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Vulnerability and pollution of groundwater in Kisauni, Mombasa, Kenya

D. Munga, S. Mwangi & H. Ong'anda
Kenya Marine & Fisheries Research Institute, Mombasa, Kenya

J.U. Kitheka
UNEP-GEF WIO-LaB Project Office, Nairobi, Kenya

S.M. Mwaguni & F. Mdoe
Coast Development Authority, Mombasa, Kenya

J. Barongo
University of Nairobi, Department of Geology, Nairobi, Kenya

H.S. Massa
Provincial Water Office, Ministry of Water and Irrigation, Mombasa, Kenya

G. Opello
Department of Government Chemist, Mombasa, Kenya

ABSTRACT: Rapid urbanisation in the Mombasa District, and in particular the Kisauni area, has increased the demand for essential services, notably water supply and waste management infrastructure. This is manifested in inadequate clean drinking water from the reticulated supply, leaving the inhabitants with groundwater to supplement their resources, or in most cases as the sole option. An assessment of the intrinsic aquifer vulnerability to contamination was carried out by applying the DRASTIC model coupled with GIS analytical tools. Monitoring data on physico-chemical characteristics showed raised concentrations of nitrates in groundwater, in particular, in the more densely populated Kisauni areas, attributed to contamination from on-site sanitation systems dominated by pit latrines and septic tank-soak pit systems and uncollected municipal refuse. Concentrations of NO_3^{-1}/NO_2^{-1}-N ranged from 0.4 to 44.4 mg l^{-1}, with an indication of seasonal variations. About 50% and 70% of the water samples tested in June/July and November, respectively, did not exceed the 10 mg l^{-1} NO_3^{-1}/NO_2^{-1}-N guideline level set for potable water by WHO. 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 sanitation. The contamination levels are more severe during the rainy season, when aquifer recharge is high. A suggested strategy for intervention includes the control of pollution sources, education and awareness creation, and the implementation of existing laws and regulations to protect and manage groundwater resources.

1 INTRODUCTION

The rapid growth of the population in Mombasa City has exerted relentless pressure on limited resources and services such as housing, water supply and sanitation, education and health facilities. The increased demand in housing has resulted in mushrooming unplanned settlements and slums, with inadequate or lack of water supply and sanitation services. Consequently, inhabitants have had to increasingly rely on groundwater to supplement their sources, or as the sole source of

Groundwater Pollution in Africa (ed. Xu, Y.:Usher, B.) 2006

Table 19.1. Out-patient morbidity annual averages in Mombasa District, 1998–2000.

Disease	Island	Kisauni	Changamwe	Likoni	Total	%
Diarrhoea	1846	2019	1714	157	5736	5.1
Malaria	12,091	14,931	11,380	1456	39,858	35.5
Worms	1082	1089	713	72	2955	2.6
Eye inf.	822	517	367	51	1758	1.6
Skin inf.	3530	4642	3664	506	12,343	11.0
Others	17,905	16,141	14,071	1457	49,574	44.2

Source: Mwaguni, (2002).

potable water supply in most parts of the city. However, groundwater in the area is under threat of contamination due to the utilisation of on-site sanitation facilities, dominated by pit latrines and septic tank-soak pit systems. Inadequate solid waste collection and disposal services have resulted in mounds of uncollected domestic refuse that are sources of groundwater contamination through leaching. With Mombasa being a coastal city, the increasingly uncontrolled abstraction of groundwater may eventually reverse the natural hydraulic gradient and cause seawater encroachment.

In formulating the national water policy and management strategy, it was recognised that the major causes of morbidity are due to diseases or conditions arising from the low level of safe drinking water, lack of hygienic sanitation and poor environmental conditions (GOK, 2002). Mwaguni (2002) documented that over 50 per cent of all reported diseases in Mombasa from 1998–2000 were water-borne and associated with inadequate wastewater management (Table 19.1). This raises the need to address the problem of groundwater contamination with the view of monitoring the situation and formulating possible mitigation measures.

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

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

It was envisaged that the study would reveal information on the vulnerability of groundwater and provide an indication of the pollution status of this key resource in the area. The vulnerability assessment is expected to highlight the critical areas and anthropogenic activities that contribute most to groundwater pollution and thus provide a knowledge base for taking appropriate action to protect the resource. The information will be useful in raising the awareness of decision makers and the public on the vulnerability of groundwater and their responsibilities for protecting the resource.

1.1 *Description of the study area*

The 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 the Likoni Division in the south. The Island Division is the smallest and most developed, while the three other suburban divisions are predominantly rural. The thrust of this study was the Kisauni area, or Mombasa north mainland (Fig. 19.1).

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 in the period from 1999 to 2004 was 956 mm, peaking in May and October.

The Mombasa district is situated on the coastal lowland with extensive flat areas rising gently from 8 m above sea level to 100 m above sea level in the west. There are three main physiographic belts,

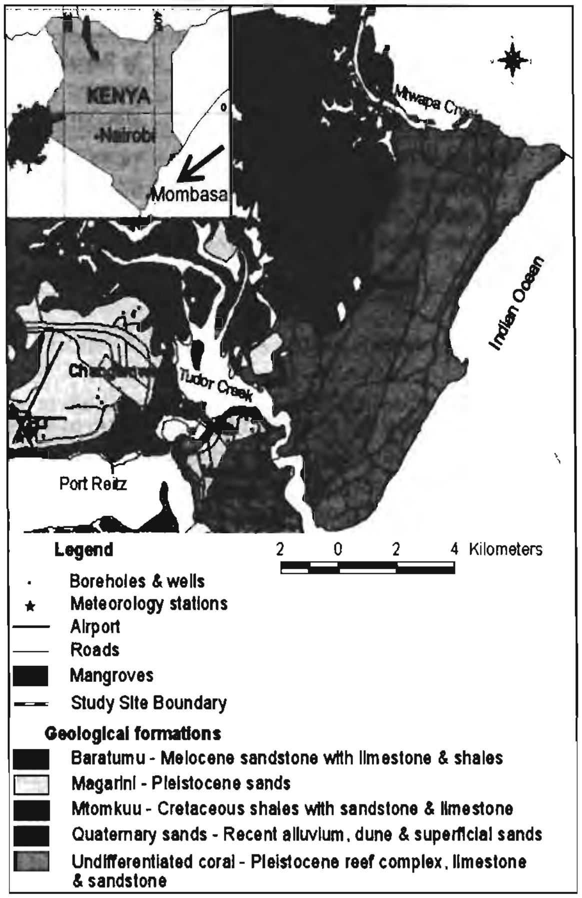

Figure 19.1. Map of the study site.

namely the flat coastal plain, which is 6 km wide, including the Island division, Kisauni on the north mainland and Likoni to the south. After this occurs the broken, severely dissected and eroded belt consisting of Jurassic shale overlain in places by residual sandy plateau found in the Changamwe division. Finally, there is the undulating plateau of sandstone that is divided from the Jurassic belt by a scarp fault. Closer to the sea, the land is composed of coral reef of Pleistocene age that offers excellent drainage (Fig. 19.1). The coral limestone and lagoonal deposit reach a thickness of 100 m.

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. Overlying the raised reefs along the shore, well-drained, shallow (<10 cm) to moderately deep loamy to sandy soils predominate. The unconsolidated deposits in the quaternary sand zone are well drained moderately deep to deep sandy clay loam to sandy clay, underlying 20 to 40 cm loamy medium sand. On the quaternary sands there are also areas with very deep soils of varying drainage conditions and colour, variable consistency, texture and salinity. Also found on the quaternary 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, consisting of the raised areas in Changamwe and the western parts of Kisauni, two soil types are dominant. Sandy to loamy soils developed on unconsolidated sandy deposits in the Magarini formation consists of well drained, very deep, sandy clay loam to sandy clay, with a topsoil of fine sand to sandy loam. Heavy textured soils developed on shales dominated by

Table 19.2. Population distribution in the Mombasa district.

Administrative division	Size: Area km²	Population 1979	Population 1989	Population 1999	% Population increase since last census	Population density/ km² 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*

* Average values.
Source: GOK (1999, 1989 & 1979), Mwaguni (2002).

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.

The Mombasa district has no permanent rivers, and the unconfined shallow aquifer on the island and coastal lowland areas of Kisauni and Likoni mostly depend on local recharge primarily through precipitation. Thus the sinking of boreholes and wells for the abstraction of groundwater to supplement the reticulated supply of fresh water has targeted the shallow unconfined aquifer (Fig. 19.1).

1.2 *Population and land use*

From the 1999 Population and Housing Census (GOK, 1999), the population of the Mombasa district stood at 665,000 persons distributed in the four divisions of the district as indicated in Table 19.2.

The rapid increase in population in the period 1979 to 1999 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.

A land-use classification study (UNEP/FAO/PAP/CDA, 1999) indicated that only 31.2% of the total land area in the Mombasa district fell under residential settlements. The direction of growth in human settlements is northwards, concentrated in the Kisauni division. This has resulted in the rapid growth of unplanned crowded settlements with very poor sanitation and generally poor infrastructural facilities (Gatabaki-Kamau *et al.*, 2000). Other significant socio-economic activities include beef and dairy farms, tourist hotels, the Shimo La Tewa School and Government Prison, the Kongowea wholesale market and Bamburi Cement Factory, which occupy large tracts of land.

1.3 *Water supply and waste management practices*

The main sources of freshwater supply for the Mombasa district are the Mzima Springs, located about 200 km west, the Baricho Water works, located about 150 km north and the Marere Springs and Tiwi Boreholes found about 40 km and 20 km, respectively, south of Mombasa, mainly supplying the Likoni area. The daily water demand for the district is approximately 200,000 m^3 against the available supply of 130,000 m^3. The water supply deficit of 70,000 m^3, about 35% of the demand, is met by exploiting groundwater sources (NWCPC, 2000). The shortfall in the water supply is further aggravated by the diminished capacity of the old and leaking reticulated supply network. With the current rapid increase in the urban population, the water supply deficit is expected to increase, thereby increasing the dependence on groundwater.

The shortage of water in Mombasa and lack of funds to undertake capital investment projects have constrained extensions of water-borne sewerage, compelling the residents to rely on on-site systems for sewage management. About 17% of households, as well as hotels and most public buildings, have septic tank and soakage pit systems. Most of the 13,000 septic tanks in use are found in high-income residential areas. A great majority of households (about 70%) use pit latrines.

Of the 34,000 latrines in the district, 55% are found in the Kisauni division, where the study area is located. It is a common practice to dig pit latrines to the water table to avoid filling up the pit in a short time. One housing estate in Kisauni discharges sewage and wastewater into an open area, which has evolved into a wetland with a poor capacity to treat the waste. The lack of adequate services for solid waste collection and disposal has resulted in a build-up of mounds of refuse in the high density housing settlements of Kisauni, posing a threat to public health. Less than 50% of the solid waste generated is collected and finally disposed of at a crude or uncontrolled dumpsite to the west of the Nguu Tatu hills in Kisauni. 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.

2 GROUNDWATER FLOW CONDITIONS

The groundwater flow in the Kisauni area was assessed using the numerical model MODFLOW (Version 5.3.0) with PMPATH (Version 6.1.0) (Chiang & Kinzelbach, 1993; Pollock, 1988, 1989). 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 and Tudor Creek, respectively. Towards the west of Kisauni the land rises to form a ridge with three prominent peaks at over 120 m, locally known as the *Nguu Tatu* Hills. Beyond the ridge the land drops into undulating hills and valleys, rising gradually westwards. This physiographic feature, that is the *Nguu Tatu* Ridge, was considered a natural hydrologic boundary on the western side of Kisauni (Fig. 19.1). It is in the coastal lowland where housing settlements are concentrated and massive abstraction of groundwater is carried out from the aquifers in the quaternary sands and Pleistocene coral reefs.

The parameters used for the model simulation consisted of the topography, areal net groundwater recharge, and aquifer properties including hydraulic conductivity and thickness. The model was developed under steady-state conditions, with the relevant parameters input into the model, consisting of the following:

- Initial hydraulic head – actual heads for specific wells under dynamic conditions were input 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 averaged at 2.31E−5 m s^{-1}.
- Aquifer recharge flux – there were two recharge zones in the area with the quaternary sand zone bearing the highest recharge rate at 6.7E−9 m s^{-1} and the coral reefs and shale areas in the west at 7.93E−10 m s^{-1}.

The output of the MODFLOW with PMPATH is presented in Figure 19.2.

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 eastwards towards the Indian Ocean (Fig. 19.2). The groundwater flow contributes significantly to maintaining the mangrove habitats, especially during the dry season when surface discharges are low. The model broadly agrees with the findings of Kitheka (1996), who reported a significant contribution of fresh water into the Nyali Beach Lagoon through groundwater flow (estimated groundwater flow of 186E+4 m^3 day^{-1} or about 2% of the total water volume in the lagoon) along the Kisauni shoreline.

3 AQUIFER VULNERABILITY

The intrinsic vulnerability to pollution of the water supply aquifer in, Kisauni particularly was assessed using the DRASTIC empirical model (Aller *et al.*, 1985, 1987) coupled with GIS analytical tools (ESRI's ArcView 3.2 and Spatial Analyst 2.0) (ESRI, 1996a, b). The DRASTIC factors, namely Depth

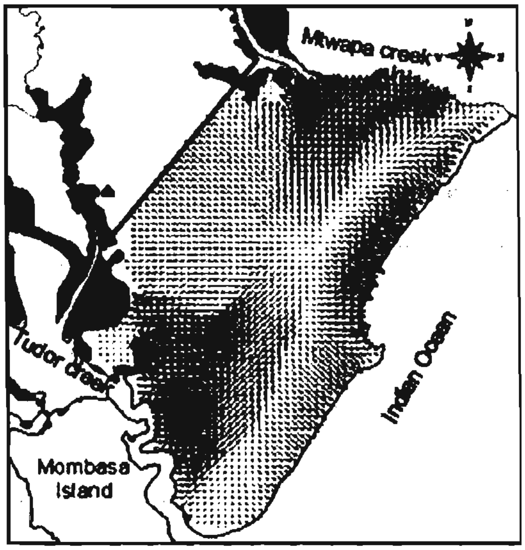

Figure 19.2. Groundwater flow in Kisauni.

to the water table (**D**), net **R**echarge (**R**), **A**quifer media (**A**), **S**oil media (**S**), **T**opography (**T**), **I**mpact of the vadose zone (**I**) and hydraulic **C**onductivity (**C**), were assigned a rating according to their influence on the pollution of groundwater by a contaminant introduced on the surface or subsurface. Typical ratings range from 1 to 10. The DRASTIC factors were assigned weights ranging from 1 to 5 relative to their significance in influencing groundwater contamination. The groundwater vulnerability to pollution is expressed by the DRASTIC Index (DI), which is the sum of the products of the ratings and weights of each factor. The higher the value of DI, the more vulnerable the area is to groundwater pollution. Thus DI can be represented by the following expression:

$$\mathrm{DI} = \mathrm{D_rD_w} + \mathrm{R_rR_w} + \mathrm{A_rA_w} + \mathrm{S_rS_w} + \mathrm{T_rT_w} + \mathrm{I_rI_w} + \mathrm{C_rC_w}$$

where the subscripts r and w denote rating and corresponding weight of the factor. The range of values of DI were then converted into qualitative values of low, moderate and high vulnerability. The GIS tools (ArcView 3.2 and Spatial Analyst 2.0) allow the computation of DRASTIC Indices, overlaying the factor DI values spatially and providing a spatial display of the intrinsic vulnerability of the area. The scheme for the analytical procedure, coupling the DRASTIC model with the GIS tools, is presented in the flow diagram (Fig. 19.3).

3.1 *Depth to the water table*

The piezometric data covered the Kisauni and 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. 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 water table.

3.2 *Recharge of the aquifer*

The aquifer recharge was assessed by considering the mean annual rainfall distribution in the district (956 mm p.a.) and the relative permeability of the underlying geological formations. The following recharge rates were adopted for the five geological formations in the region (Table 19.3).

The higher the recharge rate, the more vulnerable the underlying aquifer.

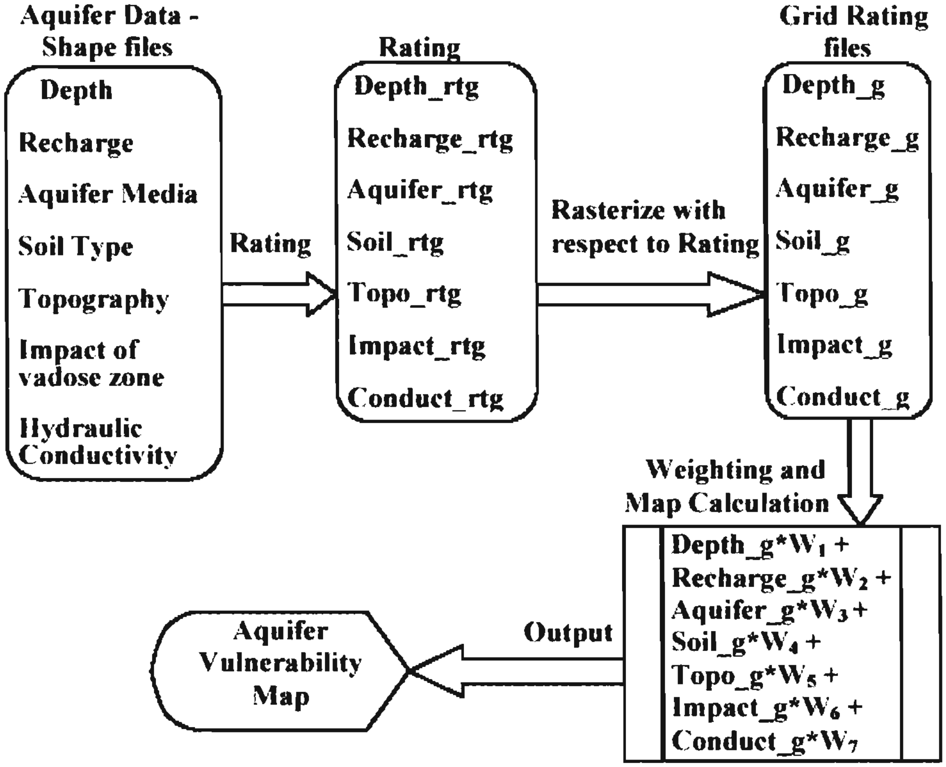

Figure 19.3. Schematic presentation of the analytical procedure.

Table 19.3. Water recharge rates and geological formations in Mombasa.

Geological formations			
Name	Formation	Recharge rate (%)	Recharge (mm p.a.)
Baratumu	Miocene sandstone with subordinate limestone and shales	3	28.7
Magarini sands	Pleistocene sands	8	76.5
Mtomkuu	Cretaceous shales with subordinate sandstones and limestone	2	19.1
Quaternary sands	Recent alluvium beach sands, dune sands and superficial sands	10	95.6
Undifferentiated corals	Pleistocene reef complex, limestone and sandstone	6	57.4

3.3 *Aquifer media*

The aquifer media determine its attenuation capacity to contaminants, 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 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

Table 19.4. 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

Table 19.5. Rating of the hydraulic conductivity to aquifer vulnerability.

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

vulnerability in the district is presented in Table 19.4. The results indicate that the unconfined aquifer on the island and in the low-lying areas in Kisauni are the most vulnerable.

3.4 *Soil media*

The soil is the most biologically active layer and the first line of defense against groundwater contamination. It contributes significantly to the attenuation of contaminants introduced on the surface. The soil type, grain size and thickness play a limiting role in attenuation processes of contaminants, namely filtration, biodegradation, sorption and volatilisation.

3.5 *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 run-off and reduced potential for groundwater contamination.

3.6 *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 is closely related to the geological formations. Thus, the zone is dominated by limestone, sandstone, sand and shale.

3.7 *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 19.5.

3.8 *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 19.6) and overlayed.

Table 19.6. 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

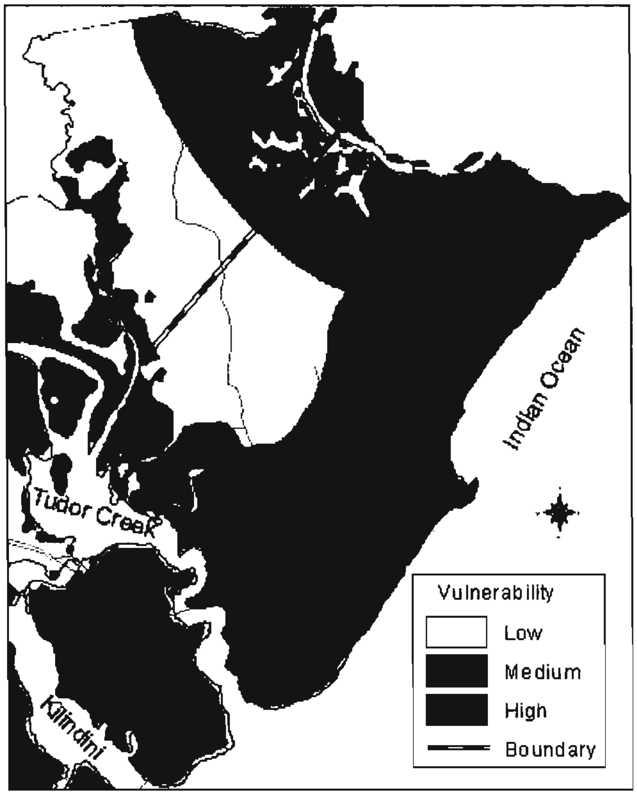

Figure 19.4. Vulnerability to pollution of water supply aquifer.

The resultant aquifer vulnerability map, primarily for Kisauni and the Mombasa Island, is presented in Figure 19.4.

The results of the vulnerability assessment 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.

4 ASSESSMENT OF GROUNDWATER QUALITY AND POLLUTION STATUS

4.1 *Methodology*

The study area covers Kisauni from the northern boundary of the Mombasa district along Mtwapa Creek to the Tudor Creek in the south (Fig. 19.5). The predominant geological formations in the

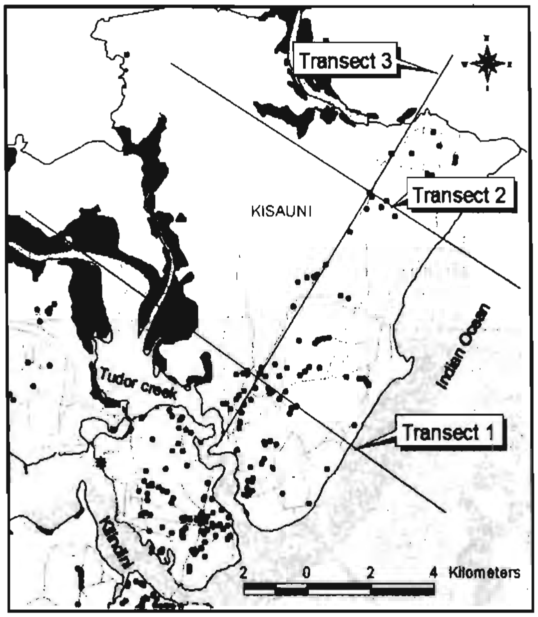

Figure 19.5. Transects of sampling points in Kisauni.

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. 19.6). Eventually, a total of 24 sampling points were identified, comprising 4 boreholes and 20 wells.

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 coolbox 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 $\{(NO_2^- + NO_3^-)\text{-N}\}$ 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°C incubation. Tubes found positive for total coliforms were used for the inoculation of fresh tubes of MacConkey broth and incubated at 44 – 45°C for faecal coliform estimation. *E. coli* was biochemically determined by indole production using the Kovacs reagent.

4.2 *Physical and chemical parameters*

Presented in Figure 19.6 are the variations of EC, salinity, TDS, total alkalinity and pH in groundwater along the three 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

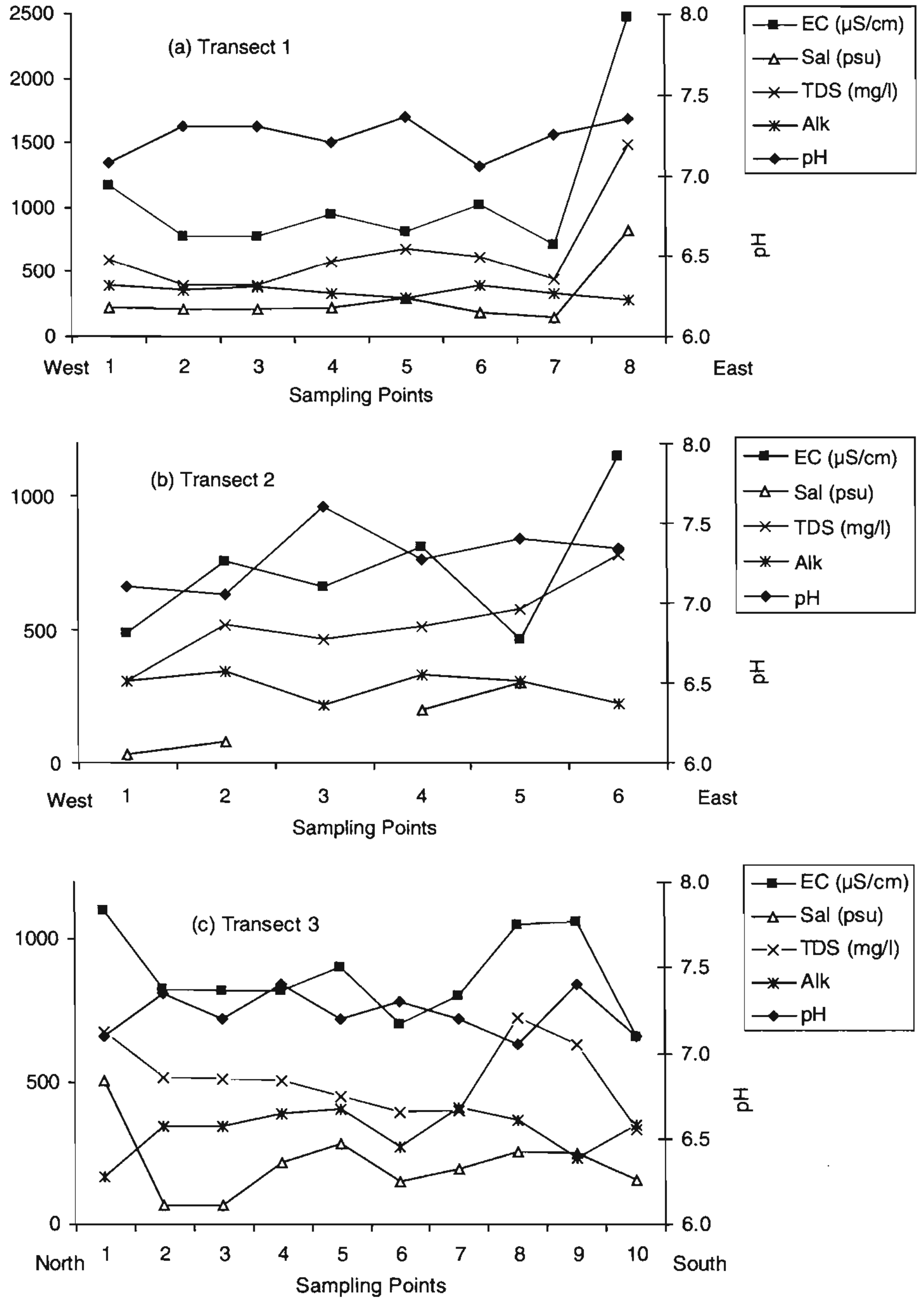

Figure 19.6. Variations of physiochemical parameters in groundwater in Kisauni, Mombasa in June 2004 along (a) Transect 1 (b) Transect 2 (c) Transect 3.

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 were investigated. 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.

The concentrations of ammonia and inorganic nitrates/nitrites and phosphates in groundwater in Kisauni during the rainy season in June/July and the short rains in November are presented in Table 19.7. Whereas phosphate levels were moderate, ammonia and nitrate/nitrite concentrations were elevated in groundwater from most of the sampling points.

Relatively higher concentrations of nitrate/nitrite were recorded in June/July (range 2.1 to 44.4 mg $\mathrm{l^{-1}}$) than in November (range 0.4 to 19.6 mg $\mathrm{l^{-1}}$). The concentrations were significantly

Table 19.7. Concentrations of ammonia-N ($\mathrm{mg\,l^{-1}}$), nitrate + nitrite-N ($\mathrm{mg\,l^{-1}}$) and phosphate-P ($\mathrm{\mu g\,l^{-1}}$) in groundwater in Kisauni.

					Ammonia		Nitrate + Nitrite		Phosphate	
ID No.	Name	B/W*	East	South	Jul	Nov	Jul	Nov	Jul	Nov
20.1	Coast Hauliers	W	39.688	4.050	0.8		13.0		97.6	
20.2	Coast Hauliers B4	W	39.692	4.047	1.0		9.8		2.8	
20.3	Swafaa Mosque	W	39.697	4.028	2.7	2.0	13.1	8.2	33.8	12.0
21	Umoja Residence	W	39.681	4.040	1.1		14.6		114.1	
26	Snake Valley	B	39.683	4.030	1.2	0.9	36.4	10.6	51.5	8.8
14	Voyager Hotel	B	39.714	4.033	7.6	0.5	44.4	3.0	100.9	75.4
72	Freretown-Nyamu	W	39.698	4.028	0.6	1.3	10.9	18.5	61.0	55.0
74	Freretown-Jared	W	39.691	4.024	1.4	0.0	16.4	14.5	112.9	227.1
75	Freretown-Mterere	W	39.691	4.025	0.4	3.7	18.6	9.1	26.5	
76	Kisimani stage	W	39.695	4.024	5.4	0.0	8.1	5.7	76.3	151.5
32	Islam Ali 1	B	39.684	4.020	0.5		43.3		41.2	
33	Islam Ali 2	B	39.684	4.019	0.4	4.9	21.8	19.6	80.5	34.1
34	Abdalla Adam	B	39.683	4.019	1.3	1.7	12.7	8.0	78.6	
36	Masjid Bidalla	W	39.681	4.020		0.4		14.8		
106	Mgongeni Mosque	W	39.693	4.020	8.1	0.3	3.4	2.9	47.9	35.8
109	Mwandoni Katisha	B	39.692	4.017	0.7	2.6	19.4	5.1	33.6	4.5
122	Masjid Hussein	W	39.698	4.002	2.4	2.9	7.4	2.4	155.2	22.0
100	Masjid Noor	W	39.704	3.993	0.1	0.2	11.9	4.5	90.2	67.4
98	Utange R.C.	W	39.713	3.981	0.1	0.1	9.4	0.9	31.2	109.7
91	Utange-Anwaralli	W	39.719	3.971	2.1	0.6	4.1	0.4	56.8	7.3
90	Shimo Annex	B	39.731	3.961	0.1	3.1	19.9	13.4	21.7	
90.1	Masjid Dar al Kam	W	39.726	3.979	1.2		3.0		10.7	
90.2	Utange Pendua Viungani	W	39.725	3.976	2.1		4.7		16.7	
90.7	Masjid Radhaa	W	39.727	3.980	1.0		2.3		90.4	
97	Utange Pri Sch	W	39.718	3.976	0.0	0.4	2.5	0.8	28.8	25.0
94	Utange Pendua 1	W	39.724	3.973	0.7	1.9	6.6	4.6	39.0	31.5
95	Utange Pendua 2	W	39.722	3.972	0.5	0.0	3.1	0.9	276.7	166.5
93	Utange-Maingi	W	39.720	3.972	0.6	0.6	2.1	1.2	86.6	27.2
				Mean	1.6	1.3	13.4	7.1	69.0	62.4
				Max	8.1	4.9	44.4	19.6	276.7	227.1
				Min	0.0	0.0	2.1	0.4	2.8	4.5
				Std	2.1	1.4	11.7	6.0	55.7	64.7

* Borehole (B) or well (W)2.

different ($t = 2.43$, $p = 0.05$, $df = 41$). The results indicated relatively higher nitrate/nitrite concentrations occurring in the southern parts of Kisauni towards the Tudor Creek and along the Indian Ocean. It is instructive that some of the nitrate/nitrite hotspots were located in the medium vulnerability areas towards the Tudor Creek. This indicates that there was/were other factor(s) that influenced the contamination levels and this was attributed to proximate sources of the contaminant in the form of housing settlements. 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 nutrients is approximately reflected by the groundwater flow model (Fig. 19.6). Thus, the contamination tends to move and concentrate towards the Tudor and Mtwapa Creeks and the Indian Ocean. The results are comparable to findings by Mwashote *et al.* (1996), who reported nitrate/nitrite concentrations in groundwater from one borehole and ten wells in the Kisauni ranging from 1.8 to 37.9 mg l^{-1}. In the present study, the nitrate concentration levels encountered in about 50% and 70% of the water samples tested in June/July and November, respectively, were within the WHO recommended potability limit of 10 mg l^{-1} NO_3^{-1}/NO_2^{-1}-N (Lawrence *et al.*, 2001).

5 MICROBIAL CONTAMINATION

An indication of the contamination of groundwater with potentially harmful microbial organisms is given in Figure 19.7. Out of thirteen facilities sampled (five boreholes and seven wells) only two wells and one borehole produced water of acceptable potable quality in June 2004. The national (Kenya Bureau of Standards) and WHO drinking water quality standards are faecal coliform counts = nil and *E. coli* counts = nil. Analysis of the water quality in July gave an indication of an improved situation. Thus all three wells and two 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

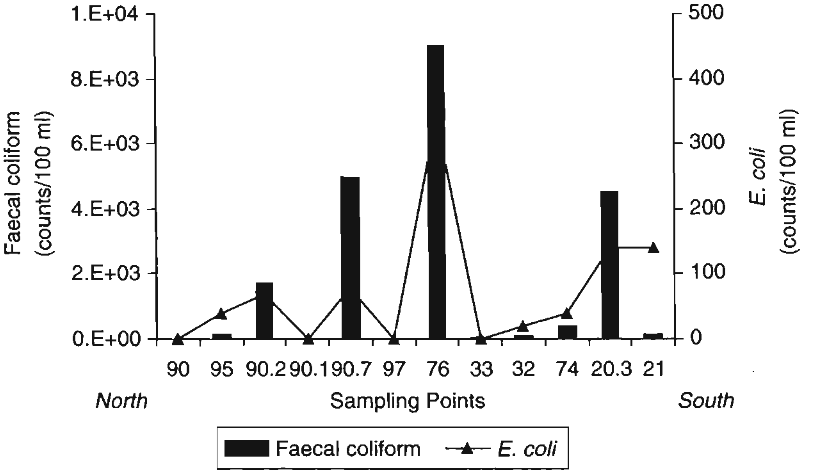

Figure 19.7. Microbial contamination in Kisauni groundwater – June 2004.

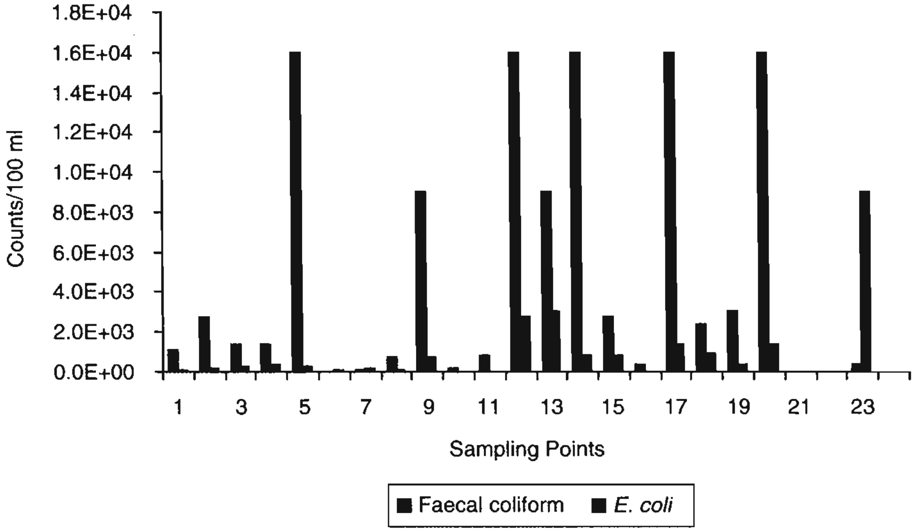

Figure 19.8. Microbial contamination in Kisauni groundwater – November 2004.

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. 19.8). The presence of *E. coli* indicated that the primary source of contamination is human waste as a result of on-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 sixteen wells sampled gave water of acceptable quality, and none of the five boreholes samples met the standards. In comparison, Mwashote *et al.* (1996) and Mwaguni (2002) found 8% and less than 10%, respectively, of the groundwater facilities examined produced water of acceptable standard.

6 STRATEGY FOR GROUNDWATER PROTECTION IN KISAUNI

It is evident that groundwater in Kisauni is contaminated and the water quality is expected to deteriorate further in view of the rising demands for fresh water with increasing urbanisation. The primary source of groundwater pollution in the area is on-site waste management and disposal practices. During precipitation, contaminants are leached from waste matter deposited on the ground surface or sub-surface, such as uncollected municipal refuse and uncontrolled dumpsites. Direct recharge also occurs from soakage pits and wet pit latrines. It is realised that the strategy to effectively control groundwater contamination in Kisauni has to address the pollution sources, in this case on-site waste management.

Thus, there is a need for improved pit latrines properly constructed to minimise leakage of faecal matter into groundwater. This would entail the construction of protected pits that do not reach the water table, unlike the case in Kisauni. Soakage pits should be designed taking into consideration the depth of the water table so that maximum attenuation of contaminants as the wastewater sinks into the aquifer is attained. Uncontrolled disposal of sewage in wetlands should be avoided and instead septic tanks be utilised. Wastewater may be disposed of in a controlled wetland. Alternatively proper sewage treatment facilities (e.g. oxidation ponds or lagoons) would be required to minimise groundwater contamination. There is a need for appropriate regulations to guide the construction of waste management and disposal facilities and the authority to enforce compliance.

The effectiveness of measures to control sources of pollution can be enhanced by raising awareness and educating the community on the vulnerability of groundwater due to anthropogenic activities and the need to protect this valuable resource. This requires the generation of pertinent information on the state of the aquifer and regular monitoring of the groundwater to ascertain its pollution status.

Presently Kenya has in place a comprehensive policy framework and the necessary legislation and regulations guiding the management of water resources (GOK, 2002a, b). The law includes specific regulations on the exploitation of groundwater that are hardly enforced. Most water supply boreholes and wells, for example, were sunk without prerequisite permits and hence supervision by the water authority. There is a need to link the exploitation and management of groundwater resources with sanitation.

7 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. The groundwater flow model gives an indication of the most probable direction of flow of contamination, which is useful for groundwater protection strategies.

The study has provided information on the general water quality in Kisauni with reference to 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. Within the sand geological zone, on the other hand, 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 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 concentrations encountered in 50–70% of the water samples analysed were, however, within the WHO recommended $10\,\mathrm{mg\,l^{-1}}$ NO_3^{-1}/NO_2^{-1}-N limit 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 rainy season when aquifer recharge is enhanced. The Mombasa City local authority in conjunction with the Ministry of Water and Irrigation 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.

In view of the findings, a comprehensive strategy to control groundwater deterioration in Kisauni should include the adoption of measures to control pollution sources, mainly on-site sewage management facilities, involving the community in groundwater protection initiatives and effective implementation of existing regulatory provisions.

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