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Prospecting for safe (low fluoride) groundwater in the eastern African Rift: a multidisciplinary approach in the Arumeru District (northern Tanzania)

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Abstract

This research was aimed at finding fresh and safe groundwater easily deliverable to an area, located in northern Tanzania, within the western branch of the Rift Valley. The study area suffers from water shortage, moreover, due to widespread alkaline volcanism, high fluoride contents (F^- up to 70 mg/l) affects the groundwater.

The achievement of this goal has been pursued through a multidisciplinary research consisting of geological, hydrogeological, hydro-chemical, geophysical and hydrological investigations.

The study area stretches over 440 km^2 and lies in the northern part of the Arumeru District, approximately 50 km from Arusha, the capital of the region. The Mount Meru (4565 m a.s.l.) and the Arusha National Park mark the boundary of the area, which includes 9 villages belonging to the Oldonyo Sambu and Ngarenanyuki Wards. The climate is semi-arid, with dry and relatively rainy seasonal alternance.

Four principal hydrogeological complexes have been identified within different lithologies. They occur within volcanic formations, singularly or superimposed on each other. Subordinate perched aquifers are present in sedimentary formations with local occurrence. The groundwater flow system has been interpreted on the basis of springs spatial distribution combined with lithological and the geometrical reconstruction of the aquifers. The dominant pattern, consisting of multidirectional flow from the higher elevation area in the south towards the lower area in the north, is complicated by the occurrence of structures such as grabens, faults, lava domes and tholoids. After the identification of the main fluoride source, an interference pattern among groundwater and high F surface water was drawn. Finally, some VES (Vertical Electrical Sounding) were performed that allowed an aquifer to be individuated within a structural high where the fluoride input is prevented. The drilling of a well, able to supply at least 3.8 l/s of low fluoride, drinkable water, successfully concluded the methodological approach for prospecting safe water in a semi-arid, naturally fluoride polluted region.

1 Introduction

Due to water shortage in the wards of Ngarenanyuki and Oldonyosambu (Arumeru District, northern Tanzania), the average per capita daily water consumption is 8 litres. The availability goes down to 3–4 litres in the dry seasons when most of the population cannot resort to using seasonal ponds or streams, being so compelled to concentrating around the few perennial water points. This datum is quite far from the Millennium Development Goal (MDGs) objectives that foresee a quantity of at least 20 l/d/p (litres per day per person) for the Developing Countries population, by 2015 (United Nations, 2000). Besides water availability, serious problems are related to water quality. In fact, the scarce water resources are affected by high fluoride contents that characterises both surface water and groundwater. This circumstance affects the entire East Africa Rift System due to the widespread alkaline volcanism (Tekle-Haimanot et al., 2006; Jaroslav and Annukka, 2007).

Nevertheless, within the Rift, the fluoride level of the groundwater can exhibit meaningful variations, even at local scale (Tekle-Haimanot et al., 2006), depending on the influence that different geological features exert on the geochemical composition; in addition the low scale variability of the climate factors, which are typical of the Rift Valley, also contribute in modifying fluoride levels.

It is generally accepted that groundwater is enriched with fluoride by prolonged water-rock interaction (Banks et al., 1995; Gizaw, 1996; Frengstad et al., 2001; Carrillo-Rivera et al., 2002). Lithology, therefore, is regarded as an important factor in determining the fluoride concentration of groundwater. Previous studies show that fluoride is generally enriched in groundwater from bedrock aquifers in alkaline magmatic rocks and metamorphic rocks (Banks et al., 1995; Dowgiałło, 2000; Botha and van Rooy, 2001; Shanker et al., 2003). Common natural sources responsible of F release are minerals, such as fluorspar, fluorapatite, amphiboles (e.g. horneblende, tremolite) and some micas.

Since an excessive consumption of fluoride can cause serious pathologies classified as dental fluorosis and skeletal fluorosis (Moller et al., 1970; Tekle-Haimanot et al., 2006), consumption of high-F water in the Rift Valley caused the endemism of these pathologies in several Northeast and East African countries, notably Ethiopia (Lester, 1974; Tekle-Haimanot et al., 1987; Kloos and Tekle-Haimanot,1999), Sudan (Smith et al., 1953), Tanzania (Kilham and Hecky, 1973), Korean Peninsula (Kangjoo and Gi Young, 2005). The highest fluoride levels have been reported in the Kenyan lakes Elementaita (1640 mg/l) and Nakuru (2800 mg/l) (Tekle-Haimanot et al., 2006).

On this account, the World Health Organization has imposed a limit of 1.5 mg/l of fluoride (WHO, 2006), but the Tanzanian government has been forced to raise this limit from 4 to 8 mg/l, just in order to overcome the widespread problem of water shortage.

In order to find safe and fresh groundwater, this multidisciplinary study of a critical rural area within a semi-arid microenvironment, dominated by alkaline volcanic rocks, was carried out with the aim of identifing:

1. the main local source of fluoride;
2. possible aquifers spared by fluoride infiltration/release;
3. the best way to exploit eventual safe groundwater.

2 Study area

2.1 Location, climatic and physiographic setting

The project involved one portion of the District of Arumeru, that belongs to the Region of Arusha, with an area of 2966 km^2. The District is administratively divided into 6 Divisions, 37 Wards and 133 Villages. The district of Arumeru is situated in northern Tanzania, between Mount Kilimanjaro on the east, Mount Meru on the south, the road that joins Arusha (Tanzania) with Nairobi (Kenya) on the west and the National Park of Amboseli (Kenya) on the north (Fig. 1). In particular, the working area (440 km^2) is located in the northern part of the District, around 50 km from the city of Arusha, is bounded by Mount Meru (4565 m a.s.l.) and the Arusha National Park, and includes 9 villages belonging to the Oldonyo Sambu and Ngarenanyuki Wards. Three main ethnic groups are present: the Wameru, which are farmers, Waarusha and Maasai, which are cattlemen.

Despite its proximity to the equator, the study area enjoys an Afro-Alpine semi-arid climate, characterized by two distinct seasonal weather patterns. The main wet season extends from June to September and contributes to about 70% of the total annual rainfall. A minor rainy season from mid February to mid May contributes the rest of the moisture in the region. The remaining months of the year are more or less dry, at times with occasional, erratic showers. The lowest and the highest annual average temperatures are 20.6°C and 28.5°C, respectively, and the average annual rainfall is 535.3 mm (AA.VV., 2000; Gea, 2005).

As shown in Fig. 1, the topography of the area is dominated by the volcanic cone of Mt. Meru (4565 m a.s.l.); its slopes cover most of the area. The remaining land is overlain by alluvial fans, which, with gentle slopes, are fed by Mt. Meru. Recent small volcanic cones are preserved in the NW part of Meru and small maar-type flat craters occur. Permanent saline water characterises the Big Momela lake and the Small Momela alkaline lakes, both inside the Arusha National Park, east of Meru.

The drainage pattern around the Meru is clearly radial, but downhill the stream courses are modified by tilting and capture. East and north-east of Mt. Meru, the only perennial stream is the Engare Nanyuki river, the waters of which have very high fluoride content as it is mainly fed by a spring with a yield of about 5 l/s and a F^- content of 60 ppm. This stream flows northwards into the inner Amboseli Basin allowing local irrigation.

2.2 Geological and hydrogeological setting

The following, general geological descriptions are based on the Geological Sheet “Arusha”, Quarter Degree Sheet 55, 1983, scale 1:125 000 – Geological Survey of Tanzania, while the hydrogeological setting is based on results from this research.

The age of the volcano-sedimentary sequences of the study area is Cenozoic: in particular, the older ones go back to Miocene-Pliocene, whereas, the most recent are sub-actual. The dominant lithology is represented by volcanic rocks and, subordinately, by alluvial deposits (Fig. 2). The crystalline basement does not outcrop in the area, however, it has been found at a shallow depth, a few kilometers north of the study area.

Mt. Meru can be considered an active volcano, representative of the alkaline magmatic activity that characterises the east Africa rift system. Its last eruption dates back to 1910, when small amounts of black ash were ejected for a few days from the Ash Cone. Most of the recent lava activity took place during the half-century prior to the ash eruption in the form of lava domes. Up to 1954, significant fumarolic activity was recorded in the Ash Cone area. In 1974, a careful survey showed neither fumarolic activity nor anomalous soil temperature.

Major rift faults are present in the NW of the research area. Linear features and benches are frequent on the flanks of Meru and it is highly probable that the early volcanic structure has been block-faulted. In the central area, the faults trend N-S to NNE-SSW (Uwiro graben); in the NW area the trend is NW-SE (parasitic cone alignment). However, thick mantling ash and other younger formations make it difficult to map faults with confidence. The age of this faulting must lie between that of the flood lavas (2.3 million years BP) and that of parasitic cones (1.7 million years BP), some of whose lavas cover the fault scarp. This is consistent with the fault-phase found elsewhere about of 2.1 million years BP (AA.VV., 1983).

The hydrogeological setting has been compiled by combining an existing geological map (AA.VV., 1983) with new hydrogeological and geophysical surveys carried out during the course of this work. In this way, a broad reconstruction of hydrogeological parameters like aquifer geometry, storage capacity, permeability, recharge areas, etc. of the study area, have been assessed.

The main aquifer systems are made up of volcanic formations, occurring singularly or superimposed on each other. Subordinate perched aquifers are present in sedimentary formations, with some of these aquifer systems having been localized.

The thickness of the volcanic rocks is known only approximately because of the uncertainties associated with the geologic and geomorphologic events during the Cenozoic. However, it is clear that all these events exerted a strong control on the geometry of the aquifers, on the recharge and discharge areas and on the groundwater quality. Moreover, the scale of the map and the amount of available data does not allow a detailed mapping of all these parameters. From a hydrogeological point of view, the litho-stratigraphic formations can be grouped into two main hydrogeologic units, namely a Volcanic unit and a Sedimentary unit (Fig. 2).

2.2.1 Volcanic hydrogeologic unit

This unit is divided into four hydrogeologic complexes:

- Meru west Group (Nvm);
- Lahars of various age (Nzd_1), Ngare Nanyuki lahars (Nzd_2), Momella Lahar (Nzd_3);
- Main cone group (Nvm), Ash cone group (Nvn);
- Mantling ash (Nvf);

Meru west Group (Nvm) complex

This formation, that belongs to the “older extrusive”, is exposed into the west of Mt. Meru. The rock are essentially nephelinite lavas and breccias that contain dominant

phonolite clasts. The aquifer hosted in this formation has a fractured permeability.

Lahars of various age (Nzd_1, Nzd_2, Nzd_3) complex

From a hydrogeologic point of view, all these lahars can be grouped into a unique complex. Lahars (Nzd_1) of considerable extension were commonly formed interbedded with sedimentary sequences. These lahars are characterised by large and abundant boulders, of feldsparphyric phonolite with alkali feldspar phenocrysts, in a differently hardened fine-grained matrix. Nzd_2 and Nzd_3 are exposed North-East and East of the volcano. The former near Ngare Nanyuki and Uwiro graben and the latter near the Momella Lakes. The aquifers hosted in these rocks have a double permeability as they are both fractured and, at some extent porous.

Main cone group (Nvm) complex

The Meru volcano became active in a period ranging about 200 000–80 000 years BP. The volcanic activity built up the main cone to an altitude of at least 4877 m a.s.l., perhaps considerably higher at one time. The Main Cone group (Nvm) and Little Meru group (Nvp) materials are predominantly volcanic breccias and tuffs of all grain sizes, but phonolitic and nephelinitic (Nv) lavas are intercalated sporadically. The aquifer hosted in these rocks presents double permeability (fractured and porous). In this system, the elevation difference between recharge and discharge areas allows the infiltration of rain water, particularly where the permeability is high (intensive fracturing). This evidence, along with the considerable number of springs with important yield, leads to effective groundwater circulation with short residence time. Another feature of the Main Cone group is the common occurrence of viscous domes or tholoids (Nvg), usually of a feldsparphyric phonolite composition. These may occur at all levels, but there is a zone of especially large adventitious tholoids on the northern flanks (i.e. M. Songe). The occurrence of domes constitutes a lateral hydrogeological impermeable limit, that controls the groundwater circulation.

Mantling ash (Nvf) complex

Thick ash, pumice and tuff deposits overlie large areas in the foothills of Mount Meru, especially on the western slope. In the study area, the complex crops out near Oldonyo Sambu, and Kisimiri (North of Meru). This formation, due to fine-grained nature and clay alteration, is practically impermeable, so no springs occur within it. Sometimes this complex underlies or surrounds an aquifer.

2.2.2 Sedimentary hydrogeologic unit

This unit is made up of fine-grained alluvial and lacustrine sediments, hence it is characterised by low transmissivity. The occurrence of these sediments characterises a swampy flatland crossed by the Engare Nanyuki river, which terminates towards the west in an area scattered with alkaline lakes. A perched aquifer occurs in this formation with a low productivity: few springs are present with poor yield.

3 Materials and methods

3.1 Hydrogeological surveys

The hydrogeological surveys have been extended outside the limits of the two Wards: dealing with identification and census of 52 water points and 46 springs (30 in the Ngarenanyuki, 16 in the Oldonyosambu ward) and includes 6 surface water samples (rivers and lakes).

For each water point, the following parameters were collected: elevation, geographic coordinates, pH, electric conductivity, temperature, fluoride content, yield (estimated values) hydrogeological characteristics and spring classification (Tables 1 and 2).

Every water point was identified with an alphanumeric code and for each the following parameters were collected: elevation, geographic coordinates and hydrogeological characteristics. A global position system (GPS, Garmin – Geko) was used to locate

each feature. Analyses of groundwater samples including fluoride, pH, electric conductivity, and temperature were carried out in situ. Fluoride was measured with a Fluoride LR Photometer (Hanna Instrument HI 93739). Temperature, pH and electrical conductivity at 25°C were measured with a portable pH-conductivity meter (HI 98130 HANNA Instruments).

These parameters were acquired during an hydrological year, i.e. both in the dry and in the wet season with the aim to design a feature monitoring network.

For each water point, a monographic data sheet was completed; after which the data were organized in a digital database and GIS, using ArcView 9.2 and the open source software gvSIG.

The locality of all water points were plotted in order to have the immediate distribution of all the parameters, particularly the fluoride content (Fig. 2).

3.2 Geophysical surveys

Geophysical surveys have been carried out in the two wards of Ngarenanyuki and Oldonyosambu, with the aim of evaluating the potential of the two areas with respect to groundwater resources. Measurements have been performed by means of the VES (Vertical Electrical Sounding) technique with a Schlumberger electrode array, and an ABEM Terrameter SAS 300 as an acquisition system. The apparent resistivity curves have been interpreted using a computer software based on the linear digital filtering method (e.g. see Koefoed, 1972, 1979; O'Neill and Merrick, 1984) as is well known, modern software packages based on this method can cope with even extreme resistivity contrasts and deal with a large number of layers. On the whole, 15 soundings in the Oldonyosambu Ward and 33 in the Ngarenanyuki Ward were acquired. In the Oldonyosambu Ward, the results were rather disappointing, since no clear sign of exploitable groundwater was found in the apparent resistivity curves and respective interpretations. Conversely, in the Ngarenanyuki Ward, the VES campaign allowed the location of several areas potentially interesting for groundwater and, therefore, only soundings pertaining to this ward will be discussed. The VES position map for the

Ngarenanyiuki Ward is shown in Fig. 3.

4 Results

As shown in Fig. 2 and Table 1, most of the springs with low fluoride content (below the Tanzanian standard for rural water) outpour from unaltered lavas, either basaltic or phonolitc, mainly located in a lofty position within the *Main Cone Group Complex* in Mount Meru and, to a less extent, in its northern lower slope. Particularly, fluoride seems to concentrate in water flooding from lahars and lacustrine deposits. A meaningful exception is represented by the spring 26 Eng (Fig. 2) located within the Meru cone at 2502 m a.s.l. of altitude. This spring, considering the temperature (22.4°C) and location is of hydrothermal origin, feeds the Engarenanyuky River with a yield of 6 l/s with an exceptionally high fluoride content ranging between 59 and 68 mg/l. Such a water can be considered a pollutant for the river and, consequently, for the aquifers in hydraulic communication with it. Particularly the area of structural low within the Uwiro graben where some epiclastite-hosted aquifers can be fed by the river.

Epiclastite and also proximal lahars are separated by paleosoils (Fig. 4) that can concentrate and release fluoride due to the anionic exchange capacity of both phillosilicates and zeolites occurring as a byproduct of the ash matrix.

As for the geophysical survey, the most soundings exhibit a typical feature consisting of a low resistivity layer confined between two relatively high resistivity layers. Figure 5a shows four among the most promising apparent resistivity curves acquired in the Ngarenanyuki Ward, and the corresponding interpretations. In the figure, the portion of the apparent resistivity curve corresponding to the anomaly, which can be interpreted as a confined or semi-confined aquifer, is evidence with an ellipse, and the presumed aquifer layer is indicated with an arrow in the respective resistivity column obtained through the inversion process.

The consequent deduction is that in the sub-area, including the above discussed soundings the occurrence of a layer, associated with a confined or semi-confined

aquifer, at a depth of 20–36 m from the ground surface with noticeable thickness, is highly plausible.

For comparison, the result pertaining to sounding ENG15 is shown in Fig. 5b: as can be seen, apart from the low values associated with the clayey, more or less wet, top soil, the resistivity increases continuously and anomalies that could be associated with a confined aquifer are missing.

On the basis of the resistivity curves and taking into account the geological and hydrogeological features, several homogeneous sub-areas have been distinguished and marked with capital letters in the map of Fig. 3; in detail:

- Sub-area A: soundings ENG30 and ENG09 with possible groundwater at depths ranging from a few metres to a maximum of 35 m;
- Sub-area B: the Uwiro Graben with ENG10, ENG08, ENG07, ENG13, ENGnew1 soundings. All these soundings exhibit a column with very low resistivity values (even 3–4 ohm-m) from surface to a depth of at least 90 m. Undoubtedly groundwater occur, possibly at different levels in a multi-layer aquifer;
- Sub-area C: soundings ENG05, ENG06, ENG17 indicate that aquifers could be present in the first 30–60 m from surface;
- Sub-area D: soundings Eng 14, Eng 20, Eng 21. Besides the first few meters from surface, these soundings show a resistivity curve interpretable in the same way as the soundings discussed before.

  This area is relatively far from the Engarenanyuki River and is crossed by several ephemeral streams coming from the surroundings hills;
- Sub-area E1: includes soundings MK01, MK02, MK03, MK05 and MK05b. All these soundings are located in a structural high with respect to the Uwiro Graben so that no influx of Engarenaniyuki River is expected. The sounding indicates groundwater at 30 m from surface; deeper aquifers could be found at a relatively large depth (at least 100–200 m);

- Sub-area E2: is the most promising for groundwater and includes soundings ENG00, ENG01, ENG02, MK04, ENG18, ENG03b. As seen, these soundings show very similar and rather interesting characteristics: a first conductive layer, extending from a few metres to a maximum of 15 m from surface; a relatively resistive layer, superimposed on a second conductive layer whose top is situated at depths of 36 m from the surface. The latter could be associated with an aquifer with a thickness ranging from 40 to 150 m.

5 Discussion and prospecting strategy

The hydrogeological issues, including the census of springs and the relative fluoride content, evidenced as water pouring out from unaltered volcanic rocks such as phonolite, basalt, piroclastites – generally located at a relatively high elevation on the Mt. Meru slope – are those affected by low content of fluoride. Two reasons can account for this characteristic:

1. the short resident time of the groundwater responsible for the relative low water-rock interaction;

2. the absence of byproducts such as paleosoils, which conversely are widespread within the lahars. Moreover no calcrete and lacustrine salty deposits with salty soils and scooped magadi (Nielsen, 1999) occur in the area. All these easy leachable products, instead occur in the Uwiro Graben and elsewhere in the distal and flat part of the volcanic building.

The occurrence of groundwater, evident by the sounding executed also according to social factors such as the needs of the population settled in the area, is synthesized in Table 3. The third and fourth columns of Table 3 indicate the “drilling suitability” and the suggested “maximum drilling depth”, respectively. The “drilling suitability” ranges from 0 (zero) to 5, with the following meaning: 0=“do not drill at all”; 5=”area particularly suitable for drilling”. The “Maximum drilling depth” has the meaning: “if drilling is decided, do not drill below that depth”.

This table shows the drilling suitability of productive aquifers regardless of the quality of water. Some indications on this basic aspect can nevertheless be derived from geological and hydrogeological considerations. In fact, if the water flooding from lahars and from the superficial lacustrine sediments show fluoride values systematically above 10 ppm with maxima of 68 ppm. It can be argued that the aquifers of the entire area between Uwiro and Momela Lakes would be affected by high-F water. This area is also crossed by the only perennial river of the district, fed by at least one hydrothermal spring (Eng 26), that contribute to the dramatic increase of the fluoride values (34 ppm) of its water. These considerations is sufficient to exclude this lowland with the sub-areas A, B, C and D from any exploitation project due to the high risk of drilling naturally polluted aquifers. Conversely, the uplifted area, NW of the fault zone marked by the NNE trending cones alignment (Fig. 2), not only is out of the Engarenanyuky influence, but also exhibits a wide outcrop of basalt flood pertaining to the relatively old NVj volcanic suite, which can host a productive “’unpolluted” groundwater reservoir. On this basis, the area E2 was chosen as that which best fits the local needs (Maasai settlement) and the hydrogeological conditions for safe water so suitable for a pilot borehole drilling.

5.1 The borehole

The drilling operation, lithological log (drill cuttings were collected every one metre), well design, well completion and development joined to a pumping test have been carried out by the Tanzanian Company “Water Solutions Drilling Company” on January 2008. During the drilling, water samples were collected in order to measure the chemical-physical parameters and the fluoride content. In Figs. 2 and 6 the borehole, named Ichnusa Well1, is shown. Technical data are reported in Fig. 6d. The Ichnusa Well1 has provided a detailed stratigraphy of the Mkuru area. In particular, the presence of a buried formation, which does not outcrop in the area, was observed. It was crossed from 38 m to 59 m below g.l. (Fig. 6); it consists of scoriaceous, autobrecciated basalt, that hosts a confined aquifer with high permeability. After drilling, the pumping test at a constant rate (drawdown log-time test) was carried out (18, 19, 20 January 2008) in order to estimate the hydraulic parameters (transmissivity and storativity). In detail, due to the limited pumping rate (3.8 l/s) allowed by the available submersible pump (lowered down the borehole at 60 m below g.l.), it was not possible to estimate the maximum pumping rate. Hence, also the evaluation of the well efficiency by means of SDT (Step Drawdown Test) was not possible. At the allowed pumping rate, the maximum drawdown was only 45 cm: such conditions permitted just a constant yield-pumping test.

Drawdown versus time measurement were collected during 48 h at a constant pumping rate of 3.8 l/s. The pumping test (Theis Method) showed a transmissivity of 9.12×10^{-3} m^2/s and a storativity of 6.30×10^{-2}. No kind of barrier boundary or recharge effect has been highlighted during the pumping test. This allows us to state that the maximum pumping rate of Ichnusa Well1 is definitely greater than 3.8 l/s. During the test, in situ fluoride analyses evidenced a constant value of 3.1 mg/l. This value is by far the lowest found all over the study area and it falls below the Tanzania security limit.

6 Conclusions

In the volcanic district represented by the northern Mount Meru slope, shallow and deep circulating groundwater has been distinguished. Shallow groundwater, which occurs in perched aquifers hosted in unconsolidated or semi-unconsolidated sediments, is scarce. These aquifers exhibit limited extension, in fact shallow groundwater has been evident only within sandy river beds and paleo-lakes superficial sedimentary deposits. Intermediate and deep groundwater circulation systems occur in areas where the permeability of the aquifers and the elevation difference between recharge and discharge areas allows relatively deep infiltration. Deeper infiltration takes place where fracturing and faulting affect brittle rocks over wide areas. In such cases, a large

recharge area joined with substantial rainfall can also result in good yielding wells and springs (e.g. Main cone group complex Nvm).

The groundwater regional flow system has been found as generally controlled by the morphology, and involving a multidirectional flow with the dominant pattern from the higher elevation area in the south, towards the lower area in the north. Recharge occurs by direct infiltration (rainfall), by infiltration following runoff, and through lateral systems where some groundwater can flow laterally between different hydrogeologic unit. In particular, the second occurrence is typical of volcanic uplands, especially in correspondence of slope changes (decrease in drainage density); the third case is that of Mkuru area, where an aquifer hosted in the weathered and scoriaceous basalts, at a depth of about 40–60 m, is fed by the groundwater, which infiltrates at high elevation in the main cone group and Tholoid phonolites.

Fractured or autobrecciated lava-flows are aquifers with low release of fluoride either for their high trasmissivity, which reduce the residence time of groundwater, or for the absence of weathering-derived products or salty deposits that, conversely, come in contact with groundwater mainly hosted within lahars or even in superficial lacustrine sediments. Also the Engarenaniuky River, mainly fed by the high fluoride hydrothermal spring 26 Eng, contributes to polluting the aquifers in hydraulic communication with it in the lowland within the Uwiro Graben.

Geo-structural and hydrogeological data (geometry and hydraulic properties of the aquifer systems, boundary conditions, spring flow, streamflow, etc.) of the whole investigated area are not enough to allow the definition of a correct water balance, that should be necessary for computing runoff, actual infiltration and groundwater recharge.

Undoubtedly, all the above data represent the basis for planning interventions aimed at improving the access to unpolluted water. As an example, the data acquired and interpreted in the frame of this work allow to evaluate, for different sub-areas, whether the water supply problem could be better faced by means of more drilled wells or by improving the springs catchment or, yet, with a combination of both. However, the above-said interventions cannot be planned only on the basis of technical results, since social and economical factors also play a relevant role. The development plans already approved by local Authorities and the expectations of local people must lead any further research.

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Table 1. Summary of springs attributes.

ID Spring	Collect Data	UTM East	UTM North	Altitude (m a.s.l.)	Spring Type	Spring Regimen	Spring Geologic Classification	Disch arge (l/sec)	*T* (°C)	Cond (mS/cm)	pH	F (mg/l)
1 eng	18 Feb 07	252 273	9 648 852	2249	localized	catched, perennial	Fracture, Nvm	0.15	18.0	0.64	7.4	3.0
2 eng	18 Feb 07	252 156	9 648 544	2276	localized	catched down the valley, perennial	Fracture, Nvm	0	15.0	0.50	6.0	1.3
3 eng	21 Feb 07	259 060	9 651 282	1500	diffused	not catched, perennial	Gravity, contact, Nzd1	0	24.3	0.74	7.5	4.9
4 eng	7 Mar 07	261 073	9 648 602	1453	N/A	catched in irrigation canal, perennial	Gravity, contact, Nzd2	0	23.0	0.73	6.8	6.9
5 eng	7 Mar 07	261 243	9 648 462	1454	localized	catched in irrigation canal, perennial	Gravity, contact, Nzd2	0	23.4	0.63	6.7	5.4
6 eng	7 Mar 07	260 888	9 648 316	1465	N/A	not catched, perennial	N/A, Nzd2	0.8	23.4	1.02	6.9	10.5
7 eng	7 Mar 07	261 397	9 648 526	1450	localized	not catched	Gravity, contact, Nzd2	2.6	20.2	0.81	6.9	7.7
8 eng	8 Mar 07	261 944	9 651 008	1422	diffused	catched, perennial	Artesian, Nzd2	0	22.0	1.16	7.0	10.0
9 eng	8 Mar 07	260 480	9 645 862	1495	localized	not catched, perennial	Gravity, contact, Nvn	0.8	19.0	0.54	6.4	5.0
10 eng	8 Mar 07	261 243	9 646 006	1483	localized	not catched, perennial	Artesian, Nzd1	0.03	23.0	1.53	7.6	19.1
11 eng	8 Mar 07	263 619	9 644 238	1514	diffused	not catched, dry during the dry season	Artesian, contact, Nzd1	0.05	22.0	1.86	8.3	25.4
12 eng	8 Mar 07	263 553	9 644 286	1520	localized	not catched, perennial	Artesian, contact, Nzd1	0.02	21.8	1.86	8.2	23.2
13 eng	7 Mar 07	262 593	9 653 986	1350	localized	not catched	Fracture, Nzd2	0.01	26.6	0.90	7.4	2.6
14 eng	12 Mar 07	262 674	9 653 232	1389	localized	not catched	N/A, Nzd2	0.04	24.4	4.30	8.3	44.0
15 eng	15 Mar 07	257 259	9 647 224	1730	localized	not catched, perennial	Contact, Nvn	0.12	17.7	0.33	6.1	5.4
16 eng	15 Mar 07	257 694	9 647 686	1640	localized	catched, perennial	Contact, Nvn	3	16.6	0.33	6.4	5.3
17 eng	18 Mar 07	260 391	9 645 944	1500	diffused	catched, perennial	Contact, Nvn	5	18.5	0.56	6.1	5.1
18 eng	18 Mar 07	258 847	9 646 904	1580	localized	catched, perennial	Contact, Nvm/Nvn	3	18.6	0.47	6.7	5.2
19 eng	20 Mar 07	259 997	9 644 704	1650	N/A	catched, perennial	N/A, Nvm	2	17.5	0.40	7.3	3.5
20 eng	20 Mar 07	259 715	9 644 614	1693	diffused	catched, perennial	Fracture, Nvm	0	15.5	0.40	6.4	3.6
21 eng	24 Mar 07	252 258	9 648 646	2250	localized	catched, perennial	Fracture, Nvm	0.05	14.7	0.30	6.3	2.0
22 eng	24 Mar 07	251 460	9 647 636	2660	diffused	catched down the valley, perennial	Fracture, Nvm	0.2	13.3	0.25	5.6	1.4
23 eng	24 Mar 07	252 009	9 647 712	2654	localized	catch. in the korongo down the valley exceptionally dry	Fracture, Nvm	0	14.6	0.17	5.7	0.7
24 eng	24 Mar 07	251 540	9 649 722	2236	localized	catched, perennial	Fracture, Nvm	0	18.5	1.08	7.1	7.1
25 eng	26 Mar 07	260 045	9 641 778	1620	localized	not catched, perennial	Artesian, fracture, Nvm	3	20.2	1.51	6.0	10.0
26 eng	26 Mar 07	254 609	9 641 105	2502	localized	not catched, perennial	Artesian, fracture, Nzd3	6	20.4	4.82	7.8	60.0
27 eng	26 Mar 07	254 682	9 642 148	2550	localized	not catched, perennial	Fracture, Nvm/Nvn	0.04	12.2	0.34	6.4	3.8
28 eng	26 Mar 07	258 372	9 641 064	1969	diffused	catched, perennial	N/A, Nzd3	4	16.6	1.44	7.4	28.20
29 eng	05 Apr 07	254 378	9 641 318	2582	localized	not more catched, perennial	Contact, Nvm/Nvn	0,1	17.3	1.39	7.8	20.0
30 eng	22 Apr 07	263 749	9 654 174	1337	localized	not catched	N/A, Nzd2	0	24.8	3.74	8.1	31.0
1 old	19 Feb 07	243 163	9 645 872	2119	N/A	catched, perennial	N/A, Nvm2	6	20.4	0.70	8.2	4.3
2 old	21 Feb 07	249 443	9 657 902	1470	N/A	not catched, dry during the dry season	Shallow dugwell, alluvial fan deposits	N/A	30.0	0.40	7.0	0.9
3 old	21 Feb 07	246 328	9 649 372	2095	localized	catched, perennial	Gravity, contact, Nzd1	0,4	17.2	0.48	7.3	12.3
4 old	21 Feb 07	247 564	9 648 126	2272	localized	catched, perennial	N/A, Nvm	1	16.6	0.53	7.6	2.5
5 old	22 feb 07	242 323	9 650 010	1800	diffused	catched, perennial	Fracture, Nzd1	0.4	20.0	0.62	7.5	13.0
6 old	13 Mar 07	249 420	9 649 314	2100	localized	catched, perennial	Contact, Nvm	0,5	14.0	0.64	6.0	2.5
7 old	13 Mar 07	242 249	9 649 874	1800	diffused	catched, perennial	Fracture, Nzd1	0.6	21.0	0.56	7.5	14.3
8 old	14 Mar 07	249 148	9 645 944	2600	localized	catched, perennial	Fracture, Nvm	3,5	11.5	0.20	7.2	4.6
9 old	23 Mar 07	246 262	9 649 347	2055	localized	catched, perennial	Gravity, contact, Nzd1	2.5	13.9	0.51	7.3	14.7
10 old	23 Mar 07	245 338	9 648 282	2099	diffused	catched, perennial	N/A, Nzd1	2	15.4	0.50	7.3	17.6
11 old	27 Mar 07	242 900	9 641 576	2515	localized	catched, perennial	Contact, Nvm2	0.35	14.8	0.60	6.5	3.1
12 old	27 Mar 07	242 899	9 641 592	2515	localized	catched, perennial	Contact, Nvm2	0,2	14.7	0.49	6.5	4.1
13 old	27 Mar 07	243 048	9 643 464	2479	localized	catched down the valley, perennial	Fracture, Nvm2	0,8	14.6	0.63	7.5	4.0
14 old	27 Mar 07	245 636	9 642 156	2841	localized	catched, perennial	Fracture, Nvm	0,01	12.9	0.63	6.4	2.9
15 old	2 Apr 07	245 225	9 643 710	2616	diffused	catched, perennial	Fracture, Nvm	0.5	13.2	0.45	7.3	3.0
16 old	2 Apr 07	246 635	9 644 878	2634	N/A	catched, perennial	N/A, Nvm	1	14.4	0.21	7.0	1.6

Table 2. Summary of rivers attributes interesting for groundwater and, therefore, only soundings pertaining to this ward will be discussed. The VES position map for the Ngarenanyiuki Ward is shown in Fig. 3.

ID River/Lake	Collect Data	UTM East	UTM North	Altitude (m a.s.l.)	*T* (˚C)	Cond (mS/cm)	pH	F (mg/l)
1 River	7 Mar 07	265 220	9 656 432	1282	26.6	1.08	8.5	28.0
2 River	12 Mar 07	262 671	9 653 238	1386	23.2	1.67	8.2	14.0
3 River	12 Mar 07	261 987	9 651 728	1417	22.8	1.21	7.6	6.2
4 River	12 Mar 07	260 664	9 651 158	1456	24.5	0.96	7.2	5.4
15 River	14 Mar 07	247 450	9 647 930	2280	19.0	0.43	7.3	1.9
29 River	22 Mar	261 137	9 642 677	1572	19.1	2.07	8.5	22.8
21 River	21 Mar 07	261 297	9 647 032	1469	25.4	1.89	8.1	13.0
23 River	19 Mar 07	262 096	9 649 314	1441	23.6	2.06	8.4	26.2
24 River	19 Mar 07	263 053	9 651 684	1405	25.0	2.40	8.8	26.8
22 River	19 Mar 07	261 639	9 647 560	1455	23.3	1.74	8.4	23.2
26 River	22 Mar 07	261 387	9 643 697	1537	20.4	1.78	8.4	29.4
30 River	21 Mar 07	243 477	9 644 073	2467	14.6	7.80	0.6	3.1
28 River	26 Mar 07	261 072	9 642 508	1583	17.9	2.12	8.5	28.0
1 Lake	23 Apr 07	265 699	9 643 622	1440	26.1	7.10	9.8	149.1
2 Lake	23 Apr 07	267 261	9 643 727	1440	25.8	N/A	10.3	528.0

Table 3. Operative synthesis of the survey results. The sub-areas in the second column are shown in Fig. 3.

Ward	Sub-area	Drilling suitability (0–5)	Maximum drilling depth (m)
Ngarenanyuki	A	1	40
	B	2	100
	C	1	80
	D	3	80
	E1	2	50
	E2	5	100

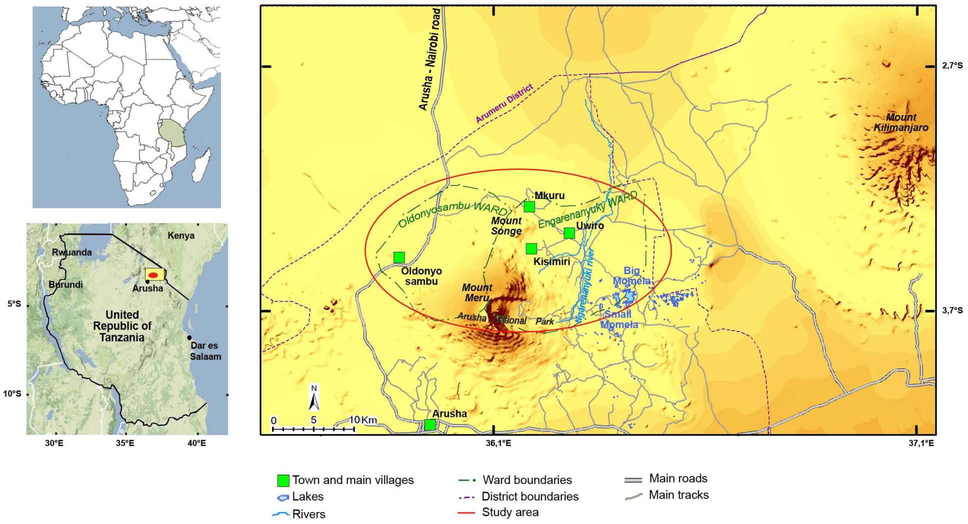

Fig. 1. The study area.

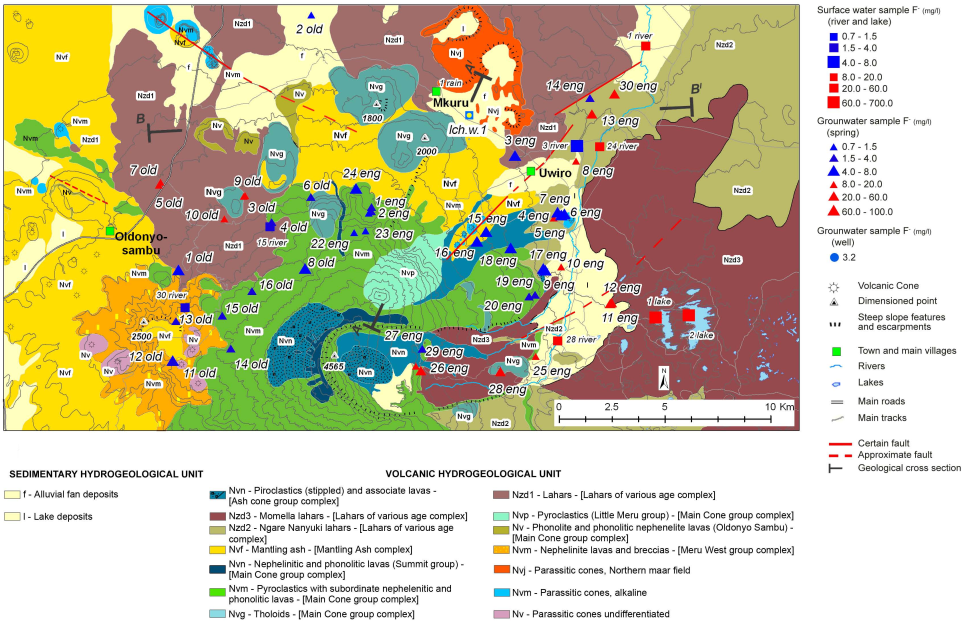

Fig. 2. Geological-Hydrogeological map with water location points.

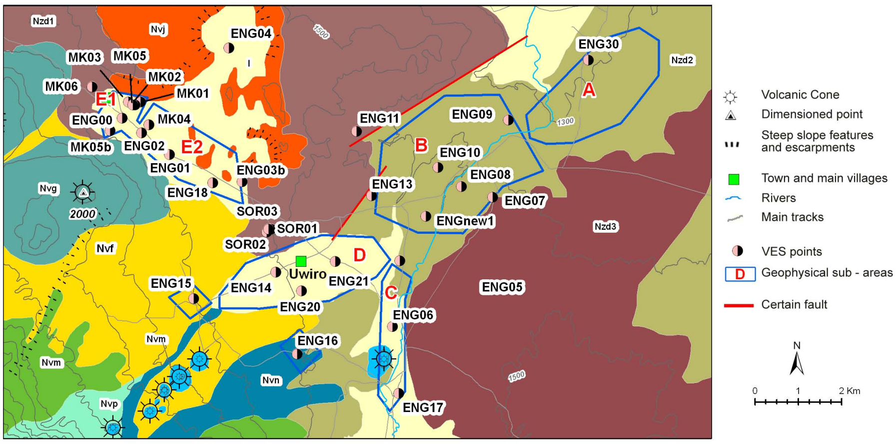

Fig. 3. Position map of the electrical soundings in the Ngarenanyuki Ward. Sub-areas defined on the basis of the results (see Table 3). For the geological legend, see Fig. 2.

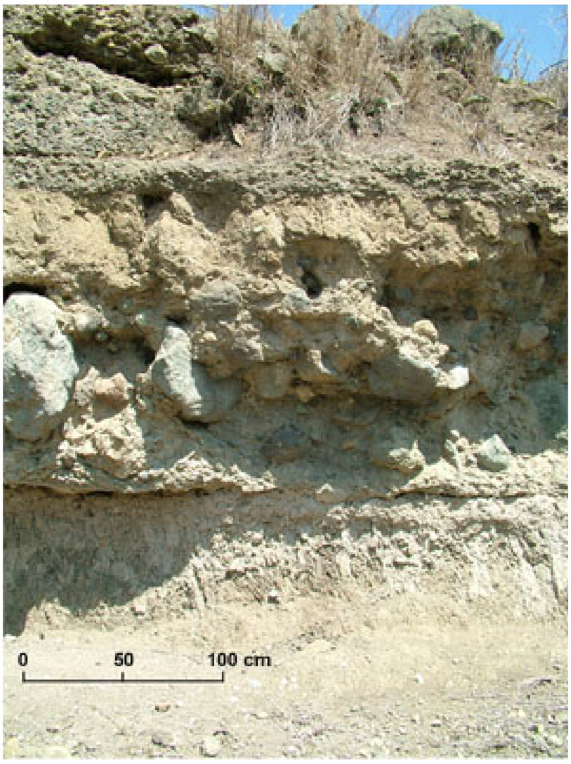

Fig. 4. Clayey level (paleosoil) between lahars and mantling ash.

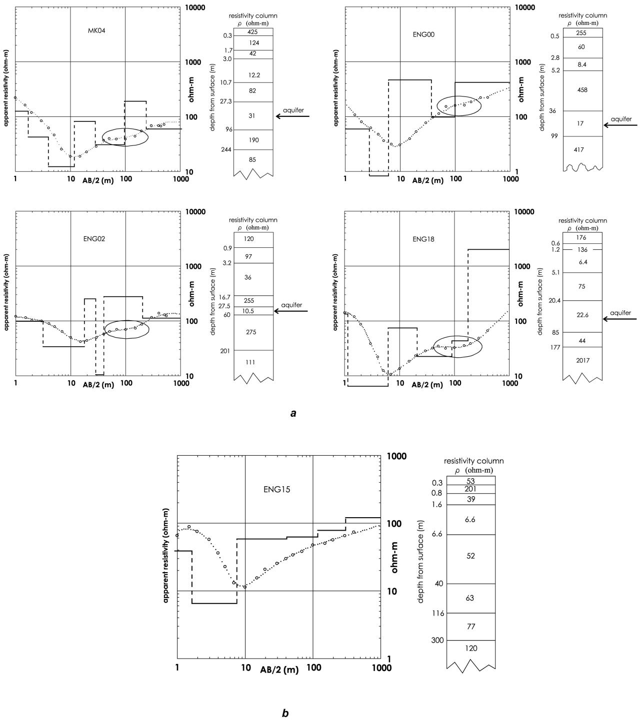

Fig. 5. **(a)** Apparent resistivity curves (left) and interpreted resistivity column (right). In the diagram, the small circles represent the experimental values, and the dotted line the apparent resistivity curve corresponding to the resistivity column on the right. **(b)** Apparent resistivity curve and interpretation of VES ENG15. The resistivity column does not show any sign that could be associated with a confined aquifer.

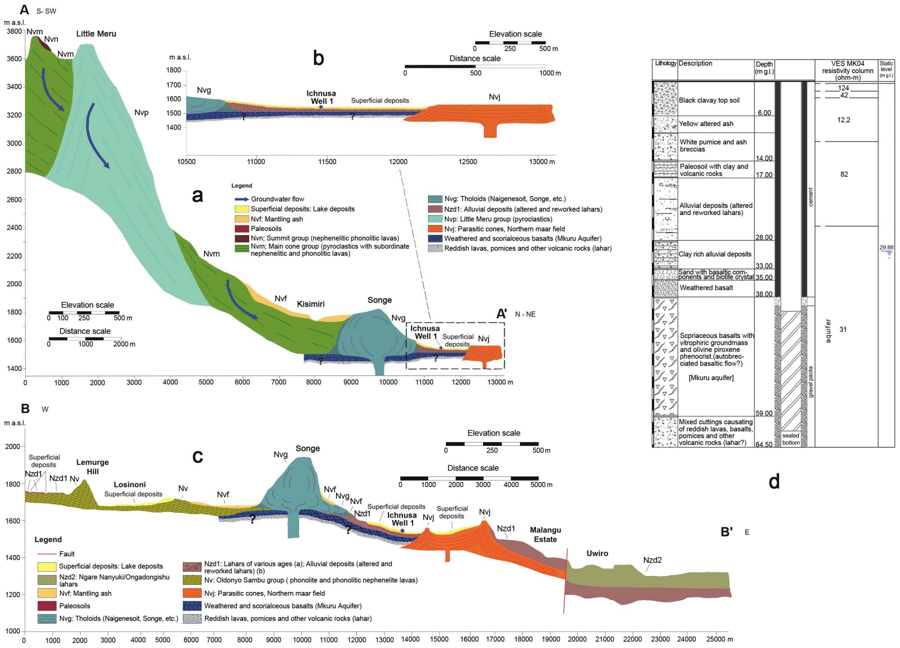

Fig. 6. **(a)** Geolocical-Hydrogeological cross section A-A' (vertical exaggeration about x4). **(b)** Detail of the area surrounding the Ichnusa Well 1. **(c)** Geological-Hydrogeological cross section B-B' (Vertical exaggeration about x7) **(d)** – Ichnusa Well 1: lithological log and well construction report. Comparison between the stratigraphy and the resistivity column of the electrical sounding MK04.