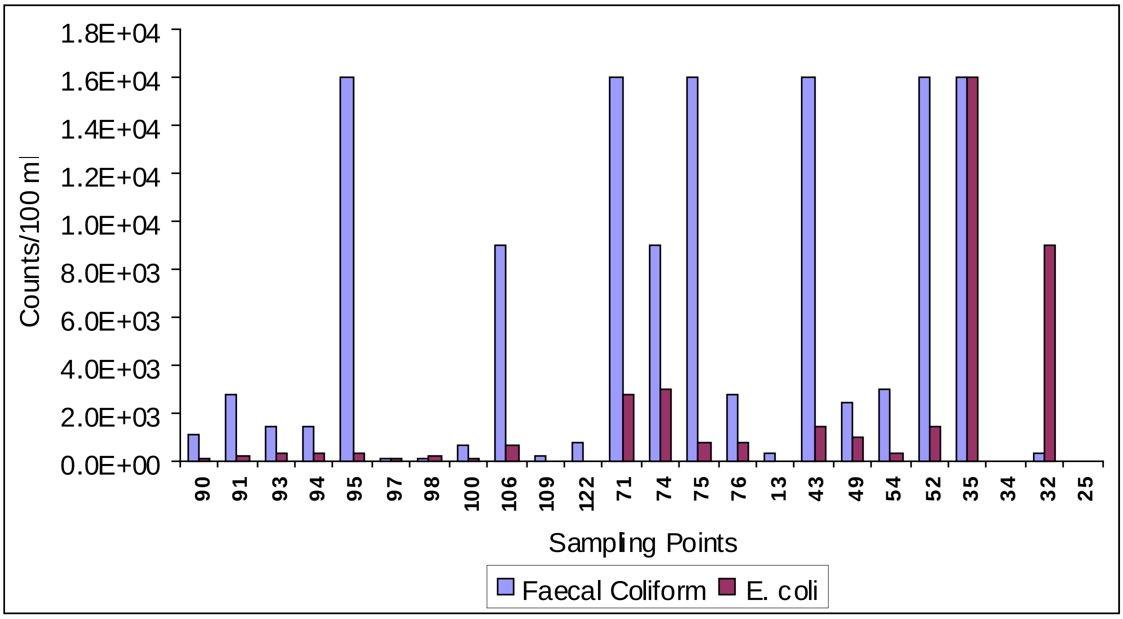

Figure 24: Microbial contamination in Kisauni groundwater – November 2004

CONCLUSION

The output of the DRASTIC model indicates that the water supply aquifer in the northern and south-eastern parts of Kisauni and the south-western part of the Mombasa Island are the most vulnerable to pollution. Application of the Modflow and Pmpath models indicate that in the Kisauni area the dominant groundwater flow direction is towards the Mtwapa creek along the northern boundary and Tudor creek along the southern boundary of the study site and relatively less intense flow towards the Indian Ocean (Fig. 18). The groundwater flow gives an indication of the most probable direction of flow of contamination which is useful information for strategies at groundwater protection.

The study has provided information on the general water quality in Kisauni with reference to the physico-chemical characteristics. It is generally the case that water obtained from abstraction facilities located in the limestone geological zone is brackish and unsuitable for drinking. Whereas, within the sand geological zone, groundwater of acceptable potable standard is obtainable. The study does not reveal sufficient evidence of saline water intrusion into the aquifer. It is, however, realised that groundwater in particularly the high population density Kisauni areas has raised concentrations of nitrates, which is an indication of contamination from on-site waste disposal systems, dominated by pit latrines and septic tank / soak pit systems as the mode of sewage disposal. Other sources of groundwater contamination in the area are uncollected municipal refuse. The nitrate concentration levels, however, have not exceeded the 50 mg l^{-1} level set by WHO for potable water.

The Kisauni area is indicated as experiencing a high degree of groundwater contamination by microbial contaminants, especially in the high-density housing settlements. This is primarily attributed to the sewage disposal method dominated by pit latrines and septic tank / soak pit systems. The contamination levels are more severe during the rain season when aquifer recharge is enhanced. The Mombasa City local authority in conjunction with the MWRDM have put in place measures to ensure the availability of contamination-free water to the inhabitants by providing chlorinating agents free of charge especially during the wet season. This direct intervention by the concerned authorities helps to control outbreaks of water borne diseases such as cholera and typhoid.

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