

Lithology and Geological Structures as Controls in the Quality of Groundwater in Kilifi County, Kenya

ABSTRACT

Aims: Saline and brackish water has been encountered in more than half of the boreholes across Kilifi County. The purpose of this study was to analyze the relationship between lithology and structural geology and the quality of water encountered in boreholes in the study area.

Study design: The study involved field observation of boreholes and collection of hydrogeological data and analysis of geological and structural setting and water quality.

Place and Duration of Study: Borehole data was collected between January and June 2012. Field observation of boreholes was carried out between June and September 2012. Data analysis was carried out between October 2012 and July 2013 at Masinde Muliro University and University of Nairobi.

Methodology: Drillhole information for 180 boreholes with depths ranging from 5 m to 300 m was obtained from the Ministry of Water and Irrigation Archives. Subsurface profiles for the individual boreholes representative of various locations were plotted using Strater software (by Golden Software). The quality of water encountered in the boreholes was related to the mode of deposition of the sediments and the faults or folds at the borehole site.

Results: Groundwater quality, especially the salt content was compared in borehole drilled through the various formations at distant locations. With the exception of Mazeras sandstones, water quality in Duruma sediments is generally saline owing to the lacustrine deposition of the sediments. The great depths of aquifers and poor quality of the water have prohibited drilling of wells to the Taru Formation. Magarini and Pleistocene sands yield water suitable for most domestic purposes. The groundwater in the Mtomkuu formation and the Reef Complex is saline and brackish. Sea water intrusion occurs along the coast and the water levels in the wells remain the same throughout the year. Adjacent boreholes in areas where aquifers juxtapose against impermeable materials are found to have different qualities of water while slow and fast pumping regimes too produce different qualities.

Conclusion: In spite of a topographic difference of more than 200 m between the coast and the inland of Kilifi County, aquifers are expected at the following depth ranges: 11-22 m; 30-34 m, 45-50 m, and; 70-84 m. The quality of groundwater in Kilifi County is determined by the geological materials through which it travels the position of the well in relation to the geologic structures, proximity to the ocean and pumping regimes.

Keywords: lithology, structural geology, sedimentary environment, groundwater quality

1. INTRODUCTION

Kilifi County is an administrative unit located in the coast of Kenya (Figure 1). It stretches 75 km along the Kenyan coast and for several tens of kilometres inland. Scarcity and unpredictability of rainfall in Kilifi County is a major impediment to development. Some parts of Kilifi County such as Ganze and Bamba on the western part experience 5-6 months of continuous dry weather. Groundwater provides nearly 50% of the water in Kilifi County through more than 200 shallow and deep wells with depths ranging from 6 m to 300 m.

21 The groundwater in Kilifi County occurs in confined and unconfined aquifers in sedimentary
22 formations of fluvial and lacustrine origin. Groundwater flow direction is generally eastward
23 with recharge rate decreasing westward from the central part. Records of chemical analyses
24 indicate that saline and brackish water has been encountered in more than half of the
25 boreholes across the study area. Boreholes bordering the Indian Ocean experience minimal
26 drawdown during months of continued dry weather indicating the possibility of sea water
27 intrusion. The purpose of this study was to analyze the relationship between lithology and
28 structural geology and the quality of water encountered in boreholes in the study area.
29
30



Figure 1: Location of Kilifi County

31
32

33
34
35

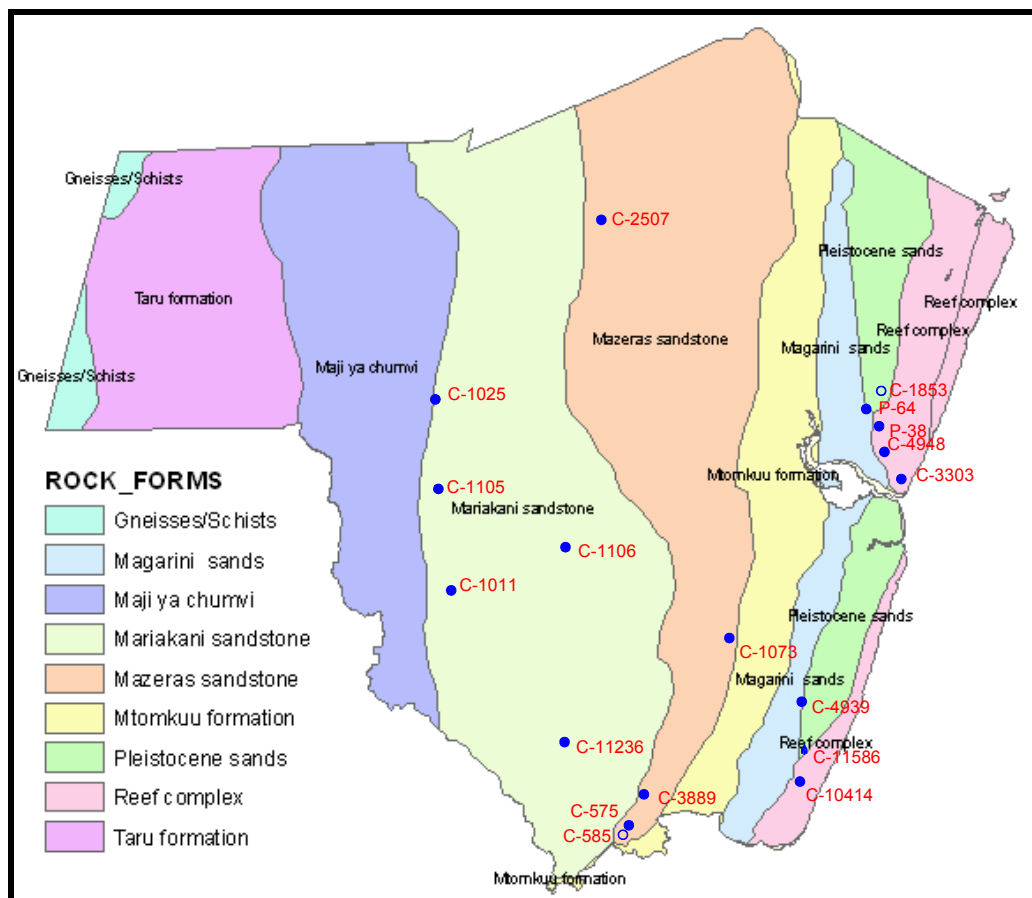
2. LITERATURE REVIEW

36 Many authors have made discussions in relation to lithology, stratigraphy and structural
37 geology of Kilifi County. These include: Geology of the Mombasa-Kwale Area [1]; Geology of
38 the Kilifi-Mazeras Area [2]; Notes on the Geology and Mineral Resources of the Mtito Andei
39 – Taita Area (Southern Kenya) [3]; Notes on the Geology and Mineral Resources of the
40 Southern Kenyan Coast [4]; and, Depositional history of the Late Pleistocene limestones of
41 the Kenya coast [5]. Much of the information written in recent documents is collated from

42 these researches. Of all the work that has been done, however, none has exhaustively dealt
 43 with the relationship between the subsurface materials and the water quality in Kilifi County.
 44

45 The regional geological setting of Kilifi County is dominated by the rifting and break-up of the
 46 Palaeozoic Gondwana continent and the development of the Indian Ocean [6]. Upper
 47 Proterozoic gneisses of the Mozambique belt form the basement of an intra-cratonic basin,
 48 filled with continental Permo-Triassic clastics [3]. Rifting during the early to middle Jurassic,
 49 presumably preceded partly by up-doming along the incipient rift, transformed it into a
 50 marine marginal basin at the trailing edge of the African plate [4].

51 Almost three-quarters of the area is underlain by the continental Permo-Triassic sediments
 52 assigned to the Duruma Group [1], which is generally considered as the Kenyan equivalent
 53 of the Karroo system of southern Africa [4]. The Duruma group includes the Taru Formation,
 54 Maji ya Chumvi formation, Mariakani Formation and Mazeras Formation. The Duruma
 55 sediments essentially comprise grits, arkosic sandstones, and shales accumulated under
 56 lacustrine, sub-aerial conditions with minor marine incursions in a broad, roughly NNE-
 57 SSW trending intra-cratonic trough, which formed towards the end of the Paleozoic within
 58 the Proterozoic gneisses of this part of the Gondwana [6]. This trend controlled the
 59 deposition of all the other formations as shown in Figure 2.



60

61 Figure 2: Map showing the NNE-SSW trending geological formations and study boreholes of
 62 Kilifi County (adapted from the geological map of Kenya)

63 During the initial development stages of this trough, down warping was fairly rapid, and the
64 basal Taru formation that consists mainly of coarse-grained, poorly sorted arkoses
65 intercalated with shales containing freshwater fauna was formed [5]. Intra-formational
66 reworking and sedimentary structures are widespread, and indicate rapid denudation and
67 short transport with subsequent re-deposition in a high-energy lacustrine environment [3].

68 Towards the top, the grain size of the Taru sediments decreases and the generally fine-
69 grained Maji-ya-chumvi formation overlies the Taru sediments along a slight unconformity.
70 Current bedding and ripple marks are common and indicate deposition in shallow water [5].
71 A basal sequence, composed of fissile dark shales with thin intercalations of sandy
72 siltstones, frequently shows rain pits and desiccation cracks together with appreciable
73 amounts of precipitated salts [2]. It therefore indicates a period of arid climate during which
74 the trough apparently dried-up frequently. This facies is terminated by a marine ingression
75 which deposited fish-bearing shales followed by flaggy, fine-grained argillaceous
76 sandstones, siltstones, and shales with a wealth of sedimentary structures (cross-, current-,
77 and convolute bedding, rippled laminations, slump folding, etc.); they contain Triassic fauna
78 indicating the return of brackish and even fresh-water conditions [4].

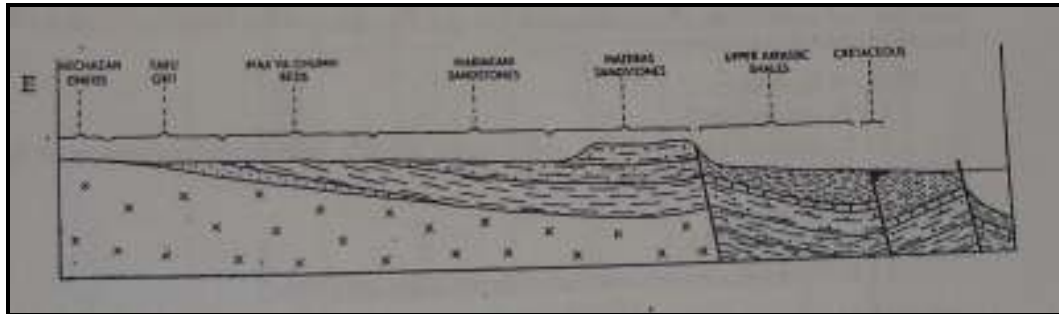
79 During the deposition of the Mariakani formation which conformably overlies the Maji-ya-
80 Chumvi beds, erosion became more intensive and a rhythmic succession of fine to medium
81 grained sandstones and impure shales was deposited, probably again under lacustrine
82 conditions. Massive, fine-grained sandstones with distinct mottling prevail in the basal part of
83 the formation while flaggy arkosic sandstones with usually well developed cross-bedding
84 prevail in the upper part [2].

85 More pronounced erosion persisted during the deposition of Mazeras formation which
86 unconformably overlies the Mariakani formation [1]. It starts with coarse-grained, cross-
87 bedded arkoses, with lenses of grits and minor siltstone/shale intercalations. The
88 sedimentation rate eventually surpassed the rate of subsidence of the trough, and dry areas
89 covered by forest emerged, as evidenced by a well-defined horizon containing abundant
90 fossil wood [4]. Coarse-grained, massive arkoses and grits of terrestrial origin with infrequent
91 sub-aqueous intercalations terminate the Mazeras formation. This decline of the subsidence
92 rate possibly already indicates incipient up-doming prior to the Jurassic rifting of Gondwana
93 [7].

94 After the termination of the Duruma sedimentation, major faulting and rifting led to the break-
95 up of Gondwanaland; it caused a fundamental facies change from a continental cratonic
96 trough to a marginal marine basin with sediments, located at the trailing edge of the
97 continent [4]. This transition is marked by a middle Jurassic marine ingression. The basal
98 sediments of the Mtomkuu (Kambe) formation were deposited under near-shore neritic and
99 estuarine conditions. Basal transgression conglomerates, largely composed of Duruma
100 detritus, are overlain by impure micritic limestones, occasionally with small bioherms, and
101 near-shore oolitic limestones, which were deposited in a shallow shelf environment with
102 only moderate terrigenous contamination [5].

103 Erosion prevailed during the Tertiary until the Upper Pliocene, when tectonic reactivation
104 resulted in increased erosion [6]. Fluvial pebble beds, gravels and sands of the Magarini
105 formation were deposited on down-faulted and eroded Jurassic and Duruma sediments.
106 After a regression during the Late Pleistocene, dunes which form the bulk of the Magarini
107 formation were blown-up. This led to the formation of Pleistocene sands. At the same time,
108 corals accumulated to form the Reef Complex along the coast. Figure 2 is an outline of these
109 geologic formations; the oldest rocks are the Gneisses of Neo Proterozoic Era while the
110 youngest is the Reef Complex of Recent Age.

111 The structural pattern of the area is dominated by vertical faults striking parallel to the
 112 coastline and displacing SE-dipping sediments downward to the east. The major faults,
 113 along which rifting and break-up of Gondwana did occur, are located offshore [8, 9]. The
 114 faults generally trend NE and are thought to form the northward extension of the NNE
 115 striking Tanzanian "Tanga fault belt" [8]. A schematic section through the coastlands as they
 116 are seen at the present day, but without the superficial cover of Cenozoic deposits is shown
 117 in Figure 3.
 118



119
 120 Figure 3: Schematic section through the coastlands as they are seen at the present day
 121 (After Caswell, 1953)
 122

123 3. MATERIALS AND METHODS

124 The study involved field observation of boreholes and collection of hydrogeological data and
 125 analysis of geological and structural setting and water quality. Borehole data was collected
 126 between January and June 2012. Field observation of boreholes was carried out between
 127 June and September 2012. Data analysis was carried out between October 2012 and July
 128 2013 at Masinde Muliro University and University of Nairobi.
 129

130 Drillhole information for 180 boreholes with depths ranging from 6 m to 300 m was obtained
 131 from the Ministry of Water and Irrigation Archives. The information provided for most
 132 borehole included: borehole number, owner, date drilled, location, total drilled depth, type of
 133 aquifer encountered, yield, water quality and remarks on the drilling process. The water
 134 quality parameters reported include major and minor cations, anions such as sulphates,
 135 nitrates, chlorides and fluoride as well as turbidity and salinity.

136 Borehole logs for the 180 wells were analyzed to determine lithology, thickness and
 137 hydraulic characteristics of the aquifers. Geological information for each of the sample
 138 boreholes was typed in worksheets for purposes of plotting profiles. Each drill hole log
 139 consisted of the following information: borehole identity (BHID); geographic coordinates
 140 (x,y); thickness of the stratum (from-to); the name of the geologic unit (formation) or
 141 hydrogeologic unit identity (HGUID) i.e. if it is a sandstone, limestone, shale, clay or sand as
 142 well as description of the formation and code (HGUCODE) as given by the driller.

143 Subsurface profiles for the individual boreholes representative of various locations were
 144 plotted using Strater 3 software (by Golden Software). At most three borehole logs drilled
 145 through the same formation could be presented in each borehole view. This was to ensure
 146 that the information was easy to compare on the depth scale and fault pattern. Information
 147 on each borehole view includes depth scale, core recovered, the description of the formation
 148 by the driller and the depth of encounter of water as well as the quality of water where
 149 available, locality and borehole identity. The quality of water encountered in the boreholes
 150 was related to the mode of deposition of the sediments and the faults or folds.

4. RESULTS AND DISCUSSION

The boreholes used in this study are as shown in Figure 2. Majority of the commissioned boreholes draw water from Mariakani sandstones, Mazeras sandstones, Magarini sands, Pleistocene sands and the Reef Complex. Most boreholes drilled into the Mtomkuu formation strike very mineralized water in limestone aquifers and are thus abandoned.

Figure 4 presents subsurface information for boreholes drilled to depths of 62 m, 20 m and 24 m at Kilifi Plantations, Kilifi Town and Mtwapa respectively. Aquifers at these locations occur within corals of the Reef Complex and in the bands of clay and sand encountered at 13 and 18 m. The water is mainly saline and very small drawdown is experienced during test pumping. The absence of drawdown indicates the possibility of sea water intrusion [10].

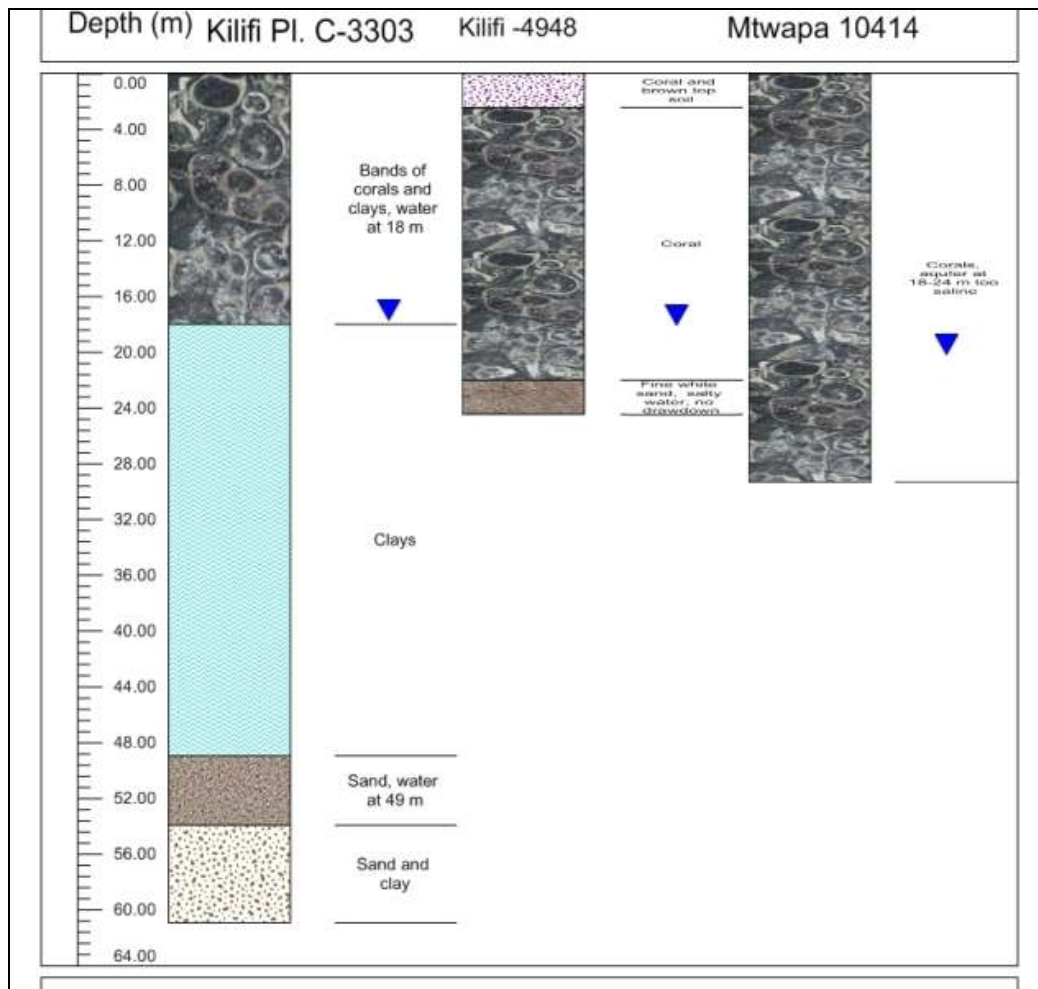


Figure 4: Subsurface information for boreholes drilled in the vicinity of the Reef Complex

The subsurface formations encountered in boreholes drilled into Pleistocene and Magarini sands at Vipingo, Kilifi and Mtwapa are shown in Figure 5. Water suitable for domestic purposes is encountered in unconfined aquifers at depths between 22 and 32 m. Caving of the sands is reported in many boreholes drilled through this aquifer. Another good aquifer is encountered at 70 m in borehole C-1853. Most boreholes in Vipingo have encountered very saline water in coral and clay bands at depths of 41 m to 50 m. Drilling through the clay band

in a borehole at Vipingo (C-4949) encountered very saline water and had to be quickly plugged to avoid contamination of the water from upper aquifers. Lateral influx of the saline water is probably restricted by the presence of the small displacement fault at Vipingo [11]. A similar displacement is observed at Mtwapa where adjacent boreholes have different profiles. The presence of faults with throws to the coast restricts the inland movement of sea water [12]. The presence of shallow saline aquifers in the Mtomkuu formation was found to reduce the area that can be regarded as having the potential for artificial recharge through shallow wells [13].

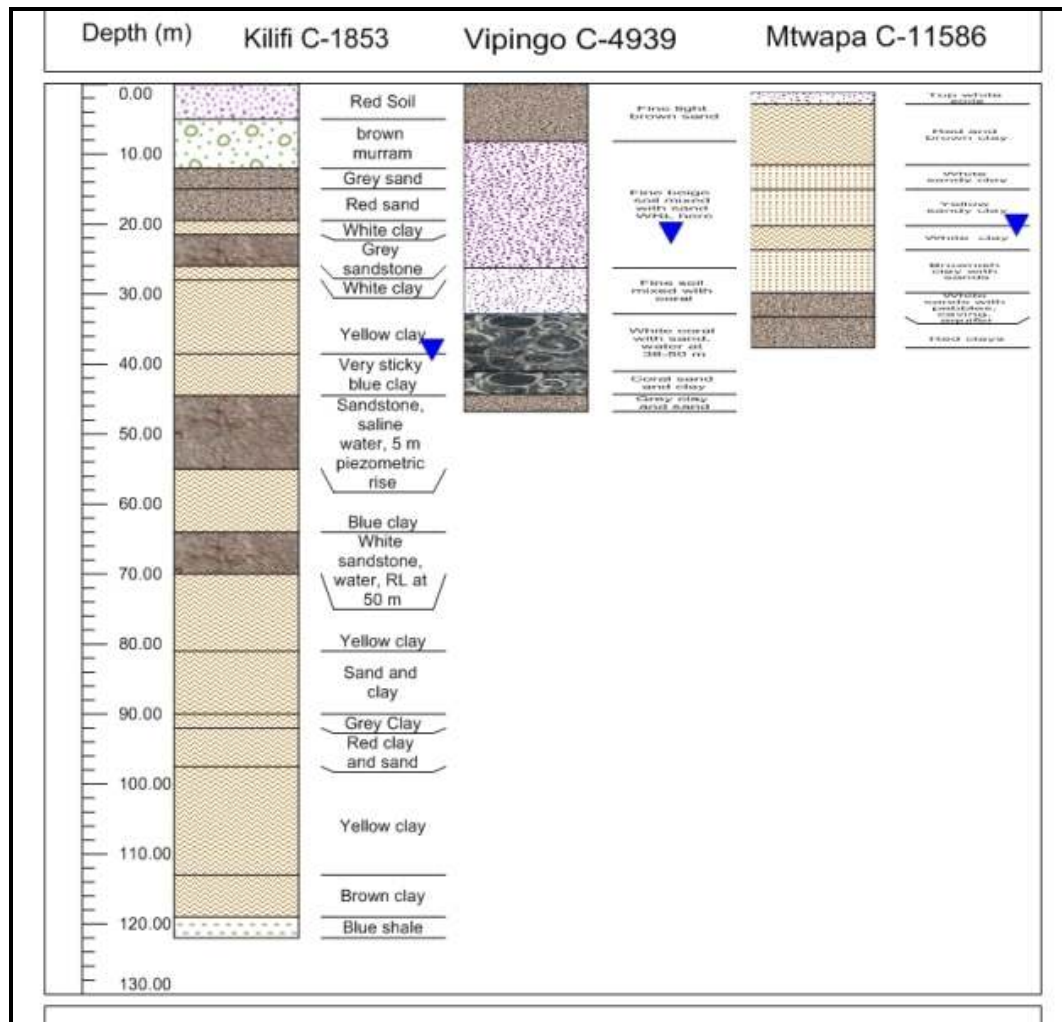


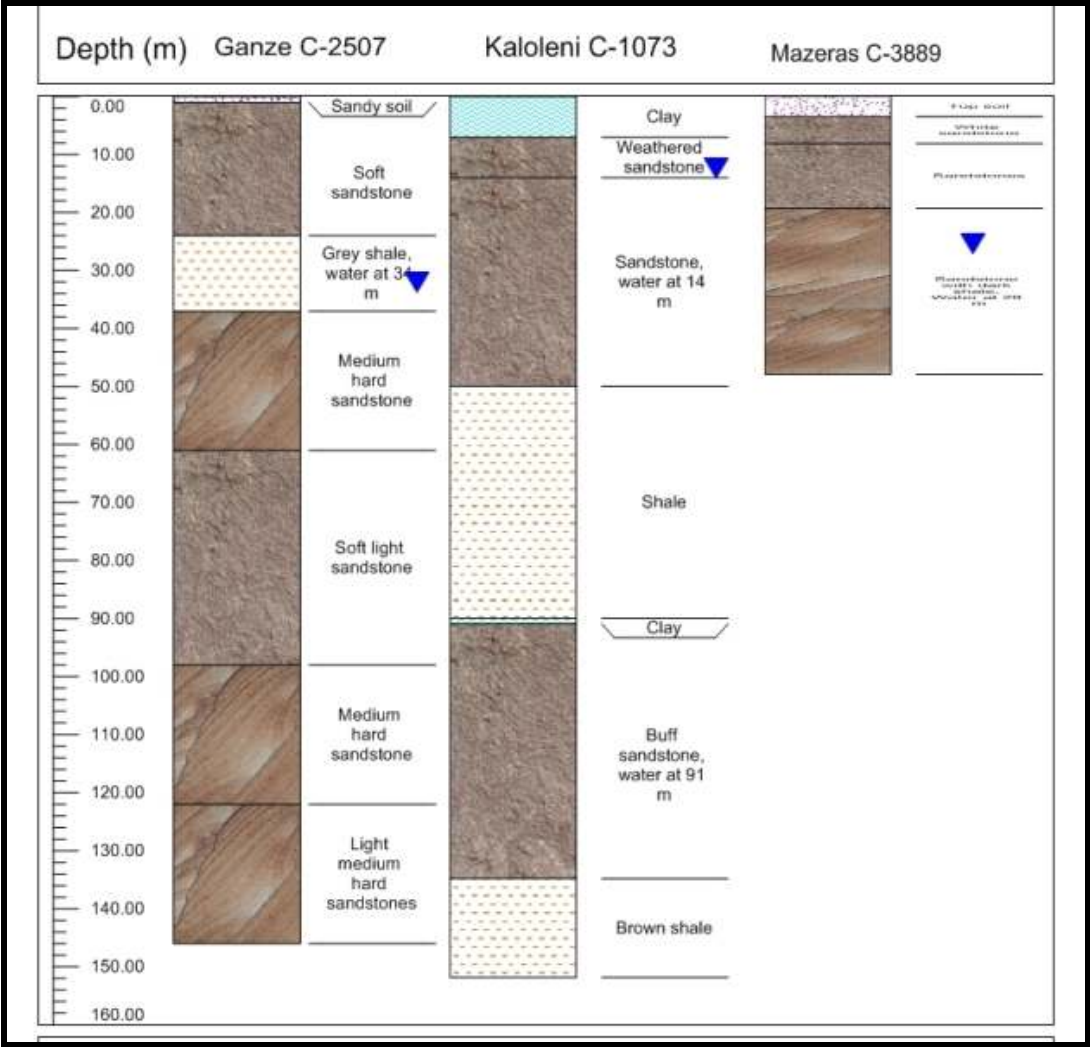
Figure 5: Subsurface information for boreholes drilled into Pleistocene and Magarini sands

Variable thicknesses of Mazeras sandstone are encountered at Kaloleni, Ganze and Vilagoni (Figure 6). Several layers of hard, medium hard and soft sandstones intercalated with shales are encountered during drilling. The first aquifer is encountered within the sandstones at depths ranging between 11 m and 14 m. The second aquifer is commonly within the shales at 34 m to 35 m. The third and fourth aquifers are encountered within the sandstones in the vicinity of 70 m and 100 m to 125 m respectively. The first aquifer encountered within the weathered sandstone produces saline water. Good quality water is encountered in the other aquifers within the sands/sandstones at depths ranging between 76 and 91 m. The Mazeras Formation is faulted near Mazeras Town. Two adjacent boreholes

193 drilled in the town (C-585 and C-575) encountered different qualities of water; borehole C-
194 575 drilled to 68 m encountered good quality water with a yield of 26 m³/day while borehole
195 C-585 encountered water with 4000 ppm salts and a yield of 2.4 m³/day. Borehole C-585
196 was drilled to a depth of 74 m.

197
198 Many of the boreholes drilled in the vicinity of borehole C-1853 in Roka before 1960 struck
199 water at 12 m to 18 m but were abandoned due to high salinity. Several boreholes such as
200 C-3263 drilled in 1963 struck water suitable for domestic use in Roka Settlement after the
201 period of no pumping. The salinity kept increasing with time until the water was found
202 unsuitable for many uses and the boreholes were thus abandoned. Boreholes drilled later
203 were installed with hand pumps; dug wells in these locations supply water suitable for most
204 domestic uses except drinking.

205
206



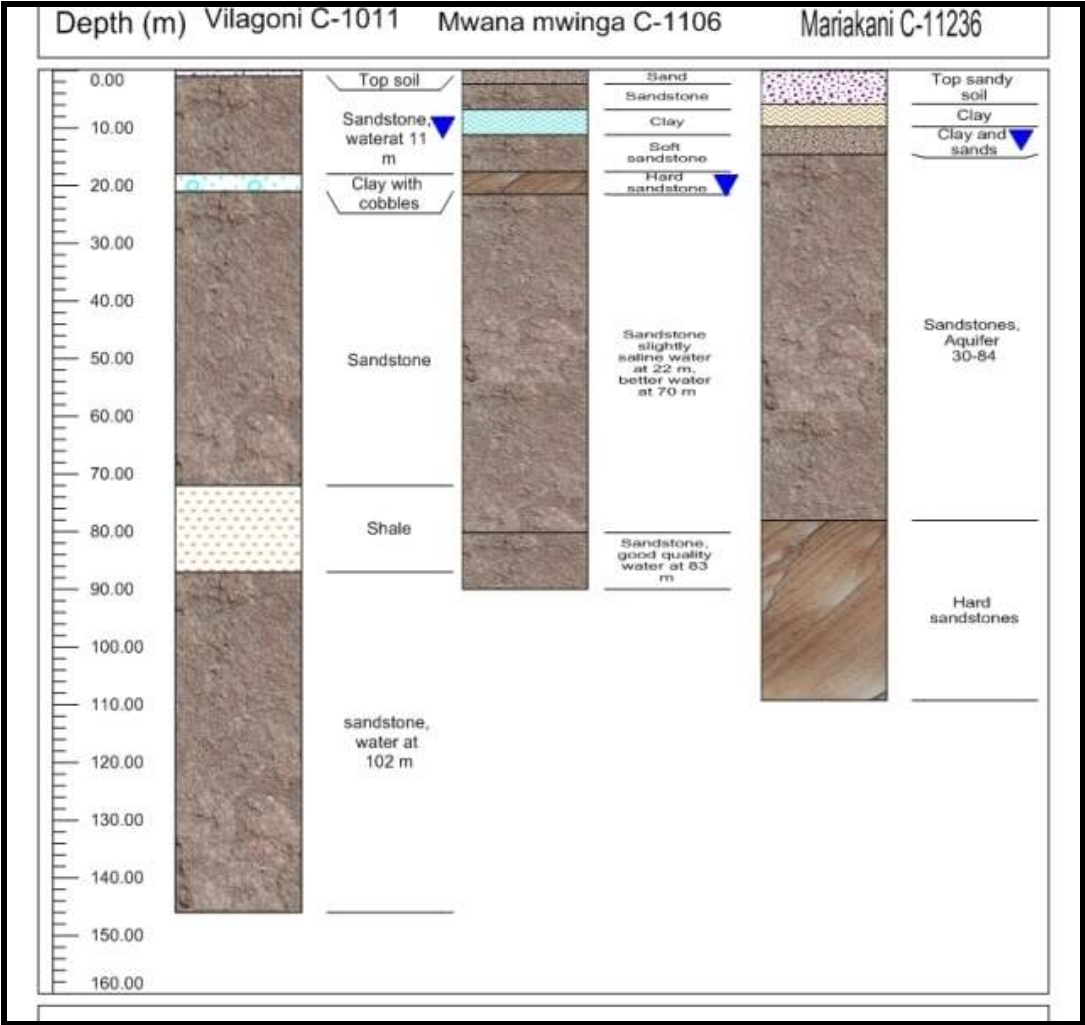
207

208 Figure 6: Subsurface information for boreholes drilled to 148 m and 152 m depths

209

210 Core logs of sample boreholes drilled into Mariakani sandstones to depths of 144 m, 84 m
211 and 110 m at Vilagoni, Mwana Mwinga, and Mariakani respectively are plotted on Figure 7.
212 Aquifers are encountered within the Mariakani Sandstones intercalated with bands of clay.

213 Water can be expected in the vicinity of 11 to 22 m, 30 m, 70 to 84 m and 102 m; Good
 214 quality water is encountered in the aquifer at 70-84 m. Encounter of deeper aquifers in
 215 Mariakani sandstones leads to piezometric rises of between 5 m and 15 m showing that they
 216 are semi-confined; very few boreholes have the rest levels at the level of encounter of the
 217 first aquifer. Water in the other aquifers is mainly saline; the salt content in Mariakani
 218 sandstone aquifers ranges between 1700-2000 ppm of which chloride contributes about 900
 219 ppm and Calcium 71 ppm and carbonate 18 ppm. The salinity of the water can be related to
 220 the deposition of Mariakani sandstone in shallow basins susceptible to evaporation. A study
 221 on the potential for Aquifer Storage and Recovery from Mariakani sandstones and Maji ya
 222 Chumvi beds by [14] indicates that the recovered water could contain considerable amounts
 223 of salts.
 224



225

226 Figure 7: Subsurface information for boreholes drilled to Mariakani Sandstones

227 Displacements of up to 100 m have been observed at Mariakani [10]. Juxtaposition of
 228 aquifers against impermeable materials due to faulting may be the reason behind the
 229 variable yields and water quality in this area. The significant feature of all the faults is that
 230 they are normal; principally trend northerly to north-easterly and have downthrows towards
 231 the Indian Ocean [4]. It has been observed elsewhere that Permian sedimentation occurred
 232 in broad basins leading to formation of shales in low-lying areas and limestones in high-lying

233 areas. The restricted circulation in the basins led to calcium carbonate concentration [15]. In
234 this kind of depositional environment ground water is expected to have different levels of
235 salinity depending on the position of the sediments in the basin.
236

237

238 **5. CONCLUSIONS**

239

240 Groundwater provides nearly 50% of the water in Kilifi County through more than 200
241 shallow and deep wells with depths ranging from 6 m along the coast to over 300 m in the
242 west. Geology of the study area comprises Upper Proterozoic Mozambique belt
243 metamorphic rocks, Permo-Triassic Duruma sediments, Plio-Pleistocene sands, Pleistocene
244 Reef Complex and Recent Alluvium. Four main structural events can be recognized: initial
245 faulting in the Lower Carboniferous that affected the metamorphic rocks; subsidence and
246 down-warping in Upper Carboniferous – Lower Triassic; major faulting in Lower Jurassic and
247 faulting in the Upper Pliocene. The geological formations are normally faulted with down-
248 throws towards the Indian Ocean. Lithology and groundwater quality from 180 shallow and
249 deep wells were considered in this study. Sample geologic profiles were drawn and the
250 quality of water in each aquifer indicated on four geologic sections. In spite of a topographic
251 difference of more than 200 m between the coast and the inland of Kilifi county, aquifers are
252 expected at the following depth ranges: 11-22 m; 30-34 m, 45-50 m, and; 70-84 m. the
253 quality of groundwater in Kilifi county is determined by the geological materials through
254 which it travels the position of the well in relation to the geologic structures, proximity to the
255 ocean and pumping regimes. Groundwater quality, especially the salt content was compared
256 in borehole drilled through the various formations at distant locations. With the exception of
257 Mazeras sandstones, water quality in Duruma sediments is generally saline owing to the
258 lacustrine deposition of the sediments. The great depths of aquifers and poor quality of the
259 water have prohibited drilling of wells to the Taru Formation. Magarini and Pleistocene sands
260 yield water suitable for most domestic purposes. The groundwater in the Mtomkuu formation
261 and the Reef Complex is saline and brackish. Sea water intrusion occurs along the coast
262 and the water levels in the wells remain the same throughout the year. Adjacent boreholes in
263 areas where aquifers juxtapose against impermeable materials are found to have different
264 qualities of water while slow and fast pumping regimes too produce different qualities.
265

266 **ACKNOWLEDGEMENTS**

267

268 The authors are grateful for the assistance offered by the following: International Foundation
269 for Science Grant No. W/4655/1 through which the Strater software was purchased; Ministry
270 of water and Irrigation for freely giving the data; Masinde Muliro University and University of
271 Nairobi for all the services that they offered.
272
273

COMPETING INTERESTS

The authors have declared that no competing interests exist.

AUTHORS' CONTRIBUTIONS

Author² carried out the analysis of lithology and structural geology of the study area and reviewed the manuscript while Author¹ drew the subsurface profiles, carried out the analysis on the relationship between lithology and structural geology and water quality and wrote the first draft. Both authors read and approved the final manuscript.

REFERENCES

1. Caswell PV. Geology of the Mombasa-Kwale Area. Geological Survey of Kenya Report 24. 1953; 69pp.
2. Caswell PV. Geology of the Kilifi-Mazeras Area. Geological Survey of Kenya Report 34. 1953; 54pp.
3. Pohl W and Horkel AD. : Notes on the Geology and Mineral Resources of the Mtito Andei – Taita Area (Southern Kenya). Mitt. oesterr. geol. Ges. 1980; 73: 135-52.
4. Horkel AD, Neubauer W, Niedermayr, G Okelo RE and Wachira JK. Notes on the Geology and Mineral Resources of the Southern Kenyan Coast. 1984; 77:151-9.
5. Braithwaite CJR. Depositional history of the late Pleistocene limestones of the Kenya coast. Geological Society of London. 1984;41 (4):685-99.
6. Embleton BJ and Valencio DA. Paleomagnetism and the reconstruction of Gondwanaland. Tectonophysics. 1977; 40: 1-12,
7. Neugebauer HG. Crustal Doming and the Mechanism of Rifting. Tectonophysics. 1978;45:159-86.
8. Kent PE, Hunt MA and Johnstone DW. The Geology and Geophysics of Coastal Tanzania. Inst. Geol. Sei. Geoph 1971; 6: 101 pp.
9. Rabinowitz PD. Gravity anomalies across the Eastern African Continental Margin. J. Geophys. Res. 1971; 76(29): 7101-17.
10. Hove A. Sectorial Study and National Programming for Community and Rural Water Supply, Sewerage and Water Pollution Control. Report No. 7, Groundwater Resources in Kenya, World Health Organization. 1973; 212pp.
11. Sikes HL. The Drowned Valleys on the Coast of Kenya. Journal of East Africa and Uganda National History. 1930; 38(39): 1-9.
12. Mohammed EA and Worden RH. Groundwater Compartmentalisation: a Water Table Height and Geochemical Analysis of the Structural Controls on the Subdivision of a Major Aquifer, the Sherwood Sandstone, Merseyside, UK. Hydrology and Earth System Sciences. 2006; 10:49–64
13. Onyancha C, Khaemba A and Sabuni B. GIS Application in Artificial Groundwater Recharge: Case Study of Kilifi District in the Kenyan Coast. Journal of Science, Technology, Education and Management. 2008. 2 (2): 78-87.
14. Onyancha C, Khaemba A and Sabuni B. Aquifer Storage and Recovery and Surface Basins for a Greener Kilifi District. Nile Water Science and Engineering Journal. 2010; 3 (3): 26-33.
15. John MH. Late Paleozoic Sedimentation in West Texas Permian Basin. The American Association of Petroleum Geologists Bulletin. 1972; 56(12):2303-22.