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

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Authors' contributions

This work was carried out in collaboration between both authors. Author CN carried out the analysis of lithology and structural geology of the study area and reviewed the manuscript while Author CO 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.

Short Research Article

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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 6 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

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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 of water.
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 lithology in which it is stored and through which it flows, 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 (Fig. 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.

The groundwater in Kilifi County occurs in confined and unconfined aquifers in sedimentary formations of fluvial and lacustrine origin. Groundwater flow direction is generally eastward with recharge rate decreasing westward from the centre of the county. Records of chemical analyses indicate that saline and brackish water has been encountered in more than half of the boreholes across the study area. Boreholes bordering the Indian Ocean experience minimal drawdown during months of continued dry weather indicating the possibility of sea water intrusion. 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.

Fig. 1. Location of Kilifi County

2. LITERATURE REVIEW

Many authors have made discussions in relation to lithology, stratigraphy and structural geology of Kilifi County. These include: Geology of the Mombasa-Kwale Area [1]; Geology of the Kilifi-Mazeras Area [2]; Notes on the Geology and Mineral Resources of the Mtito Andei – Taita Area (Southern Kenya) [3]; Notes on the Geology and Mineral Resources of the Southern Kenyan Coast [4]; and, Depositional history of the Late Pleistocene limestones of the Kenya coast [5]. Much of the information written in recent documents is collated from these researches. Of all the work that has been done, however, none has exhaustively dealt with the relationship between the subsurface materials and the water quality in Kilifi County.

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

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

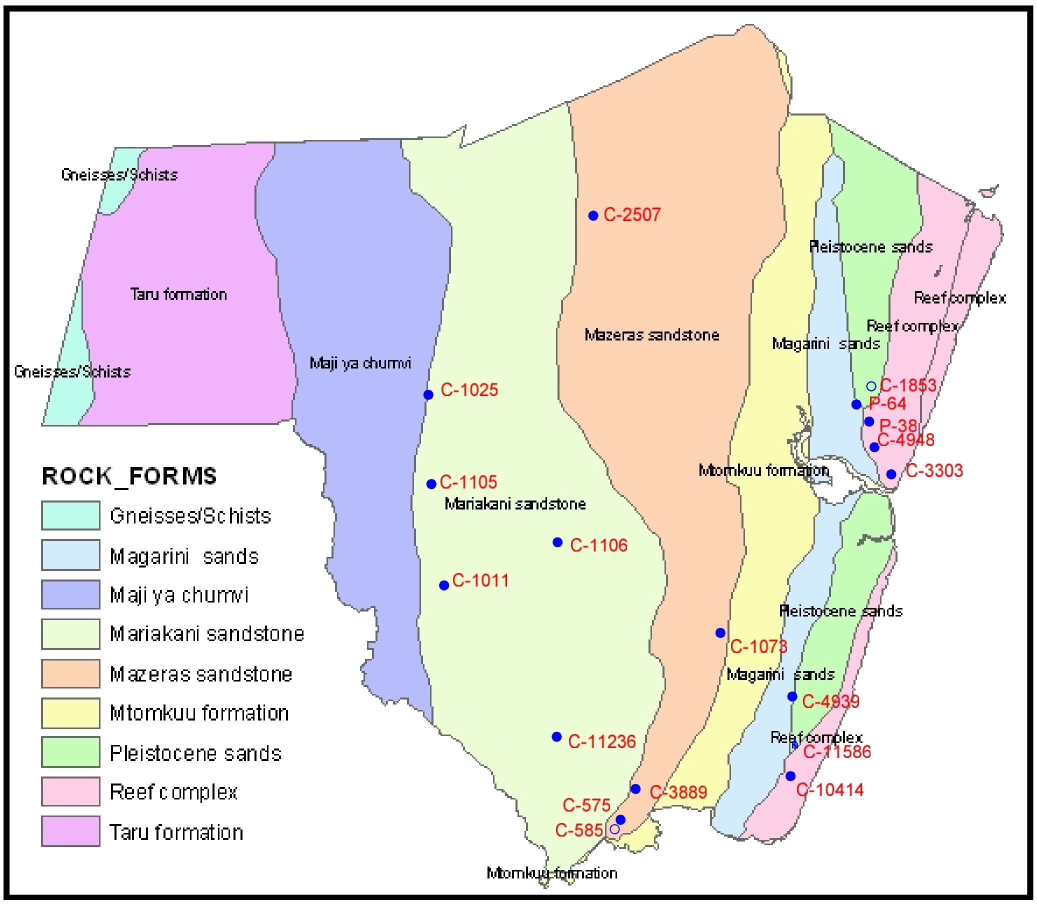

Fig. 2. Map showing the NNE-SSW trending geological formations and study boreholes of Kilifi County (adapted from the geological map of Kenya)

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

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

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

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

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

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

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

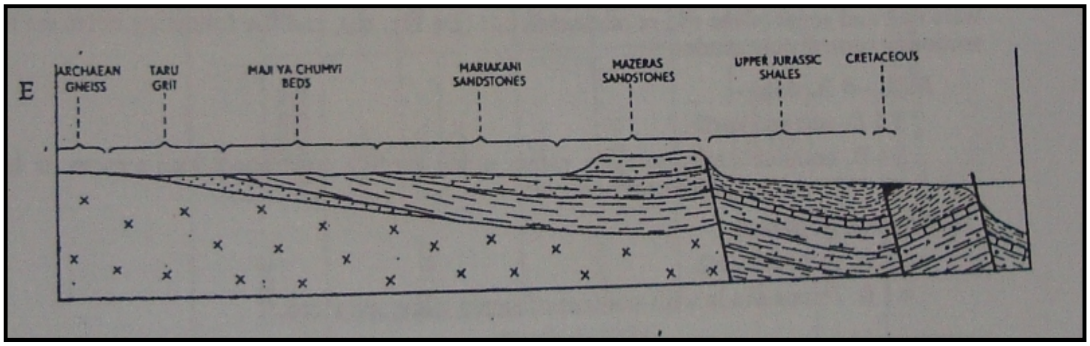

Fig. 3. Schematic section through the coastlands as they are seen at the present day (After Caswell, 1953)

3. MATERIALS AND METHODS

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

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

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

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

4. RESULTS AND DISCUSSION

The boreholes used in this study are as shown in Fig. 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.

Fig. 4 presents subsurface information for boreholes drilled at Kilifi Plantations, Kilifi Town and Mtwapa. 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]. Given that the Reef Complex was formed from accumulation of corals along the coast, limestone cavens allow sea-water intrusion inland causing little drawdown in boreholes even with continuous large-scale abstraction.

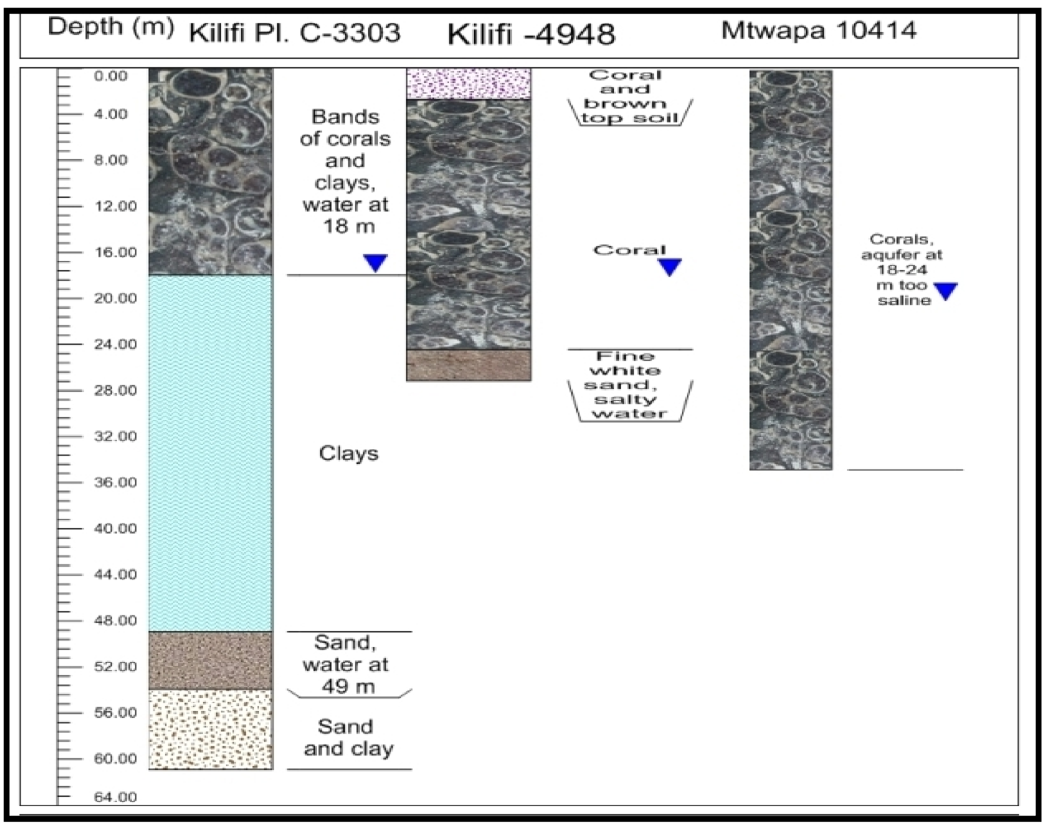

Fig. 4. Subsurface information for boreholes drilled in the vicinity of the Reef Complex

The subsurface formations encountered in boreholes drilled into Pleistocene and Magarini sands at Vipingo, Kilifi and Mtwapa are shown in Fig. 5. Magarini sands comprise of fluviatile pebble beds of gravels and sands deposited in fresh water environment while Pleistocene sands were formed from blowing up of Magarini sands during the Pleistocene times. 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 these aquifers. 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 borehole C-4949 nearby borehole C-4939 at Vipingo 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].

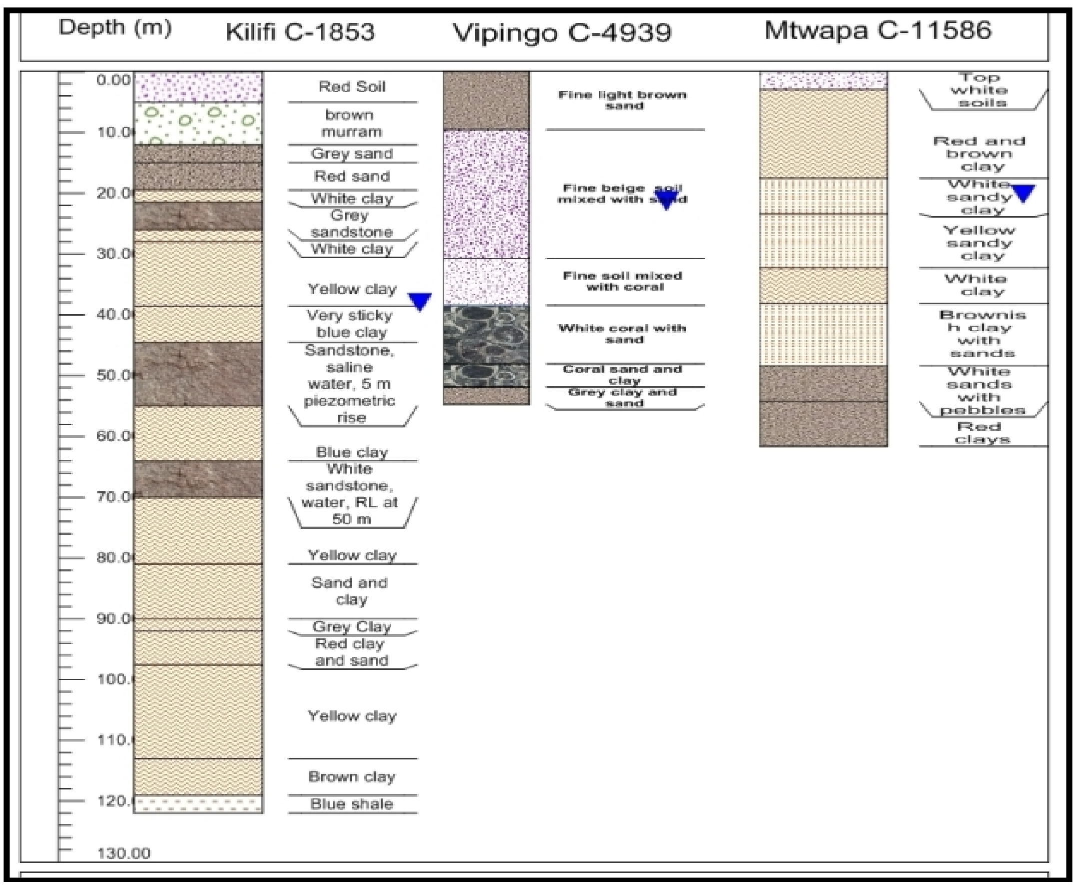

Fig. 5. Subsurface information for boreholes drilled into Pleistocene and Magarini sands

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

Mtomkuu formation which is commonly referred to as Kambe limestone was formed from mid-Jurassic marine ingression and sedimentation of near-shore limestones intercalated with Duruma detritus. Very saline water is encountered within the Duruma shale detritus and within the limestones shown in Fig. 3. 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].

Mazeras formation consists of coarse-grained massive arkoses and grits of terrestrial origin with minor shale intercalations. Variable thicknesses of Mazeras sandstone are encountered at Kaloleni, Ganze and Mazeras (Fig. 6).

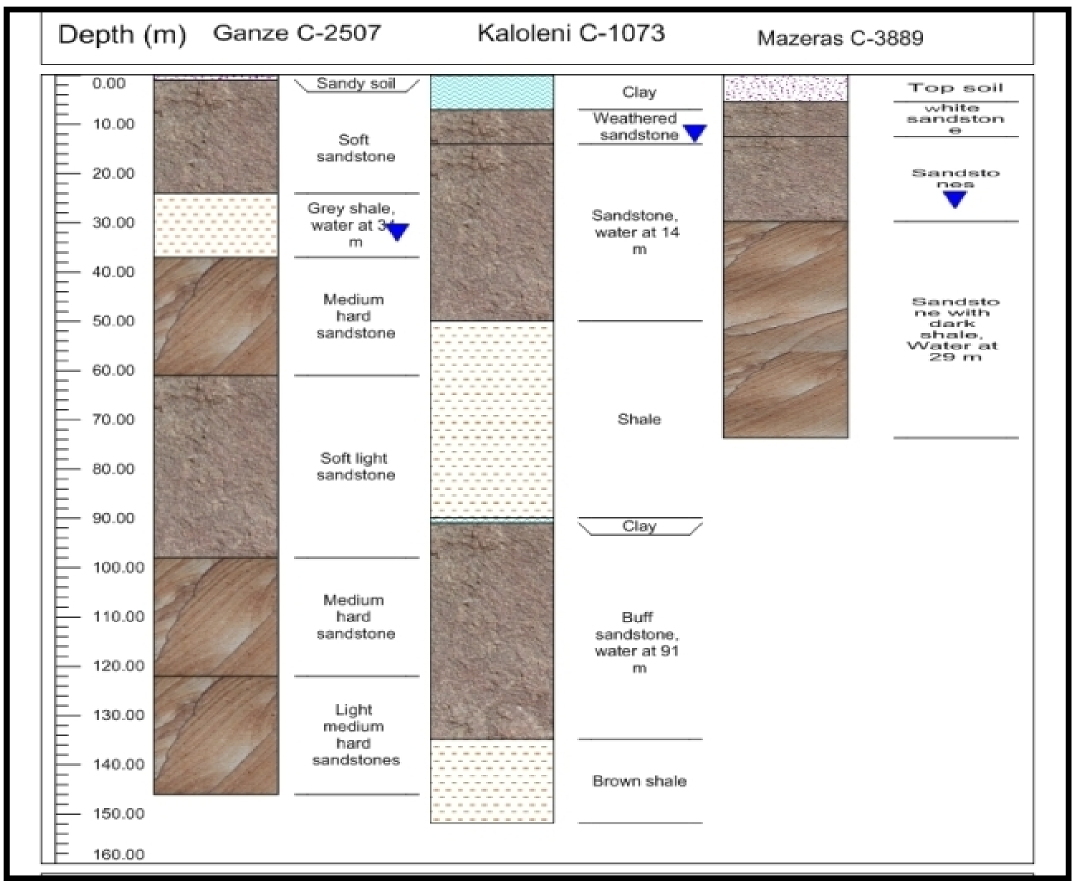

Fig. 6. Subsurface information for boreholes drilled into Mazeras formation

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; this could be due to recharge of the unconfined aquifer by the run-off from the saline Mariakani Formation. 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 drilled in the town (C-585 and C-575) encountered different qualities of water; borehole C-575 drilled to 68 m encountered good quality water with a yield of 26 m³/day while borehole C-585 encountered water with 4000 ppm salts and a yield of 2.4 m³/day. Borehole C-585 was drilled to a depth of 74 m.

Lacustrine environment persisted during the deposition of Mariakani Formation. The formation includes fine-grained sandstones at the base and coarse-grained sandstones at the top with impure shale and clay intercalations. Core logs of sample boreholes drilled into Mariakani sandstones to depths of 144 m, 84 m and 110 m at Vilagoni, Mwana Mwinga, and Mariakani respectively are plotted on Fig. 7.

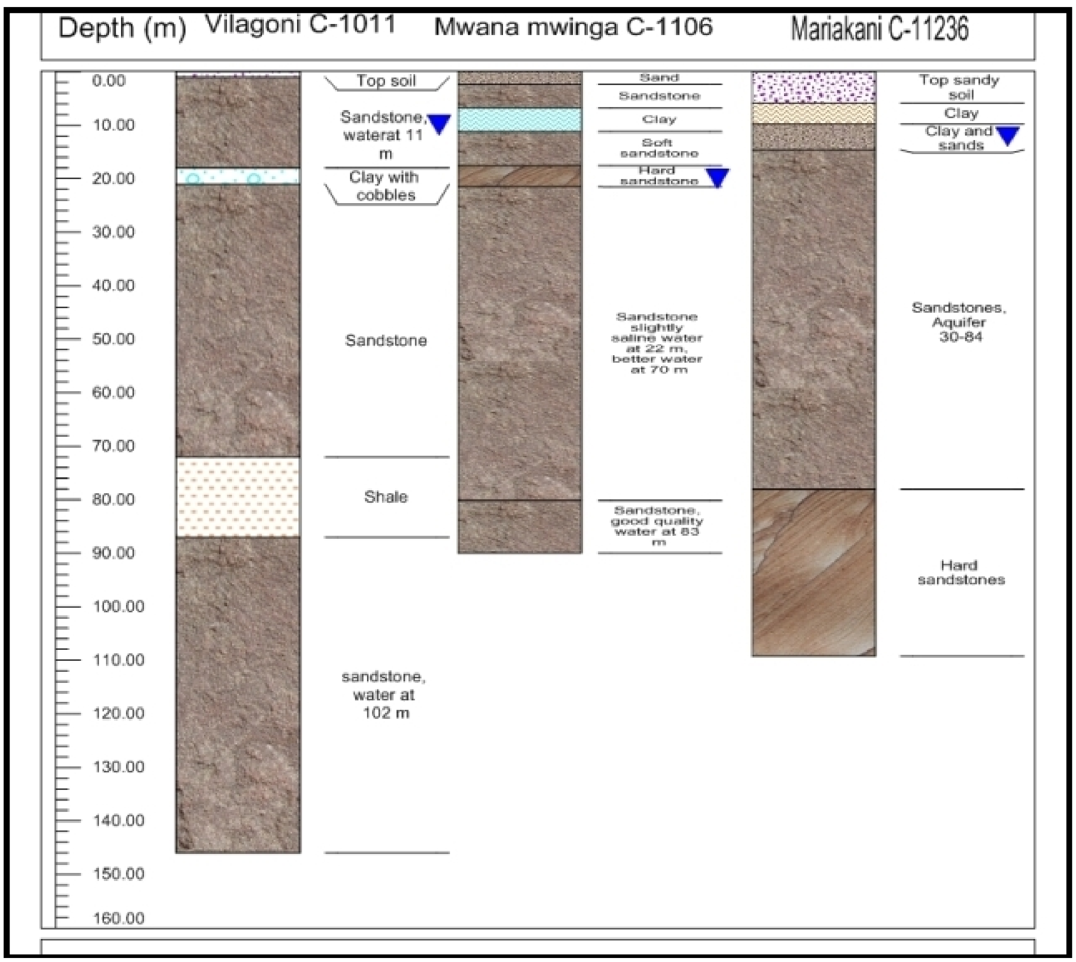

Fig. 7. Subsurface information for boreholes drilled into Mariakani sandstones

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

Displacements of up to 100 m have been observed at Mariakani [10]. Juxtaposition of aquifers against impermeable materials due to faulting may be the reason behind the variable yields and water quality in this formation. The significant feature of all the faults is that they are normal; principally trend northerly to north-easterly and have downthrows towards the Indian Ocean [4]. It has been observed elsewhere that Permian sedimentation occurred in broad basins leading to formation of shales in low-lying areas and limestones in high-lying areas. The restricted circulation in the basins led to calcium carbonate concentration [15]. In this kind of depositional environment, ground water is expected to have different levels of salinity depending on the position of the sediments in the basin.

Maji ya Chumvi (salty water in Kiswahili) beds were deposited in a shallow water trough during a period of arid climate when the trough was frequently dried up. It has significant amounts of precipitated salts [2]). River water flowing through the formation is very salty; boreholes drilled into the Majiya Chumvi Formation are abandoned before commissioning. Taru Formation was deposited in high energy lacustrine environment and comprises of poorly sorted arkoses intercalated with shales. The great depths of aquifers and poor quality of the water have prohibited drilling of wells to the Taru Formation. The few wells that have been drilled to depths of up to 300 m to extract water from the underlying gneisses have encountered very mineralized water with characteristically high fluoride content. Shallow water pans dug into the silt to capture run-off at the surface during rainy seasons supply water for domestic use but dry up during prolonged droughts.

5. CONCLUSIONS

Groundwater provides nearly 50% of the water in Kilifi County through more than 200 shallow and deep wells with depths ranging from 6 m along the coast to over 300 m in the west. Geology of the study area comprises Upper Proterozoic Mozambique belt metamorphic rocks, Permo-Triassic Duruma sediments, Plio-Pleistocene sands, Pleistocene Reef Complex and Recent Alluvium. Four main structural events can be recognized: initial faulting in the Lower Carboniferous that affected the metamorphic rocks; subsidence and down-warping in Upper Carboniferous – Lower Triassic; major faulting in Lower Jurassic and faulting in the Upper Pliocene. The geological formations are normally faulted with down-throws towards the Indian Ocean. Lithology and groundwater quality from 180 shallow and deep wells were considered in this study. Sample geologic profiles were drawn and the quality of water in each aquifer indicated on four geologic sections. Groundwater quality, especially the salt content was compared in boreholes 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. 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. 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 flows, the position of the well in relation to the geologic structures, proximity to the ocean and pumping regimes.

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COMPETING INTERESTS

The authors have declared that no competing interests exist regarding publication of this paper.

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