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RESEARCH ARTICLE

GEOLOGICAL AND TOPOGRAPHICAL INFLUENCES ON HYDROGEOLOGY OF KENYAN MARBLE QUARRY AREAS, KAJIADO COUNTY, SW KENYA: POSSIBLE INDICATIONS FOR POLLUTION

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ABSTRACT

The Kenyan Marble Quarry (KMQ) community is famous for its abundant crystalline limestone deposits, mined for the past eight decades or more at an industrial scale. The area is underlain by a lithologically and structurally complex mix of basement system rocks, and being semi-arid, there are no perennial waters in the area; hence, almost total dependence is on groundwater derived from confined basement aquifers whose occurrence is affected by geological and morphological intricacies. Long-term active mining, coupled with intense weathering processes, are potential geological triggers that could influence the hydrogeological makeup of the area, hence affecting groundwater flow and the physicochemical character of the aquifer. This study aims to interpret data from geological ground-truthing, remote sensing, and existing borehole logs to gain insights into the likely morphological, geological, and structural impacts on surface run-off and sub-surface flow in the KMQ community and its surrounding localities. Run-off flow patterns over the drainage area correlate strongly with surface elevation trends, but the multi-directional dendritic stream flow is highly impacted by soil nature and surface lineaments, evidenced by a SE mean directional stream flow, which correlates with the NW-SE principal orientation of foliations in the area. Patterns of spatial groundwater table elevation over the area show average correlation with surface elevation patterns. Subsurface water flow directions differ to some extent, indicating strong geological controls with NEE-SWW and NW-SE major trending fractures serving as conduits. Accurate point information from borehole logs indicates that weathered and fractured biotite gneisses are the main aquiferous zones over the study area. They are confined by fresh metamorphic basements and clays, which raise the water table upward to depths of up to 17m in some places. The weathered aquifers are highly prone to chemical reactions such as hydrolysis, leaching, or dissolution, all favouring pollution. Also, rock disintegration from mining, exposed surfaces of abandoned mines, and mine tailings could favour acidic conditions and pollution by metallic and non-metallic agents, washed down the drains as run-off. This paper provides a background for further scientific research into possible soil and water pollution from geogenic sources triggered by industrial mining in the KMQ area and extending to its neighbouring localities.

KEYWORDS

Geology, Hydro-structural, Topography, Remote-sensing, Geo-environmental, Mining, Pollution.

1. INTRODUCTION

1.1 Background

Hydrogeology of an area is of the utmost importance for scientific studies and a thriving ecosystem. To a large extent, it forms an aspect of human survival due to man's dependence on water resources. As precipitation infiltrates the subsurface through voids or cracks within a rock formation over time, it gathers in large quantities in the saturated zones beneath the water table. This makes up groundwater, a major earth resource and the key target in hydrogeology. Therefore, the occurrence, constant flow, distribution, and access to groundwater are key ingredients to a successful hydrogeological campaign, not ignoring its quality standards (Polizzi et al., 2022). This is especially crucial in regions where groundwater constitutes the main source of water supply for livelihoods. Hydrogeological conditions vary with location, depending on a complex mix of factors, which revolve around natural geological activities, geomorphology, and sometimes man-induced factors that foster constant water-soil/rock interactions, finally telling on the nature and occurrence of the resource (Elhag and Elziem, 2013; Onyancha and Nyamai, 2014; Idris et al., 2018; Hussien et al., 2020; Zarate et al., 2020; Li P., et al., 2021). Groundwater is required at certain thresholds of physical, chemical, and biological properties to be considered safe for domestic, agricultural, or industrial uses (EPA, 1998; WHO, 2024). Pollution or contamination is imminent, where the concentration of these constituents exceeds their threshold values. Oord, 2017 indicated the occurrence of brackish groundwater in Kajiado town which is in proximity to the KMQ areas. It is necessary to investigate possible sources and migration paths in more detail. More so, there have been calls for detail-scale hydrogeological studies and monitoring campaigns in these areas which will serve as baseline data for future water-related developmental projects (Olago, 2018).

In furtherance to the attainment of equitable living standards, the 17-

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agenda sustainable development goals (SDG-2030) which cut across various important spheres of human endeavours was formulated and adopted in 2015 by all United Nations member states. Specifically, SDG goals 6 and 11 focus on the sustainable provision of clean water as well as ensuring a resilient and sustainable environment respectively (https://sdgs.un.org/goals). The government has been active in its SDG implementation strategy through policy formulations and action schedules (KCIDP 2018-2022). In Kajiado County, the water scarcity problem is projected to increase over time due to climate change effects (Onyango, 2018). The County Government proposes to tackle these problems through the production of more boreholes which constitute the main source of water supply in the area. Other proposed alternatives include the construction of mega dams, water pans, and enhancing water harvesting (Kajiado-CADP-2023). Detailed background hydrogeological information is therefore imperative for equitable project implementation.

1.2 Study Area

The area is located within latitude S01°54'00'' to S02°00'00'' and longitude E36°40'00'' to E36°45'00'', forming a part of the Elangata Wuas Sheet 161/3. It covers the Kenyan Marble Quarry (KMQ) community in Iloodokilani almost at its center, linking to parts of other neighboring areas such as Enkaron, Oliosurr, Emarti, Opirikata, Ildamat, Enyarat, Olondero, Esambu Kike, Ndorosei, Olkesumet, Okilotiti, and Karero, all within central and western Kajiado, south-western Kenya. It has total area coverage of 120 km² and is accessible through the Kajiado-Namanga highway, with several other minor graded roads and footpaths linking the communities (Figure 1). It is a rural area, almost entirely dominated by people of the nomadic Masai extraction, whose main occupation is crop and livestock farming.

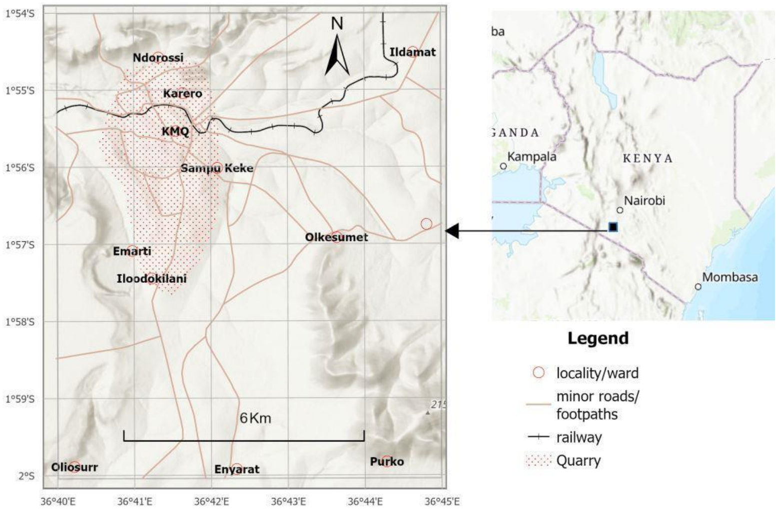

Figure 1: Location and Accessibility Map of the Study Area

KMQ areas are classified as semi-arid, characterised by a bi-annual rainy season from February to May (long rains), and October to December (short rains) with a mean annual rainfall value of approximately 500 mm/year (Andrew, 2010; Maina-Gichaba, 2013). The area is characterized by numerous perennial streams, minor rivers, and run-offs, which eventually drain into the adjacent rivers Turoka and Kajiado lying westward and eastward respectively, outside of the study area. Surface water sources are not reliable, especially during dry seasons; hence much reliance for water is on deep-sited boreholes (Oord, 2017). Vegetation varies with topography and soil types with shrub areas and moderately tall and densely packed thorny trees that hamper accessibility in some parts. Some of the inhabitants practice irrigational farming, with boreholes being the main source of water especially in dry seasons. In wet seasons, rain is harvested into tanks, man-made ponds, and small dams for animal consumption, agricultural and other domestic uses. The area is mostly surrounded by basement hills (Plate 1) with the most prominent ones being the Ilemelepo hills on the south-eastern flank and Emart-Olkimpai hills on the south-western flank, stretching northward (Figure 2).

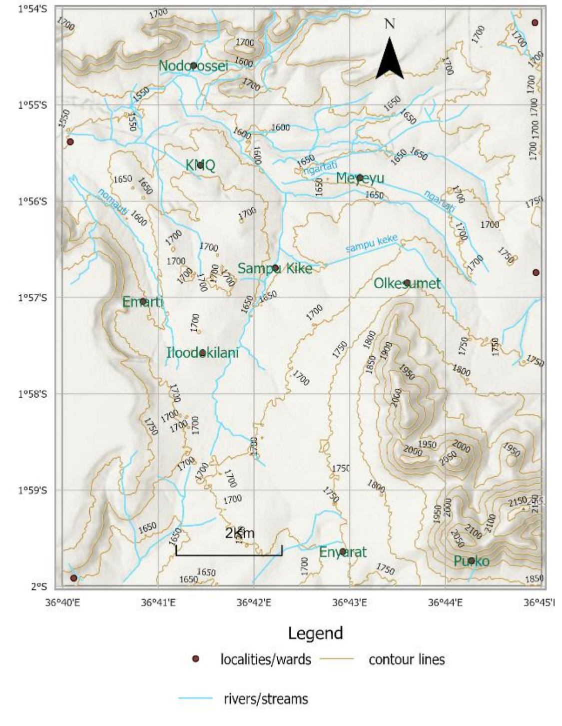

Figure 2: Relief and Drainage Map of the Study Area

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It is characterised by undulating landform networks of hills, valleys, and flatlands of varying heights, ranging from about 1500 to 2100m. Several perennial streams drain dendritically into smaller rivers within the drainage area (Figure 2). Famous for its rich mineral resources potential, there has been extensive quarry mining of crystalline limestone, started by Kenyan Marble Quarry Ltd, established as far back as 1923 and still continues to date (https://kenra.or.ke). In the present time, several other mining operators actively exist within the quarries. Other mineral resources in the area include wollastonite, garnet, and some gemstones but the crystalline limestone quarries constitute the major surface mines with tons of mined materials hauled on a constant basis for industrial processing.

Plate 1: a. view of KMQ community surrounded by basement hills

b. one of several crystalline limestone quarries in the study area

This paper relates geological and morphological contributions to groundwater behaviour in central and western portions of Kajiado County with the KMQ mining community being central, to further gain initial insights into possible impacts of geogenic and anthropogenic triggers for possible geo-environmental pollution. Information derived from this study contributes to the existing pool of scarce related pieces of literature covering the study area.

2. MATERIALS AND METHODS

2.1 Geological reconnaissance

Pre-existing geological maps (Matheson, 1966; Guth, 2014) and the Elangata Wuas Topographic Sheet 161/3 (Survey of Kenya, 1973) covering the study area served as base maps providing vital background geological and geographical information prior to field mapping. Detailed geological reconnaissance was conducted in March 2024 on a scale of 1:12,500 by ground traversing and making direct observations on outcrops to map rock types, contacts, structures, nature and lateral spread of weathering, as well as other mappable geological and morphological features. This was achieved mainly with the aid of a global positioning system, measuring tape, compass clinometer, digital camera, and geological hammer. Trends of hydro-structural features such as minor folds, faults, joints veins, and foliations were keenly measured. Field values recorded for various linear features were each entered into the GeoRose software for plotting rose diagrams. Information derived from the mapping exercise was used to construct a geological map of the study in the ArcGIS Pro environment.

2.2 Remote sensing

Lineament extraction through the analysis of remotely sensed raster data has been widely employed in geological studies. Key research (Waswa and Ogendo, 2019; Bawallah, 2020; Hussien et al., 2020; Mohamed et al., 2023; Oyawole et al., 2020) has demonstrated its effectiveness. For this study, lineament extraction was achieved through analysis of digital elevation raster (DEM) data covering the study area (USGS-EROS, 2022). The Hillshade raster analysis tool in ArcGIS Pro (https://www.esri.com) was utilized, with a directional view orientation of 350° at an angle of 30° to best portray linear features which were then digitized to produce lineament, lineament density, and kernel density maps. Direction values for all digitized lines were exported to GeoRose software (www.yongtechnology.com) for plotting Rose diagram. The output was compared to the structural data obtained from the field geological ground survey to determine their level of correlation.

Derivation of streams and rivers drainage system and delineation of outlets or pour points to produce a water shade or drainage basin was achieved from DEM raster using the spatial analyst tools (flow direction, flow accumulation, and watershed) in ArcGIS Pro environment (Li et al., 2021). Surface flow direction was determined by resampling using an output cell size of 0.4 for both the x and y axis and defining the flow direction in each pixel using ESRI's D8 flow directional code (https://www.esri.com). Inverse Distance weighted Technique (IDW) was used to construct a groundwater level map from groundwater table elevation data. Digital soil classification data was downloaded from the Food and Agricultural Organisation's website (https://www.fao.org) and symbolized in ArcGIS Pro to determine soil classes in the area.

2.3 Borehole inventory

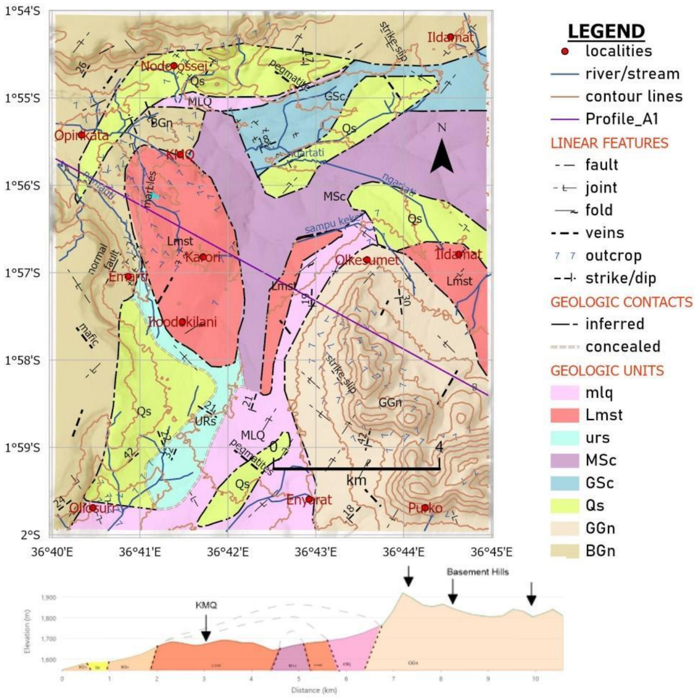
A field inventory of twenty existing boreholes within the rural communities was carried out to obtain first-hand information on the spatial distribution of existing wells in the area. No shallow well was encountered during the exercise due to the dip-sited nature of aquifers within the area. Information on the surveyed wells was obtained from the Kenyan Water Resources Management Authority (WARMA) including borehole logs – indicating depths and thicknesses of sub-surface geological formations (mainly the aquifers), water struck levels, static water levels. Values of borehole static water level were subtracted from surface elevation values to obtain groundwater contours. The groundwater contour values were gridded, and flow directions were determined using gridded vector layering. 3D wireframes for both surface and subsurface contours were constructed, all using Surfer Golden software (https://www.goldensoftware.com).

3. RESULTS AND DISCUSSIONS

3.1 Surface Geology

Rocks of the Kajiado area have been extensively mapped over the past decades by renowned researchers, notably (Parkinson, 1913; Smith, l950; Saggerson, 1964; Baker 1987; Ichangí & McLean, 1990; Nyamai, 1993; Guth, 2016). Rock suites of this area range in age from Achaean (Precambrian), through Miocene, Pliocene to Pleistocene, culminating in recent transportation and deposition of sands, sediments, and volcanic materials washed from uphill areas. These age ranges depict various orogeny regimes of folding and metamorphism, erosion and formation of peneplains, rift faulting, and grid faulting (Matheson, 1966).

The Precambrian metamorphic basement system rocks exposed in the study area form part of the Mozambique Belt and represent the closure of the Mozambique Ocean, whose deposition was suggested to have been initiated at about 1.4GA during the Pan-African Orogeny (Nyamai, 1993). These metamorphic rocks were formed between 800MA and 600 MA, from altered sediments associated with the ancient Mozambique Ocean. Lithologies include calcareous and crystalline limestone, quartzites, garnet-bearing biotite gneisses, banded gneisses, and graphitic and muscovite schists, being cross-cut by mostly quartz-feldspathic and other mafic veins and dykes, indicating minor igneous activities (Figure 4). There is a notable presence of phonolites, which are most probably what Parkinson (1913) referred to as the post-Kapiti Phonolites. They appear to have been transported and deposited along riverbeds due to their rounded shapes, predominantly outcropping around Ndorossei. Basement hills constitute the highlands and are typically composed of gneisses, also outcropping in Olliosur, Enkaron, and KMQ communities. Schists in the area occur almost entirely as low-lying and gentle dipping rocks trending mostly NW-SE along rivers and stream channels where they are exposed at side bottoms. They are highly weathered as a result of their weak, schistose nature. Quartzites occur predominantly as cobbles and pebbles, scattered along river channels roadsides, and feet of hills where they are exposed. They are most notable in areas around Olkesumet. Marbles are being quarried from within lateral limestone bands, in combination with somewhat gneissic bands which are exposed on the surface notably in the KMQ community, Emarti, along the road leading to Olkesumet and close to Meyeyu.



EXPLANATION

Geological units mapped in this present study in KMQ and its surrounding is been classified under the Turoka Series of the Precambrian Basement System rocks of Kajiado area as first postulated by Parkinson, 1913.

mLq - Limestone and quartz Lmst - Crystalline limestone
Ur - Undifferentiated rocks and sediments GSc - Graphitic Schist
Msc - Muscovite Schist Qs - Quartzite GGn - Garnetiferous Gneiss
BGn - Banded Biotite Gneiss

Figure 4: Geological Map of the Study Area

The predominance of garnets in the gneisses, with no notice of such minerals as kyanite or sillimanite which are all indicative of metamorphic grades suggests a garnet zone metamorphic facie, which means that metamorphism in the area, was highly intense (Saggerson, 1991). Megascopic observations on the various rocks encountered are given as follows;

i. Crystalline limestone mapped is mostly composed of calcite, making up white marbles but also, but other varieties of blue to green-coloured marble were encountered sporadically in the area, developed in quarry surfaces. Researchers suggests a staining effect on the coloured marbles after investigating a similar Crestmore blue marble (Rosenhaltz and Smith, 1950). Crushed limestone dust makes up a thin topsoil layer mostly within the quarries and some parts of the KMQ community (Plate 1).

ii. Muscovite schist consists of muscovite and biotite, with muscovite flakes being more dominant. It also composes a few fine-grained quartz and feldspar within its matrix. It is flaky and shatters easily along its cleavage planes.

iii. Graphitic schist appears flaky but has a pronounced graphitic luster which makes them quite distinct from the muscovite schist. It consists mostly of muscovite and biotite, associated with the graphite, and a yellowish amorphous alteration product most probably formed from the graphite.

iv. Banded biotite gneiss occurs in the study area as fine to medium-grained bands of melanocratic and leucocratic minerals, with the melanocratic bands dominating its matrix, thereby giving it a dark-greyish appearance. They are exposed on a quarry surface at Loodokillani, where they occur as folded bands within limestone layers. It consists mostly of biotite, hornblende, and feldspar with minute constituents of calcite.

v. Garnetiferous biotite-gneiss appears similar to biotite gneiss but differs due to the presence of abundant garnet knobs all over the rock matrix. Some of the garnet crystals are well formed, displaying visible rhombic faces within the rock-in-hand specimen. The rock also consists of some proportions of quartz hornblende and microcline, with biotite imparting a strong foliation on it.

vi. Quartzite occurs in the area as highly resistant, translucent, and homogenous crystalline grains. Most of their surfaces appear weathered, with interstices of some minerals such as iron occurring as impurities in some places. Aside from the presence of such dotted mineral impurities they are entirely made of quartz and occur in contact with gneisses and limestone in places.

vii. Phonolites consist of a grey-coloured microcrystalline groundmass, dotted with numerous, slightly elongated patches of felsic phenocrysts. They mostly occur as rounded cobbles, with few scattered ones, about the size of boulders.

viii. Minor Felsic/Mafic veins/dykes - Pegmatite makes up a large percentage of this unit, concordantly and discordantly cutting across the various rocks in the area. They are later hydrothermal products consisting mainly of large-grained quartz-feldspathic materials filling up fissures to form veins or dykes. They are also composed of micas and other accessory minerals occurring at lower proportions.

ix. Undifferentiated rocks are exposed predominantly along rivers and stream channels, constituting a mixture of river sands, quartzite, garnet-bearing gneisses being cross-cut by felsic/mafic veins and dykes alongside poorly sorted hornblende and iron-bearing cobbles and boulders scattered throughout the sand.

3.1.1 Structures

Regionally, the development of the Basement system rocks has been attributed first to a major ENE plunging orogenic folding, with most of the accompanying minor folds having dip angles between 20 to 30 degrees.

However, mutually perpendicular minor folds observed along river Kajiado displayed an NNW-SSE direction, an indication of possible major folds aligned in a similar direction believed to have occurred concurrently with the ENE trending folds. Foliations in the Basement System rocks strike principally toward NNW-SSE while lineations trend in a similar ENE-WSW fashion, both in tandem with the minor folds trends. Metamorphism which succeeded the folding regime resulted in the formation of migmatites and the injection of concordant pegmatites amidst resistant quartzites and limestone. Granitization, which marked the final stages of the metamorphic events led to the formation of quartz-feldspathic gneisses and the injection of discordant pegmatites, all prominent in the western areas of the Ngoragaishi (Matheson, 1966).

Minor structures mapped at a smaller scale provide key indications to the major ones in the sense that; interpretation of the major structures to a great extent depends on their evidence. As related to groundwater, key hydro-structural features mapped in this survey constitute the fractures, which include joints, veins, faults, folds, and foliations (Plates 2 and 3).

Plate 2: a. Joint sets, exposed at Okilotiti

b. Dip slip faulting on folded foliation planes at Meyeyu

Plate 3: a. Recumbent folds on gneissic bands exposed on a marble quarry face at Loodokilani

b. Quartzo-feldspartic vein at Emarti

About 1km southwest of KMQ mining areas, prominent folding signatures were observed on crystalline limestone quarry surfaces (Plate 3a) enclosing biotite gneiss which represents a manifestation of the Turoka fold (Joubert, 1957). The folds are recumbent in form, with almost parallel limbs, dipping 10°. Several minor symmetrical and asymmetrical folds were mapped sporadically within the study area (Figure 5a). Foliation planes dip mostly at angles ranging from 9° to 30° while striking principally toward NW-SE (Figure 6a). Numerous micro-fractures comprising joints, faults, and veins believed to have been formed by the final release of stresses from folding were also mapped. The veins are mostly comprised of quarto-feldspathic materials with quite distinct margins; cutting across foliation planes either discordantly or concordantly, in different locations. Joints and veins display principal trends along NEE-SWW, NE-SW, and NW-SE (Figures 6b) which correlates in part, with the trend of remotely derived lineaments (Figure 5b) principally along NE-SW and NEE-SWW (Plate 6c). The presence and architecture of microstructures in the area provide an indication for porous and permeable secondary aquiferous zones, which characterise the hydrogeological conditions of the area.

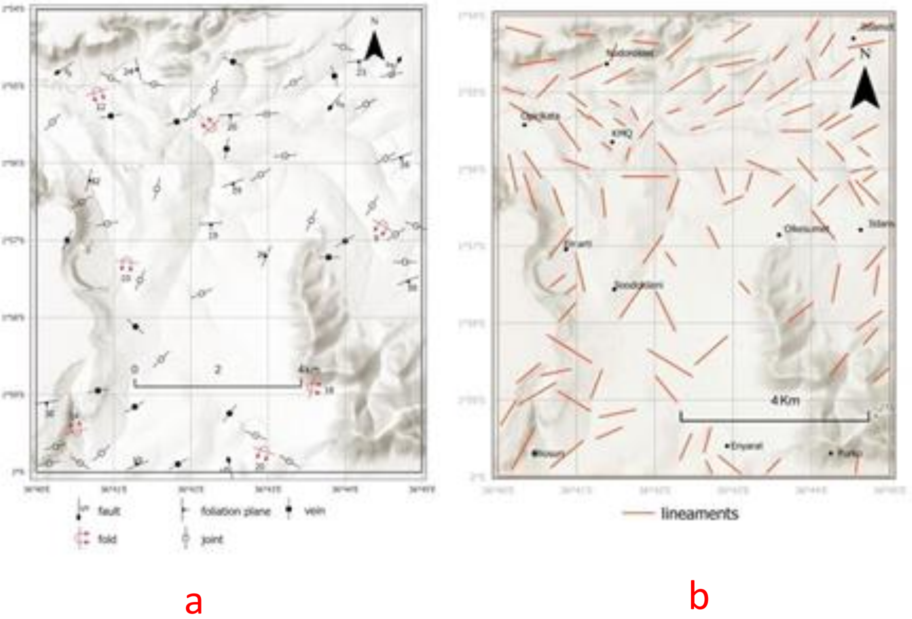


Figure 5: Structural Maps: a. Field measured linear features; b. remotely sensed lineaments

Locations with higher lineaments density depict favourable zones of groundwater accumulation or recharge areas due to their structural abundance. The linear fractures serve as storage and conduits for groundwater flow while fresh basements and impervious residual clays make up the confining layers, buttressing their significance on groundwater occurrence and movements.

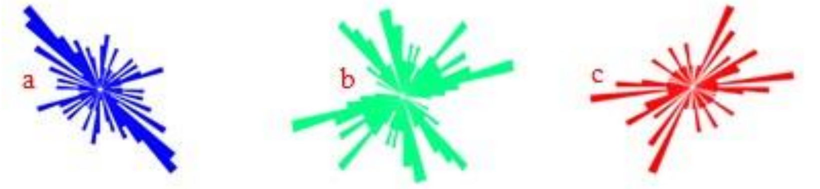


Figure 6: Structural trends: a. Foliations b. Field Joints/Veins c. remotely sensed lineaments

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3.2 Hydrogeology

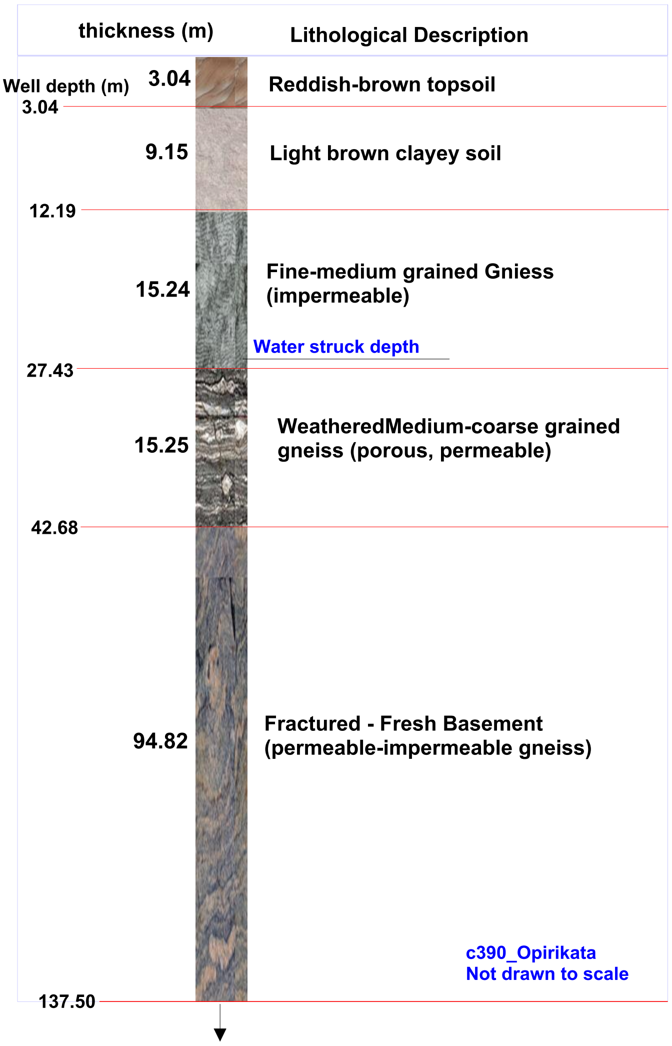
Groundwater aquifers in the study area are categorized under metamorphic basements and intrusive rocks comprising highly weathered and fractured gneiss, schist, and granites. These aquifers exist mostly in confined states, exhibiting secondary porosity with medium to low yields (Pavelic et al., 2012). Hydrogeological information from boreholes spread in different localities within the study area is presented in Table 1.

Table 1: Groundwater configuration of boreholes within the Study Area

Well No.	Locality	Depth of well (m)	Water struck level (m)	Water rest level (m)	Yield (m^3/hr)
C21265	Loodokilani	168	102	89	7.35
C25012	Kilotiti	250	155	96	3.9
C3970	Opirikata	138	25	17	2.16
C3810	KMQ	128	31	23	4.08
C3436	KMQ	76	43	36	7.2
C3951	KMQ	122	36	29	1.90
C3870	Sampu Keke	108	90	52	2.3
C2646	Mokinyo R	91	81	38	1.44
C587	Olkiloriti	92	41	23	7.57
C451	Turoka	137	109	106	5.6

(Source: Kenyan Water Resource Management Authority (WARMA).

Kernel density map from structural data indicates low-lying, valley-land areas having higher linear densities (Figure 9c). Such areas are excellent recharge areas from where groundwater resources can be accessed more readily. Generally, borehole locations in such areas as Sampu Keke, KMQ, Emarti, Kilotiti, and Loodokilani taps from aquifers lying beneath streams and river beds where recharge happens more rapidly. From Table 1, depths of boreholes range from 76 to 250 m, with water struck levels between 25 to 109 m. Water being struck at shallow depths is probably from perched lenses and is not sustainable in terms of quantity. In well C390, the water rise level reaches up to 17m which is caused by the pressure of overlying confining fresh basements. Figure 7(a-b) provides a graphical illustration of subsurface lithologies over the area.



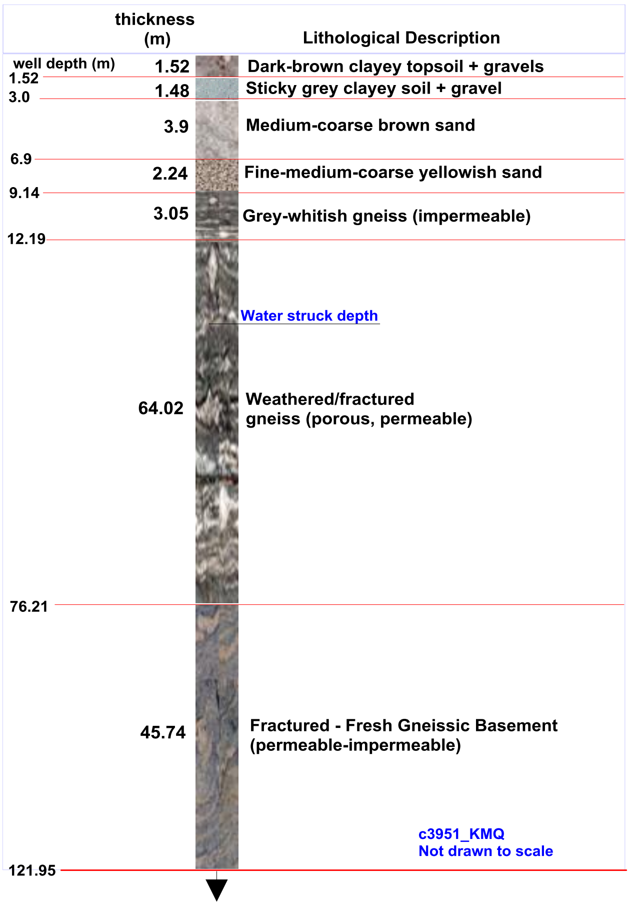


Figure 7a: Subsurface litho-logs of the borehole in Oprikata and KMQ

Depiction of actual aquifer nature and characteristics was made possible based on information gathered from borehole inventory as well as from logs for existing boreholes. The geological and structural makeup of the study area greatly influences its hydrogeology in that, the water-resistant ability of metamorphic folding in the area, formed impermeable basement rocks which confine underground fractured and weathered rocks, holding appreciable groundwater. Residual clays formed as a result of weathering also act as impervious layers at some depths as seen in borehole logs of KMQ and Oleperiakata.

Weathered and fractured gneisses almost entirely make up the aquiferous units in the study area as seen from direct point borehole logs. The viable or reliable ones are mostly deep-sited and are intermittently confined by fresh basements. Static water levels range with a small margin between 21 – 30 m indicating possibly a continuous nature of ductile impermeable confining rocks juxtaposed between weathered and fractured rock layers.

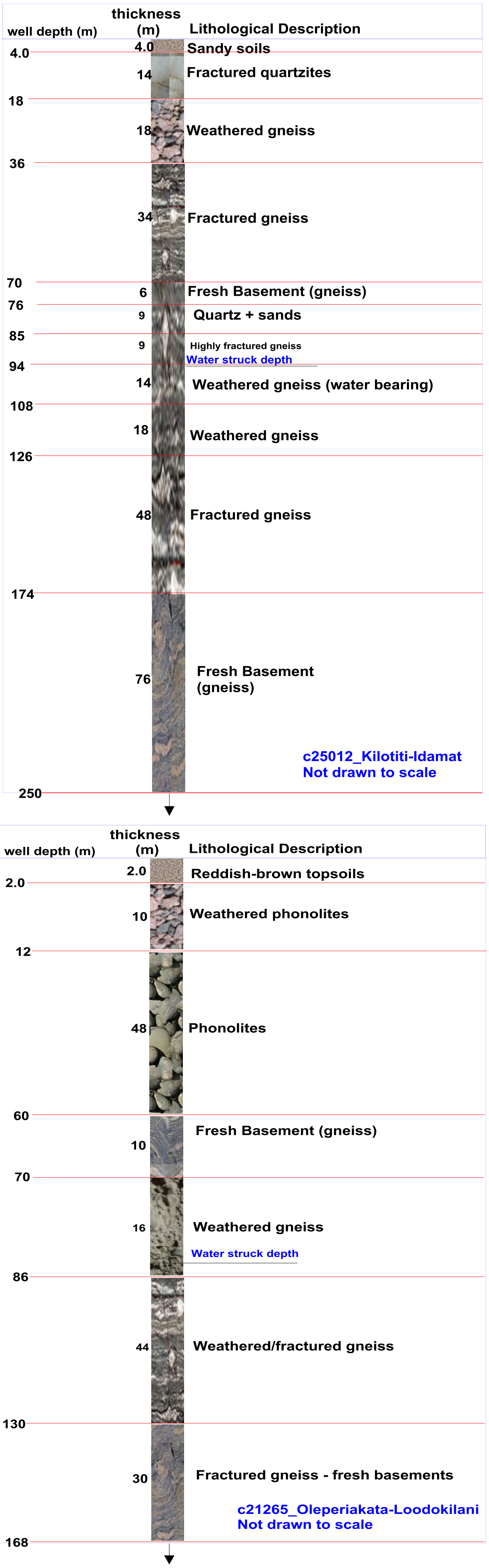


Figure 7b: Subsurface litho-logs of borehole in Ildamat and Loodokilani

Low yields (1.44 -7.35 m^3/hr) can be attributed to low recharge, occasioned by semi-arid climatic conditions of minimal precipitation. Furthermore, rapid groundwater flow in basement formations can be hampered due to their generally low secondary porosity as compared to primary porosity, and their surface drainage-dependent permeability. This makes flow prediction complex but it can be stated that weathering and fracturing extents are key determinants of the nature of groundwater and are responsible for its yield (Ganesh et al., 2018).

3.3 Geological and Morphological effects on water flow

The surface water drainage maps over the study area are presented in Figure 8. The watershed area was classified into three zones A, B, and C, with an area of 22 km2, 41 km2, and 21 km2 respectively, totaling 84 km2 for the entire river catchment basin, characterized by numerous seasonal run-offs, streams, and river courses. Comparing surface flow directions (Figure 8b) with surface elevation levels (Figure 8c), flow directional arrows diverge from regions of high elevation values, pointing towards low contour areas. This strongly suggests a morphological effect, with run-offs being topographically controlled. Various streams drain into a network of smaller, valley-stretching river courses in a dendritic manner. Their flow paths are topographically and geologically controlled, due to their random flow directions along linear surfaces. Main river courses identified within the catchment basin include; Ndorossei and Nomauti, comprising zone A, hosting the KMQ mining areas; Sampu Keke and Essiati comprising zone B, which borders south of KMQ and Ngartati, comprising zone C (Figure 8a). These water courses appear to flow towards the adjacent river Kajiado located to the east, due to a SE flow directional mean derived for surface water flow in the area.

The western, north-western, and south-western boundaries of the study area form portions of the Emarti-Olkempai hills. Water flows in a more eastward fashion from these hilly areas into lowlands within the study area. Away from the western border of the study area and mostly on the opposite side of the Emarti-Olkempai hills is River Turoka, which also falls outside the catchment basin for this study. Similarly, on the south-eastern boundary of the study area lays the Ilemelepo hills from where water flows in numerous minor directions, in and out of the water catchment areas. This means that the study area is bounded by two prominent rivers; Turoka to the west, and Kajiado to the east. On the entire southern boundary of the study area, water flows further south, out of the delineated catchment basin. Regions of flow outside the delineated catchment basin could serve as good control sampling points owing to contributions from different rivers not associated with the study area catchment.

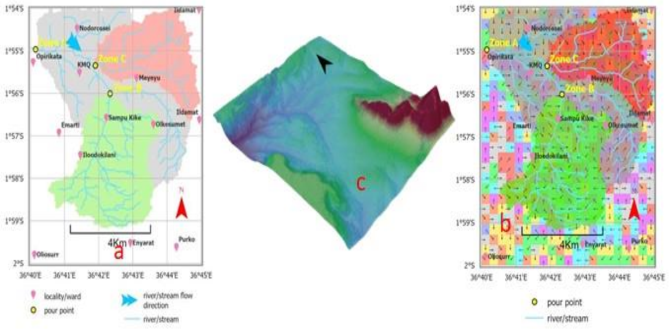


Figure 8: a. Surface water drainage area b. Surface water flow direction c. 3D Surface elevation Configuration map

The Boundaries between zones A, B, and C constitute the surface water divides from where water drains into the outlets within the catchment zones. Three recharge areas have been delineated for the study area at KMQ, Sampu Keke, and Opirikata (Turoka). Opirikata, with the largest drainage area, draws water from Olkesumet, Ndorrosei, and also KMQ. Sampu Keke derives water from numerous streams flowing towards it from the Iloodokilani. KMQ community is recharged by Ildamat and Sampu Keke. The multi-directional stream flow in the area is in tandem with the occurrence of also multi-directional micro-structures which serve as flow controls as well as passages for surface infiltrations. Mean directional water flow indicates a significant NW-SE orientation, tallying with principal trends of foliations, joints and veins which suggest strongly structural influence on stream flows.

Figure 9 (a-d) illustrates the groundwater table configuration over the study area. Main aquifers in the area are the weathered and the fractured gneiss, all characterised by secondary porosities due to the impact of tectonism in the area. They are recharged directly by topographically controlled precipitation flows and also indirectly by structurally driven subsurface flow through fractured basement systems. A key morphological consideration of groundwater exploitation in area is citing of most boreholes on depressed lowlands along river beds, to tap water from aquifers situated beneath surface water courses from where they are readily recharged. Surface water bodies become inactive in dry season, signifying that groundwater movement over the area are confined to greater depths and do not rise appreciably to shallower depths where they could feed the river and streams or even form seepages. Lack of sufficient borehole information from the southern parts of the area impeded adequate representation of ideal groundwater flow scenarios in those areas. In figure 9a, the blue and yellow areas are the recharge zones while the brown areas are discharge. Figure 9b shows a general west-ward groundwater flow pattern on the southern areas which probable might not be the true situation as earlier pointed out due to lack of adequate data in those parts. Their flow patterns assumes after the surface topographical patterns.

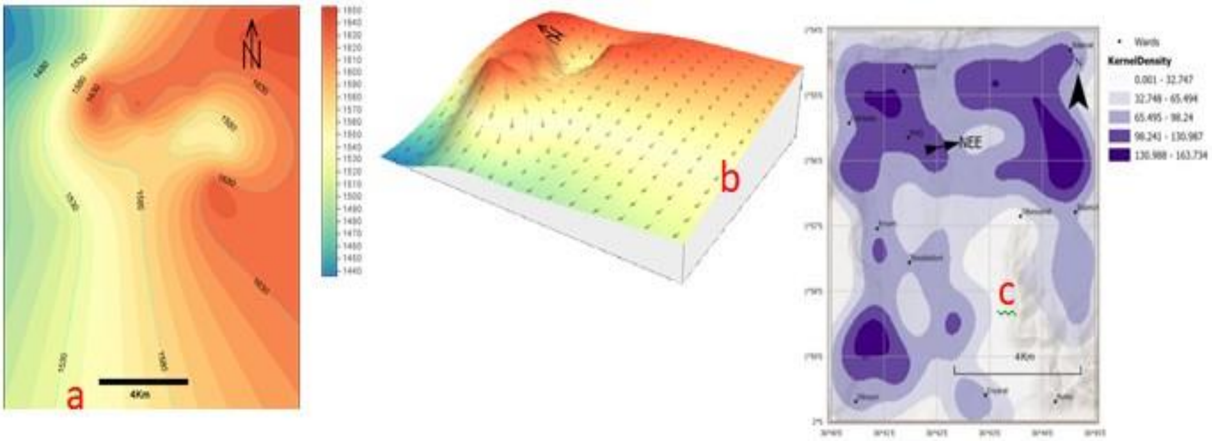


Figure 9: a. Groundwater Level Map b. Flow direction on 3D Groundwater Elevation Surface c. Lineament Kernel Density Map

Lineament density spread over the study is depicted in Figure 9c. The deep violet areas are those with high concentration of fractures while those in lighter colours have lesser concentrations of hydro-structural features. Most of the localities of interest in this study such as KMQ community, Ildamat, Ndorrosei, Olkesumet, Sampu Keke, and Opirikata fall under high to moderately high linear density areas. There is a strong correlation between the kernel density and the groundwater level map with recharge areas having high concentration of structures. In groundwater exploration studies, these combinations make up the promising areas. Constant rock-water interaction in confined states will foster more chemical reactions which determine the overall physic-chemical characteristics of the groundwater.

3.4 Indications for Pollution

As highlighted in the paragraph above, activities occasioned by the geological make-up of the study area could affect the groundwater adversely. In this study, we consider some geological pre-cursors unique to the study area, both natural and man-induced, that could pollute or contaminate soils and groundwater. Without overlooking the contributions from such practices as agriculture and others, we consider the possible geological effects of weathering and mining activities on the physic-chemical nature of groundwater.

3.4.1 Weathering effects

Recently deposited sands exist mostly along stream channels in the area, constituting the alluvial sands. Rocks and sediments in the study area that have undergone surficial modification by physical and chemical interaction with organic material and rainwater, over time, forms a substrate (soils) which support the growth of plants by providing it with nutrients. They overlie the basement to a large extent, impairing the delineation of exact lithological boundaries in most locations. The two dominant soil classes covering the study area are presented in figure 10.

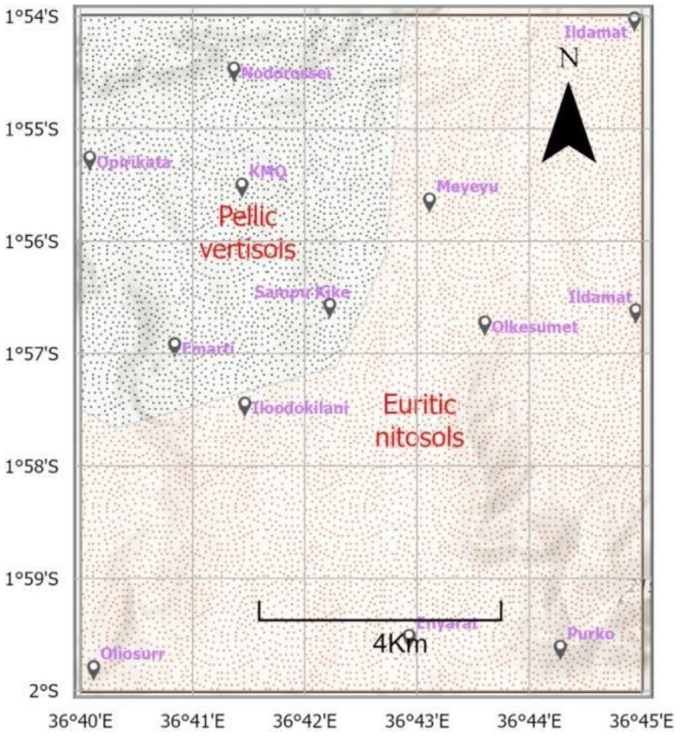


Figure 10: Soil classification map of the Study Area (www.fao.org/soils-portal/data-hub/soil-maps-and-databases/)

The pellic vertisols are dark grey soils, with high amounts of swelling clays predominant around the dark graphitic schist areas around Ndorossei, Emarti, Opirikata and KMQ; and the reddish brown euritic nitosols are felsic and aphanitic in nature, found in parts of KMQ community, Oilisurr, Enyarat, Purko, Olkesumet and Ildamat. Soils serve as interface between the lithosphere and the biosphere and are products of weathering with input of organic material as some form of carbon. As shown in Plate 3, different layers of the soil profiles in the study area are not the same as beds formed by sedimentation, instead each of the horizons forms and grows in place by weathering and the addition of organic material from decaying plants and plant roots.

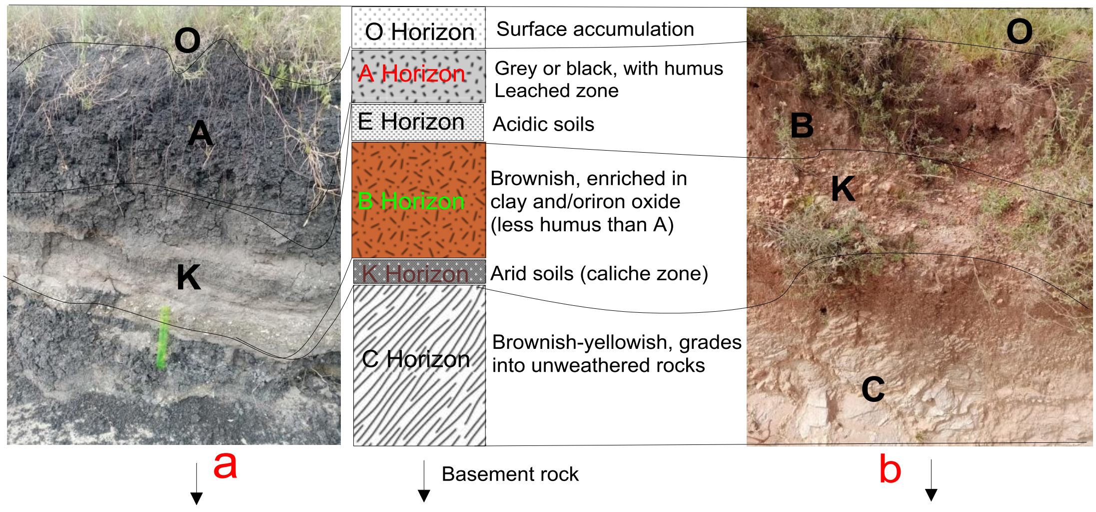


Plate 3: Soil Profile a. Pellic vertisols at Emarti b. Euritic nitosols at Olkesumet

Calcium Carbonate from limestone in soils of the study area is portrayed in the in the K horizon, formed by chemical precipitation of calcite. The Ca and Carbonate ions are dissolved from the upper soil horizons and precipitated at the K-horizon (caliche zone). In arid and semi-arid climate conditions, the amount of water passing through the soil horizons is not enough to completely dissolve this caliche, and as a result the thickness of the layer may increase with time. Excessive concentration of chemical constituents in soils significantly increases chances of pollution (Juo and Franzluebbers, 2003).

The basement rocks in the study area displays evidence of high weathering and erosional activities which leads to both physical and chemical breakdown of rocks, corroborated with geological reconnaissance in KMQ which revealed extensive weathering in response to pressure and temperature conditions, as well as the influence of water and oxygen present on the surface. This is evident in massively disintegrated of rocks and minerals by mechanical process which presents a thriving ground for chemical alteration or decomposition of rocks and minerals in the area (Plate 4).

Plate 4: Weathered portion of a NW-SE trending schist, exposed at about 2 km west of KMQ

Rocks and minerals disintegration into to smaller fragments or into minerals that are more stable near the earth's surface creates broken detritus of clay, silt, sands, pebbles, cobbles and boulders with physical weathering being most active in fractured rocks. Free spaces in fractured rocks are avenues for both physical and chemical agents of weathering to thrive (Batjes, 2009). Water percolating through these fractures and voids may contain ions that precipitate to form crystals whose growth may exert an outward force that can expand or weaken rocks. Also, immediate exposure of rocks to high temperatures may cause thermal expansion and eventual breakage of rock. Plant roots can extend into fractures and grow, causing expansion of the fracture and imminent weathering.

The low temperature- pressure and high free water-oxygen conditions of the earth surface differ greatly from those beneath the earth's surface where rocks were originally formed. When deeply formed rocks get exposed on the surface as a result of uplift and erosion, their minerals react with the new environment to form new minerals, stable under their present conditions. This results in chemical weathering, forming minerals such as hematite, gibbsite, quartz, muscovite, alkali feldspars, biotite, amphiboles, pyroxenes, Ca-rich plagioclase, olivine and other clay minerals

Chemical weathering reactions are triggered mainly by water and weak acids (with abundant free H^+ ions) formed in water. Most commonly, carbonic acid (H_2CO_3) is formed in rainwater when the water (H_2O) reacts with carbon dioxide (CO_2) gas in the atmosphere.

$$H_2O + CO_2 \longrightarrow H_2CO_3 \longrightarrow H^+ + HCO_3^- \tag{1}$$

Carbonic acid

Various forms of reactions could take place, resulting in formation of new stable minerals:

- Through hydrolysis, H^+ or OH^- replaces an ion in the mineral.

$$\underset{\text{Orthoclase}}{4KAlSi_3O_8} + 4H^+ + H_2O \longrightarrow 4K^+ + \underset{\text{Kaolinite}}{Al_4Si_4O_{10}(OH)_8} + \underset{\text{Quartz}}{8SiO_2} \tag{2}$$

- Through Leaching, ions are removed by dissolution into water. (K^+, leached in equation 2 above).
- Through oxidation, free oxygen (O_2) near the earth's surface may react with minerals to change the oxidation state of an ion, more especially for iron bearing minerals with several oxidation states, Fe, Fe^{+2}, Fe^{+3} on the surface. In the Earth's interior, most common oxidation state of iron is Fe^{+2}.

$$3Fe^{+2}SiO_3 + \ 1/2O_2 \xrightarrow{\qquad} Fe_3O_4H^+ + 3SiO_2 \tag{3}$$

Pyroxene Magnetit Quartz

- H_2O or OH^- ion is from a mineral through dissolution.

$$2FeO.OH \xrightarrow{\qquad} Fe_2O_3 + H_2O \tag{4}$$

Geothite Hematite

Complete mineral dissolution could also occur by water

$$CaCO3 + H2CO3 \xrightarrow{\qquad} Ca2+ 2(HCO3)^- \tag{5}$$

Calcite Carbonic acid Bicarbonate ion

Possible by products of weathering of rocks in the study area is summarized in table 2.

Table 2: Weathering by-products of basement rocks in the study area

Rocks encountered	Primary minerals	Common Residual minerals after weathering	Some commonly leached ions
Crystalline limestone	calcite	--	Ca^{+2}, CO_3^{-2}
Schists		Quartz, clay minerals, garnet, rutile, magnetite	
Gneisses/granites	Feldspars	Clay minerals	Na^+, K^+
	Micas	Clay minerals	K^+
	Quartz	Quartz	---
	Fe-Mg Minerals	Clay minerals, Hematite, Geothite	Mg^{+2}
Quartzite	Quartz	Quartz	

Based on variations in rock types in KMQ area, contributors of pollution is expected to be more in areas underlain by certain rocks. For instance, it is expected that gneiss consist of quartz which is stable under weathering condition as compared to limestone, whose minerals can undergo complete dissolution, of calcite in wet conditions. Fractures further provide pathways for the entry of water fostering rapid weathering. Contrasts in the susceptibility to weathering between different rocks will result in differential weathering which could play a major role in pollution distribution within the area.

3.4.2 Mining effects

Active marble mining operations in KMQ involve a range of activities, from blasting, quarrying, processing and haulage operations, and poses treats for various forms of environmental pollution (Cohen and Gorman, 1991). Inefficiently managed mine waste tailings from mining and mineral processing spell impending danger for soils, surface, and groundwater pollution in the area. Sulphide minerals, exposed to oxygen and water near the surface forms sulphuric acid which can acidify rainwater, creating toxic runoff conditions (Bolan et al., 2021). This kind of acidification can mobilize potentially dangerous heavy metals into soils streams draining the tailings. The possible discharge of excessive heat from mining, processing and haulage equipment this into water can result in thermal pollution of the water. Massive disintegration of rocks due to mining holds the potential of releasing excess heavy metals and ions into the environment. Based on topography mine tailings and disintegrated rocks (Plate 5) from uphill areas have high possibility of being washed down by rains into streams and underground rock layers.

Plate 5: Disintegrated rocks and mine wastes exposed at KMQ

4. CONCLUSIONS

Observations from surface and subsurface geological and topographical patterns, and the soil nature of the study area revealed that run-off within the drainage basin is governed chiefly by land surface elevation, as its flow directions correlate strongly with surface elevation and the nature of soils. Variations in surface lithological make-up are highly influential to patterns, rates and timing of surface stream flows and groundwater recharge in the KMQ areas. Sharp contrasts in groundwater flow directions strongly suggest structural influences on groundwater occurrence and movement occasioned by the occurrence of groundwater water in zones of fracturing and weathering as indicated by logs of boreholes spread across the study area. In as much as the introduction of foreign contaminants from anthropogenic sources cannot be completely ruled out, the deep-sited nature of confined aquifers and the contaminant's travel time form more ideal bases on geogenic factors, but investigations into possible anthropogenic sources in the area mainly from farming may be necessary. This background information can be further substantiated through geochemical and geophysical investigations to fully visualise and characterise aquifer and geo-environmental conditions.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR'S CONTRIBUTION

- Moses Ancho Isa conducted fieldwork and drafted the manuscript.
- Charles Maina Gichaba played a supervisory role in facilitating data collection, providing reviews, and structuring the manuscript.
- Aaron K Waswa played a supervisory role in facilitating data collection, providing reviews, and structuring the manuscript.

All authors hereby approve the final article.

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