Characterization of a Pleistocene thermal spring in Mozambique

Franziska Steinbruch · Broder J. Merkel

Abstract A hydrogeological study was conducted with the objective to investigate the only currently known hot spring of Sofala Province in Mozambique with respect to the origin of the water, the discharge, and its chemical composition. Field investigations comprised a general land use survey, mapping of sediment and water temperatures, discharge measurements and on-site water chemistry as well as sampling for further chemical analyses and groundwater dating. Thermal water discharge occurs along a 100m long NE–SW zone with water temperatures ranging from 42 to 64.5°C. The thermal water is a low-mineralized sodium-chloride-sulfate water enriched in phosphate, fluorine and nickel. The silica geothermometer, the silica concentration of 43mg/kg and the ratios of Br/Cl and I/Cl of 2.5×10^{-3}, suggest that the thermal water stems from approximately 5,000m depth and had a long residence time with silicate rocks. This points towards Gorongosa Mountain as the water source area. ^{14}C dating suggests a groundwater age of 11,000 years.

Keywords East African rift system · Geothermal spring · Hydrochemistry · Fractured rocks · Mozambique

Introduction

Mozambique is located in southern Africa bordering with Tanzania, Malawi, Zambia, Zimbabwe, South Africa, Swaziland and the Indian Ocean (Figs. 1 and 2).The country has undergone several tectonic cycles, of which the most recent is the Post-Gondwana Cycle (Mesozoic-Cenozoic age). The Post-Gondwana Cycle began in Mozambique ca. 175 million years (Ma) ago and consists of the final break-up of the Gondwana continent followed by a phase of epeirogenesis, and several neo-rifting phases (35 Ma to recent). The neo-rifting resulted in the extension of the East African Rift System (EAR) from the Middle East–East Africa into southern Africa (Lächelt 2004). Tertiary to recent volcanism and anomalous topographic swells are associated with the rifting of the EAR. Along the EAR, as far as southern Africa, high plateaus rise above the surrounding lowlands by more than 1 km forming the African Superswell. Mozambique is characterized by lowland—<400 meters above sea level (masl)—made of Karoo to recent sedimentary formations, by highland plateaus and mountains (up to 2,436 masl) of Archaic to Proterozoic crystalline formations, and by *inselbergs* of various ages. To account for the relationship between the African intra-plate volcanism, topographic elevation, and seismic velocity anomalies, the presence of one or several mantle plumes has been assumed (Pik et al. 2006).

About 50% of the groundwater sources of Mozambique are in fractured rocks and associated small colluvial aquifers. Further groundwater is found in sedimentary rock formations, often with total dissolved solids (TDS) above 1 g/L (DNA 1986). Thermal and mineral springs in Mozambique occur along rift borders, in conjunction with major fractures of mobile belts, reactivated tectonic blocks, and ancient volcanic zones. Thermal spring temperatures in Mozambique range from 37 to 95°C with TDS between 0.1 and 8.3 g/L, whereas the water temperatures above 50°C are always associated with rift margins (Lächelt 2004). None of the thermal springs in Mozambique is actively utilized. Although many thermal springs are concentrated in central Mozambique only one is located in Sofala Province.

The overall purpose of the study is to produce fundamental hydrogeological knowledge about the only known hot spring in Sofala for an eventual community-based, commercial utilization. The objective is to investigate the origin of the water, the discharge, and its chemical composition.

The study area

The Nhambita Hot Spring is situated just outside Gorongosa National Park (GNP) in the southwestern part of the park's buffer zone (Fig. 1). The buffer zone is a transition zone between the unfenced GNP and the rural community land

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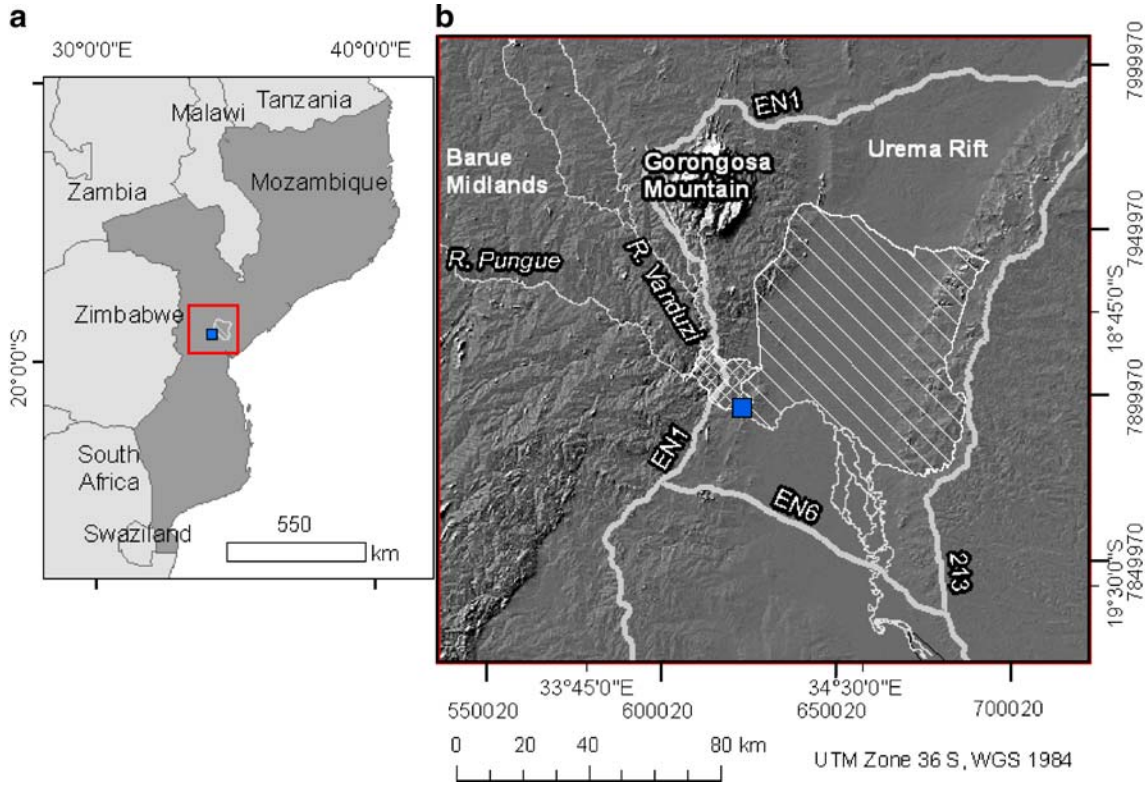

Fig. 1 **a** Overview map of Mozambique with study area (*within red square*); **b** Map of study area: Central Mozambique with Gorongosa National Park (*hatched*), Regulado Nhambita (*checkered*), Nhambita Hot Spring (*blue square*), Pungue River (*white line*), main road (*grey line*) (*hill shading* derived from NASA SRTM (shuttle radar topographic mission) 90

and is co-managed by GNP and the community authorities. The thermal spring is called Nhambita Hot Spring after its location within the Nhambita community land, or Rupice (Rupici) Spring referring to the name of the small adjacent river. The hot spring is located about 120 km west of the city of Beira, about 600 m from the northern bank of the Pungue River at an altitude of 44 masl and 55 km south of Gorongosa Mountain. The Nhambita Hot Spring is under the jurisdiction of the traditional administrative body called Regulado Nhambita, located in the village Bue Maria. The study area is bounded by the Pungue River to the south, the Gorongosa National Park to the east and north, and to the west by National Road EN1.

Geological and tectonic setting

The area of investigation is situated in the East African Rift (EAR; Figs. 1 and 3), adjacent to the marginal sedimentary Mozambique Basin. Considerably little geological and geothermal work has been done especially in the southern most part of the EAR in Mozambique, the Urema Rift zone. The hot spring area is situated on the west flank of the Urema Rift, at the southern border of the Precambrian geological Complex, called Barue Midland, which is composed of metamorphic gneisses and migmatites with swarms of granophyre and dolerite dikes (geological map 1:250,000). A dominant feature, because of its altitude of up to 1,863 masl, is Gorongosa Mountain, which is a pluton composed of fine grain granites and gabbro.Nhambita Hot Spring is located in an area mapped as Precambrian gneisses with pegmatite veins (geological map 1:250,000).

The strike slip movements related to the rift formation have created major fault and dike systems (Fig. 3). Because of the Urema Rift the existence of faults running parallel to the Urema Graben (SW–NE) and perpendicular to it (NW–SE) can be assumed. Both fault directions correspond to main directions of deep river valleys. Furthermore, there exists an older N–S (W–E) striking fault system. The entire cross-fracture system appears as a major factor of river capture and drainage (Tinley 1977). An example of the activity of the Urema Rift parallel fault system is the Vanduzi River, adjacent to the hot spring area, which has displaced the E–W striking Pungue River fault by about 100 m. It is assumed, that the faults parallel to the Urema Graben are extension faults with better permeability than the tectonically associated NW–SE contraction faults.

Climate

According to Köppen's climate classification, central Mozambique falls within tropical savannah and warm temperature rainy climate. The average annual temperature in Chitengo, situated in the rift floor is 25.7°C and in Murombodzi in the Barue Midlands, 21.8°C (COBA, Profabril 1977, Espirito Santo 1955). Generally, shallow groundwater temperatures correspond to the mean annual air temperature. According to the explanatory report to the

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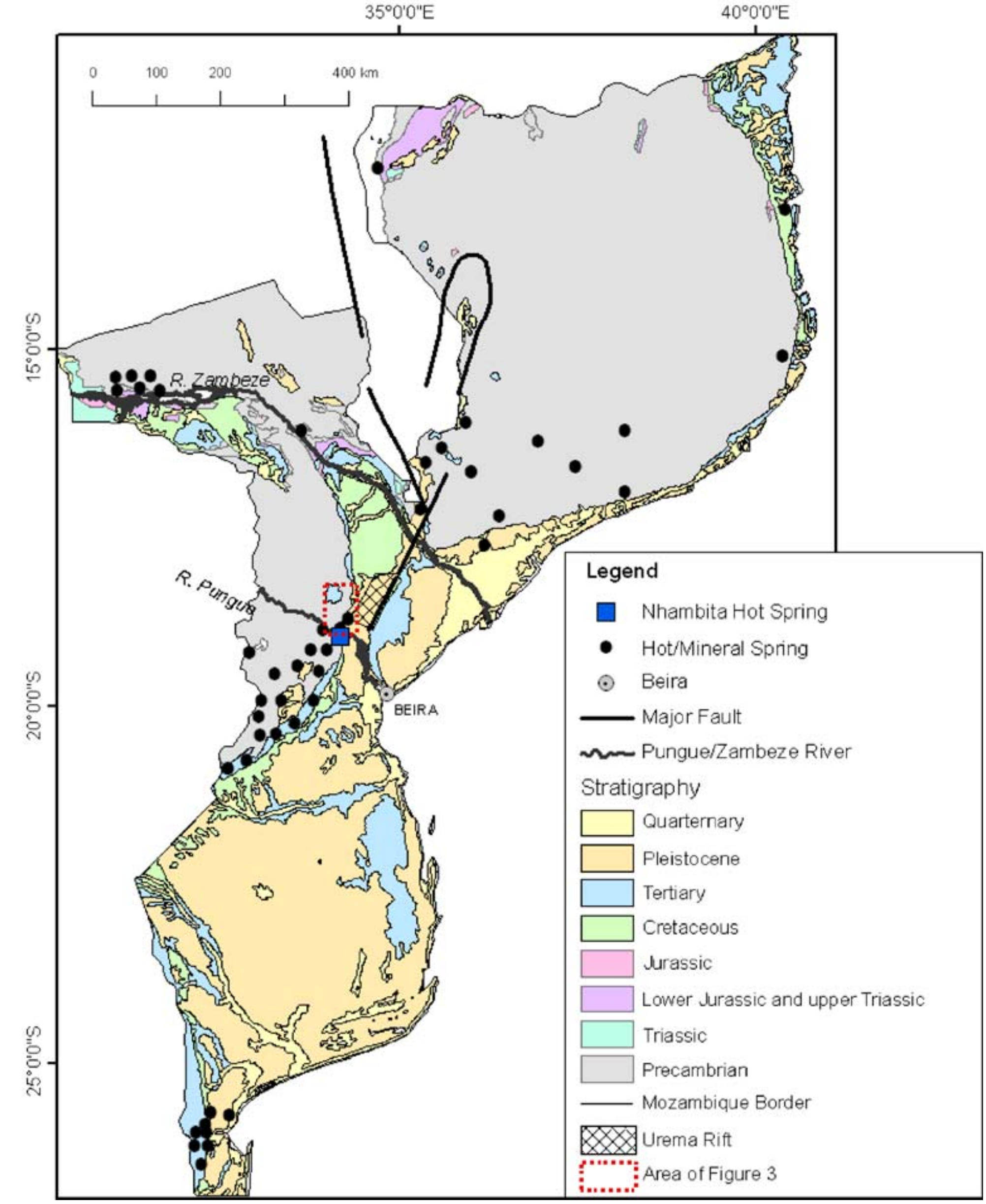

Fig. 2 Map of geology and hot springs of Mozambique (derived from Martinelli et al. 1995 and USGS Global Dataset Africa

hydrogeological map of Mozambique, scale 1:1,000,000 (DNA 1986), water with more than 40°C is called thermal water indicating that this water comes from larger depth.

The Urema Rift Valley receives an average rainfall of 840 mm, while Gorongosa Mountain, because of its *inselberg* character, catches 2,000 mm. Thus, Gorongosa Mountain is an important groundwater recharge area as well as the source of four major perennial rivers. The Barue Midlands receive rainfall of about 1,000 mm. The local rainfall distribution is visualized in Fig. 4. A rain shadow effect is observed in the Urema Rift floor.

Hydrogeology

Aquifers on the Precambrian Barue Midlands developed in pockets of weathered crystalline rock and are usually of shallow depth and small extent. Numerous small springs occur where these aquifers outcrop. Aquifers in crystalline rocks of intrusive or metamorphic origin develop only in fractured zones, whereas groundwater may circulate long distances along permeable faults and be forced up- or downwards at the contact with impermeable faults.

The geothermal gradient in Tertiary sediments of the Mozambique Basin calculated from bottom hole temperature measurements is 21.1°C per 1,000 m (Martinelli et al. 1995) and the geothermal heat flow (GTF) is 57 mW/m^2. These values may not be representative for the study area. For the Urema Rift a GTF similar to those found for the Zambezi and Malawi Rift (heat flow 77 and 75 mW/m^2, Martinelli et al. 1995) is expected. The Barue Midlands might be comparable with the adjacent Archaic Zimbabwe Craton, which has a low GTF of 46 mW/m^2 (Martinelli et al. 1995).

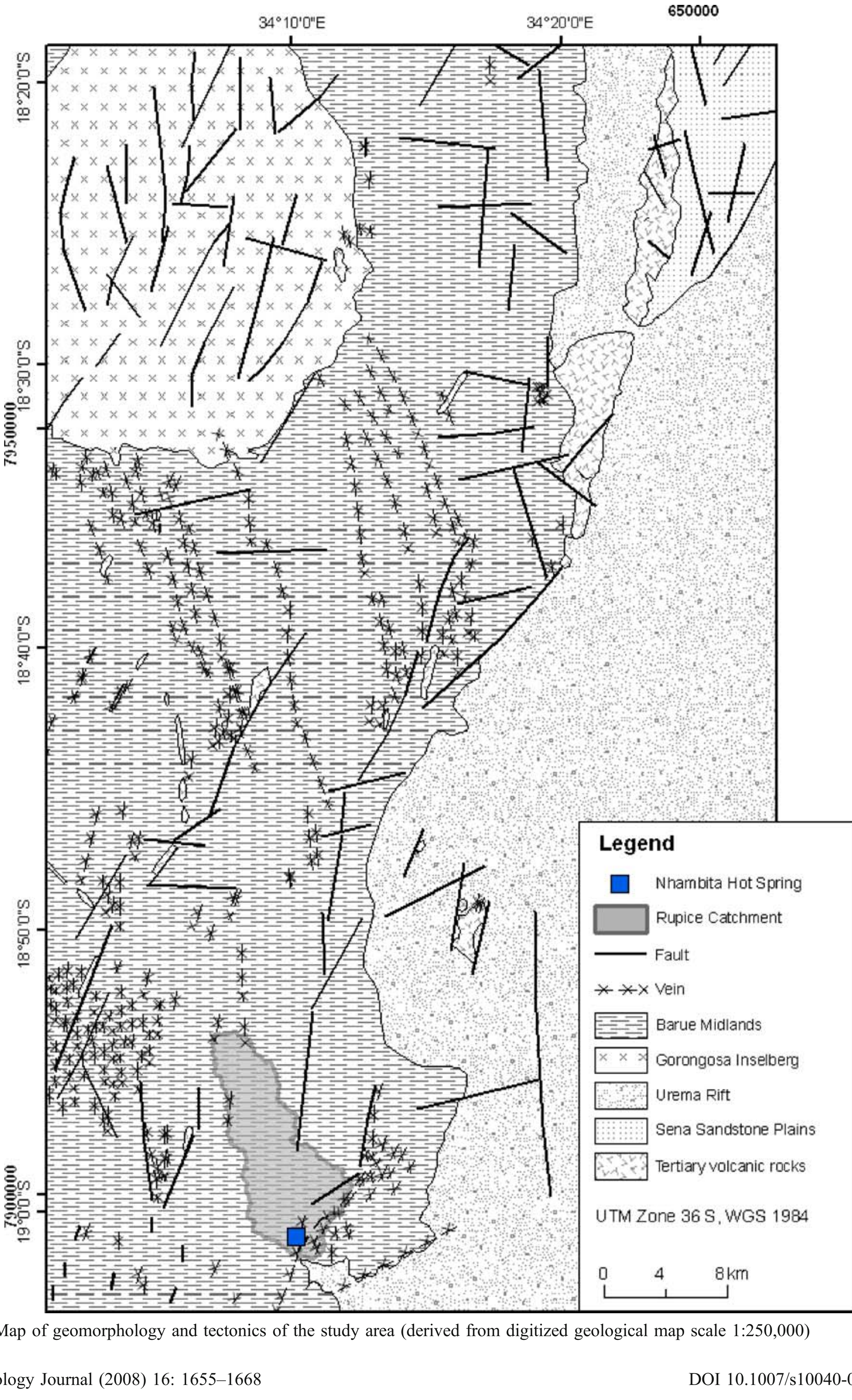

Fig. 3 Map of geomorphology and tectonics of the study area (derived from digitized geological map scale 1:250,000)

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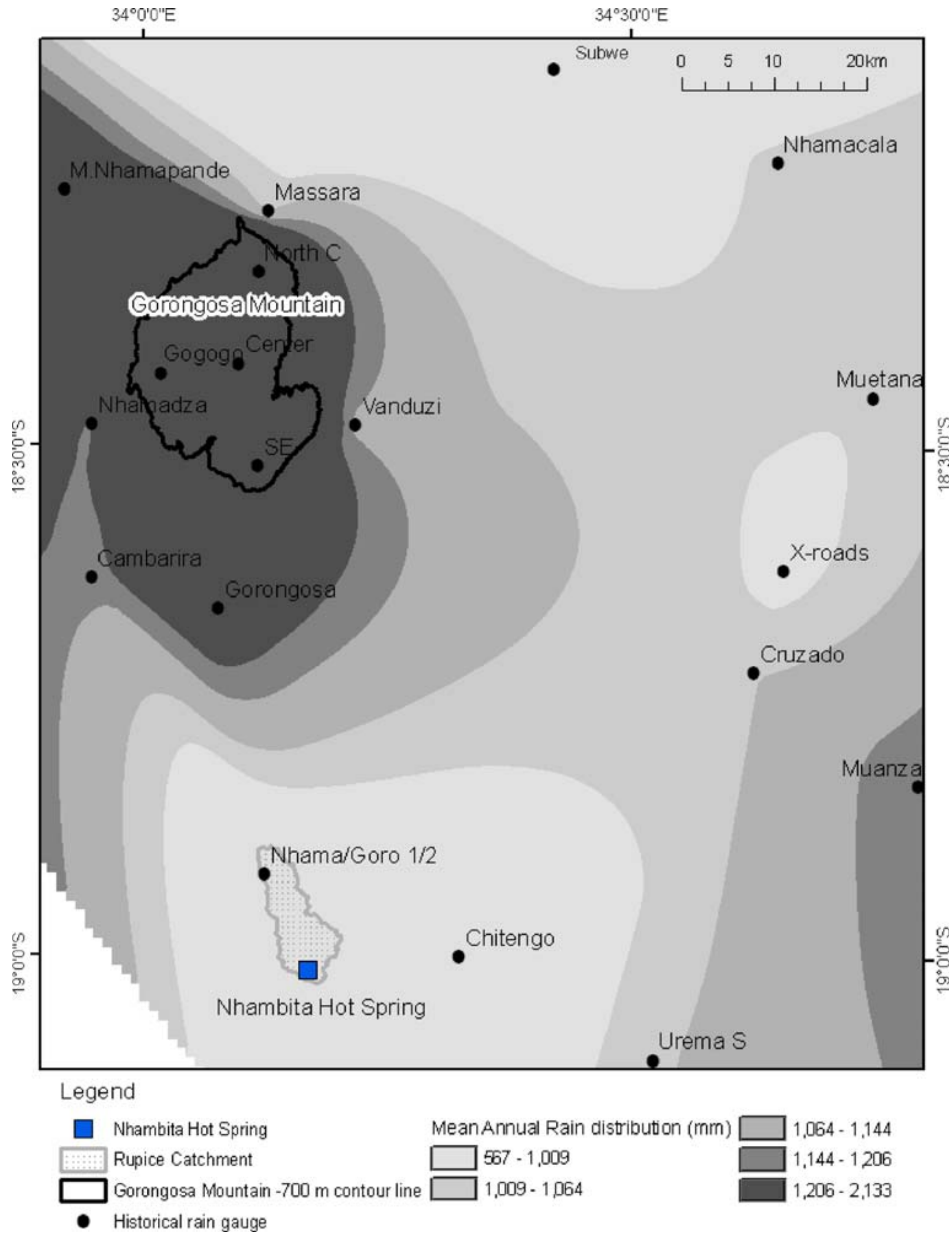

Fig. 4 Mean annual rainfall distribution of the study area (modified from Owen 2004)

Methods

Temperature and in-situ parameter measurements

Temperature measurements were performed with a hand-held digital PT-100 sensor in the water and in the river sediments at a depth of approximately 15 cm with an accuracy of ±0.1°C. O2 was measured with a Hach LDO probe and the Hach sensION156 portable meter obtaining a detection limit of 0.04 mg/L. The accuracy of the O2 reading with the optical sensors is within 0.05 mg/L. pH was read with the Hach sensION156 and a conventional glass electrode. The pH meter was calibrated with three buffer solutions (pH 4.01, 7.00, and 10.01). Equipment accuracy is within 0.1 pH units.

Electrical conductivity (EC) was taken with a WinLab Windhaus conductivity meter being checked by a calibration standard. The recorded EC was automatically recalculated to a temperature of 25°C. The accuracy of EC is within 1–2 μS/cm. Electromotive force (EMF) was read with a Winlab Windhaus pH-meter and an Ag/AgCl (3 molar) redox electrode from Meinsberg and recalculated to the Eh taking into account the temperature of the water.

The main spring was cleared of vegetation and mud before starting with the monitoring of in-situ parameters.

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Temperature measurements in conjunction with the pH, O2, and EC sensors were performed additionally and independent from the referred in situ temperature measurements. For pH, EMF, EC, and O2 measurements water was pumped with a 12 V submersible pump from the source through a 40 m PTEF (polytetrafluorethylene) hose to a flow-through cell holding the electrodes. This setup guaranteed reproducible conditions, which cannot be obtained by putting sensors in flowing river water. Furthermore, the used Hach O2 Meter (DLO) sensor has an operation limit of <50°C and thus needs cooling of the sample water before entering the flow-through-cell. In this particular case the 40 m HTPE hose was sufficient to cool the sample water below 50°C, thus no extra cooler was necessary.

Soil temperature was mapped at specific locations (GPS coordinates). Thereafter a tape-measured survey of water and sediment temperatures using the 15 cm temperature lance was conducted along the Nhambita Hot Spring drainage channel to detect diffusive hot water discharges into the creek water. This was performed by taking cross-sections and dividing them into ca. 20 cm portions, i.e. measuring about 3–7 points at each section. The temperature lance was penetrated into the creek sediment as deep as possible (mostly 15 cm).

Three water samples were taken: one from the Nhambita Hot Spring itself (Mosa P1), one sample 20 m upstream to the east of Nhambita Hot Spring (at the beginning of the water filled channel, Mosa P2), and one sample about 16 m downstream of the main hot spring (Mosa P4). Water samples were collected in different bottles (glass, polyethylene) and were treated according to special needs of preservation. Water for trace element analysis was first passed through 200 nm pore size membrane filters and then acidified to pH <2 with ultra pure HNO3. Samples were kept cool (4–8°C) and in the dark. One additional sample from Nhambita Hot Spring was taken to test for pathogenic microorganisms. Samples were taken for tritium (^{3}H), radon, stable isotopes and ^{14}C analyses. A second sample for deuterium-^{18}O analyses was taken on 23 August 2007.

Discharge measurement

Discharge of the hot spring and the channel was determined by two dilution tests. Normal table salt (mainly NaCl) was dissolved in water from the Nhambita outflow. The first experiment was performed with a 0.1 L solution (66,300 μS/cm), which was directly poured into the Nhambita Hot Spring. The change in EC was recorded in 10-s intervals about 2 m downstream at the point where the hot water joins the brook. The second dilution test was conducted for the section of the creek downstream of the hot spring. In this case, 6 L water with 46,900 μS/cm was poured into the brook water close to the hot spring and EC recorded about 16 m downstream in 10-s intervals. In both cases, the amount of water was calculated from the integral of the EC increase divided by the total injected “EC-mass”. With the use of “EC-mass” instead of NaCl masses a small bias has to be tolerated that is caused by the slight nonlinearity in the increase of EC due to the adding of NaCl. This has the great advantage of avoiding having to dry and weigh salt and to determine the specific relationship between salt and EC in a remote area.

$$Q = \frac{\int \mathrm{EC}}{M \times \mathrm{EC}_1} \tag{1}$$

Q refers to discharge (L/s)

EC is electrical conductivity in μS/cm downstream of injection point

M corresponds to the amount of water used (L)

$\mathrm{EC_I}$ is the electrical conductivity of the tracer solution (by adding NaCl)

In order to obtain discharge data over time, a simple V-shaped wooden weir was constructed and installed about 60 m downstream of the hot spring. A post with a scale bar to read water levels was installed at a distance of 2 m upstream. Since the objective was to monitor decreases or increases of hot water discharges, the measured discharge was set as the reference and calibration of the weir was not necessary. A member of the Nhambita community was trained and assumed responsibility of taking daily readings, recording weather conditions, i.e. rainy/not rainy, and maintaining the weir in good condition. The weir had to be sealed once after its installation. Readings stopped on 6 January 2007 when the first heavy rains began. The weir had to be removed with the occurrence of cyclone Favio on 23 February 2007.

From the monitored water levels, the discharge can be calculated by using the Thomson equation:

$$Q = 0.57\frac{4}{15}L \times H\sqrt{2gH} \quad \left[m^3/s\right] \tag{2}$$

H corresponds to the head of water above the apex of the notch (in m)

L refers to the width of the notch at H distance above the apex (in m)

g is gravitation

0.57 is an empirical factor, varying with conditions (L is calculated from the angle of the notch, thus only H has to be recorded)

Results

Rupice Catchment characterization

The Nhambita Hot Spring is situated in the Rupice Catchment which drains into the Pungue River. The Rupice Catchment has a size of 64 km^2 (maximum width 7 km, maximum length 16 km, Fig. 6). Land use in the Rupice Catchment comprises a forest with mapped trees as part of a carbon sequestration project in the upstream area, and a sacred forest, an abandoned cotton field, and scattered houses surrounded by family farmland in the middle and downstream area. Locals are growing sunflowers, potatoes, bananas, rice (in small swamps), millet and maize, and keep small numbers of livestock. According to the locals,

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pesticides are only applied for cotton production. The hot spring water is not currently being utilized.

A cold permanent small stream exists parallel to the drainage line of the Nhambita Hot Spring joining the creek at about 100 m downstream. About 30 m north of Nhambita Hot Spring there is one permanent pond with cold water. As observed over the period of October 2006 to November 2007, the upstream catchment only responds to local rainfall events with quick flows, thereafter drying up immediately, which indicates that no porous aquifer exists and impermeable hard rocks dominate in the catchment. In the upstream channel of the Rupice River, relicts of a dam made of rocks were discovered. Information given by the locals about the purpose of this structure was inconsistent; however all referred to the Portuguese people who used to come from the city of Beira to bottle hot spring water. Locals also indicated the location of two collapsed dug wells ca. 60 m NNE of the main hot spring. According to the locals, the white precipitate in the sediments along the creek with hot flowing water was used for cooking during the war. The main hot spring has a size of 0.6 m×1.0 m. The flow channel discharges even during severe drought periods. The width of the flow channel is approximately 2.0 m and

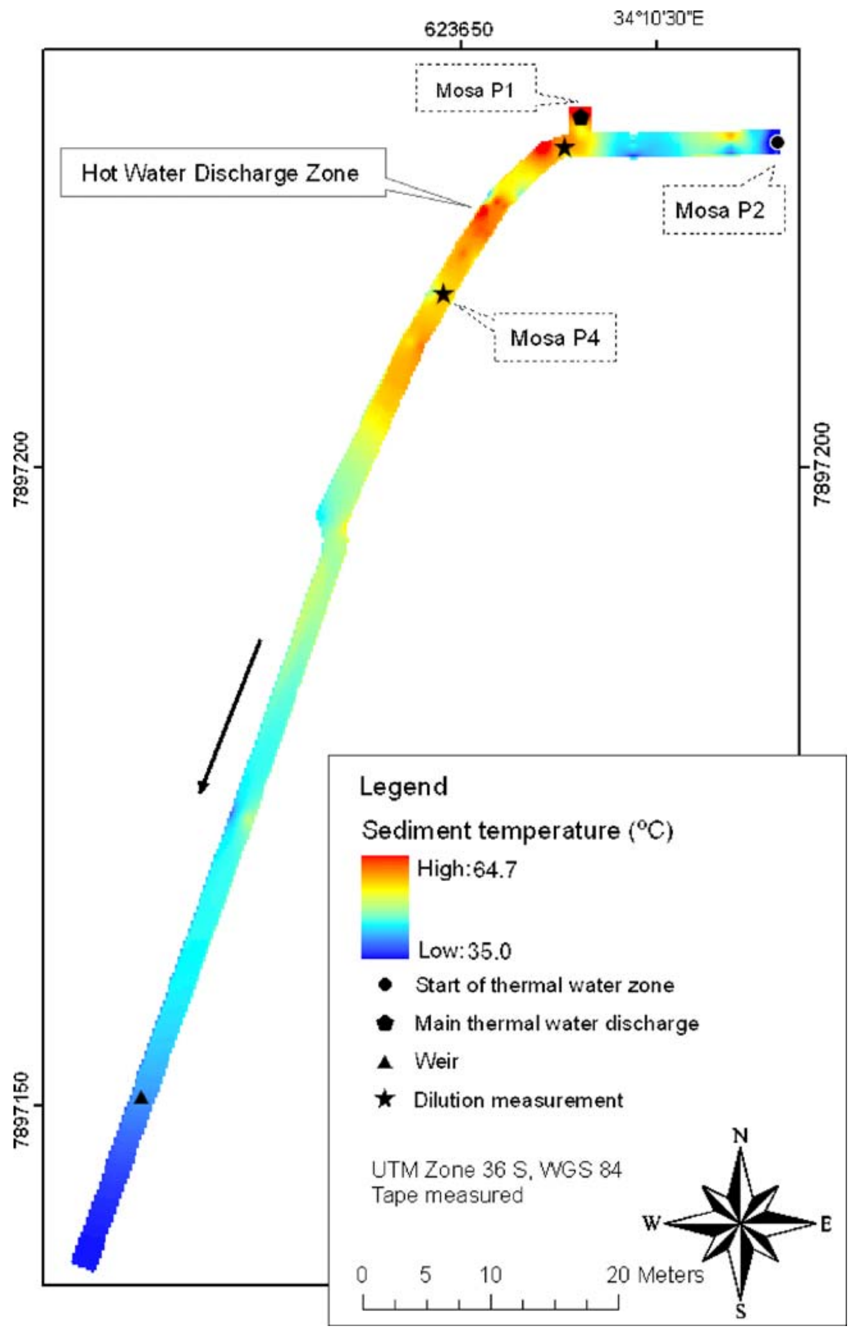

Fig. 5 Map of sediment temperature distribution in the flow channel, showing the discharge zone, the dilution measurement and water sampling sites (*Mosa P1, P2, P4*)

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the depths ca. 0.1 m. The Pungue River itself does not flood into the hot spring flow channel even at high stands; however, high Pungue River levels associated with flood peaks create a backstopping effect.

Yellow-green colored algae are only observed in the flow channel with elevated water temperatures. These algae disappeared after the first rainfall event in October 2006, when some surface runoff occurred. The hot spring itself was free of algae—obviously because of its high temperature.

Hot spring discharge

Within a ca. 100 m stretch of the flow channel, sediment temperatures were found well above water temperature (Fig. 5). In one location, a very small discharge from the bank side was visible; however, the amount of water was too small to be quantified. The Nhambita Hot Spring is the largest distinct discharge point with an amount of 0.17 L/s. A total discharge of 1.27 L/s was determined by the dilution experiment conducted at about 60 m downstream of the main hot spring and by calculating the integral of

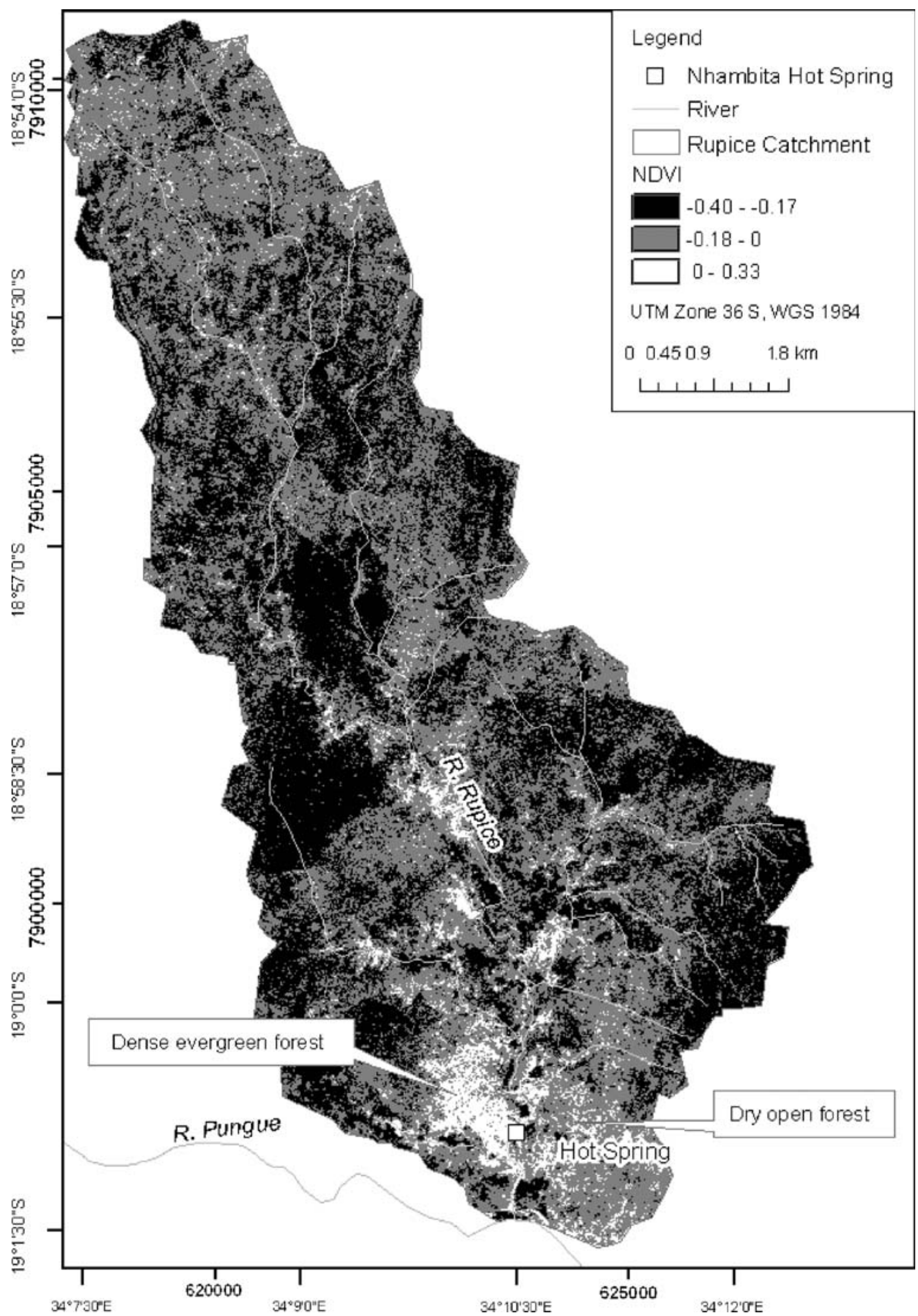

Fig. 6 Map of normalized difference vegetation index (NDVI) of the Rupice Catchment

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the tracer concentrations. Thus, several diffusive discharges along the bottom of the channel to the east and to the S–SW of Nhambita Hot Spring were identified.

The water level at the weir 1 day after having completed the installation was 12 cm. In the time following until 6 December 2007, values ranged from 12 to 14 cm, whereas all readings above 12 cm were associated with rainfall events in the Rupice Catchment. Applying the Thomson equation, these water levels translate into discharges of 2.4–3.5 L/s, respectively. The difference between 1.27 L/s (dilution) and 2.4 L/s (weir) is considerably high; however, both results cannot be compared directly, because the dilution test was performed for a point

Table 1 Selection of chemical parameters in the Nhambita Hot Spring (in mg/L if not stated otherwise)

	Mosa P1	Mosa P2	Mosa P4	WHO standard[a]	EPA standard[b]	Method
	Nhambita Hot Spring	20 m east of hot spring	16 m south of hot spring			
Sample Date	23.10.2006	23.10.2006	25.10.2006			
pH	7.6	7.65	8.16			Electro chemistry
EMF mV	–217.6	57.2	89.6			Electro chemistry
SHE mV	–5.6	269.2	301.6			
O_2 mg/L	0.42	3.78	5.58			LDO sensor[c]
O_2%	6.42	53.6	90.6			LDO sensor[c]
Temp. °C	61.2	38.4	39.5			PT_100 sensor[d]
EC μS/cm	1680	1643	1656			Electro chemistry
DOC	0.3	1.39	0.17			Non dispersive IR[e]
Na	297	295	300			IC[f] and ICP-MS[g]
K	10.5	10.8	10.4			IC[f] and ICP-MS[g]
Ca	32	33	31			IC[f] and ICP-MS[g]
Mg	0.27	0.15	0.26			IC[f] and ICP-MS[g]
TIC	11.0	13.1	10.2			Non dispersive IR[e]
F	8.63	9.52	9.13	1.5	4	Ion selective probe
Cl	228.2	241	232.1			IC[f]
NO_3	<0.5	<0.5	<0.5	50	44.3	IC[f]
SO_4	309.1	333.2	320.1			IC[f]
S^{2-}/H_2S	0.006	0.015	0.017			Photometry
PO_4	1.72	0.83	0.65			Photometry
Si	43	45	44			ICP-MS[e] and photometry
NO_2	<0.001	0.016	0.101	3	3.3	Photometry
NH_4	0.1	0.11	0.02			Photometry
Fe	0.06	0.15	0.06			Photometry and ICP-MS[g]
Mn	0.047	0.047	0.051	0.4		IC[f] and ICP-MS[g]
Ni	0.027	0.035	0.033	0.02		IC[f] and ICP-MS[g]
Br	0.58	0.59	0.57			IC[f] and ICP-MS[g]
Rb	0.084	0.085	0.083			IC[f] and ICP-MS[g]
Sr	0.8	0.82	0.82			IC[f] and ICP-MS[g]
I	0.58	0.33	0.33			IC[f] and ICP-MS[g]
Cs	0.015	0.014	0.014			IC[f] and ICP-MS[g]
Ba	0.053	0.055	0.051	0.7	2	IC[f] and ICP-MS[g]
W	0.026	0.024	0.027			IC[f] and ICP-MS[g]
As	0.0007	0.0015	0.0015	0.01	0.01	IC[f] and ICP-MS[g]
B	No data	No data	No data	0.5		IC[f] and ICP-MS[g]
Mo	0.002	0.002	0.002	0.7		IC[f] and ICP-MS[g]
Tl	0.00008	0.00005	0.00007		0.002	IC[f] and ICP-MS[g]
Cr	0.01	0.011	0.011	0.05		IC[f] and ICP-MS[g]
Pb	<0.0001	<0.0001	0.0001	0.01	0.015	IC[f] and ICP-MS[g]
Se	<0.002	0.007	0.004	0.01	0.05	IC[f] and ICP-MS[g]
U	<0.00001	0.00004	0.00004	0.015	0.03	IC[f] and ICP-MS[g]
Cd	<0.0001	<0.0001	<0.0001	0.003	0.005	IC[f] and ICP-MS[g]
Cu	<0.002	<0.002	<0.002	2	1.3	IC[f] and ICP-MS[g]
Sb	<0.0001	<0.0001	<0.0001	0.02	0.006	IC[f] and ICP-MS[g]
Hg	<0.002	<0.002	<0.002	0.001	0.002	IC[f] and ICP-MS[g]
Be	<0.001	<0.001	<0.001		0.004	IC[f] and ICP-MS[g]

Sampling conditions: air temperature at 25–37°C, clear skies

[a] WHO (2004)

[b] EPA (2002)

[c] Luminescent dissolved oxygen

[d] Platinum resistance thermometers

[e] Nondispersive infrared spectroscopy

[f] Ion chromatography

[g] Inductively-coupled-plasma mass spectrometry

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16 m downstream of Nhambita Hot Spring. This is another indication that the flow channel is collecting groundwater in addition to the obvious discharge points.

The Nhambita Hot Spring is located on the triple junction of the SW–NE fault systems on the NW flank of the Urema Graben and the NW–SE fault systems, eroded and deepened by the Pungue River. The geometry of the catchment suggests two directions of tectonic development, primarily SE–NW and secondarily by a swarm of veins in a SE–NW direction (Fig. 3). The striking feature in the field is the dense evergreen sacred forest along the SW bank of the hot spring drainage, as opposed to the very dry NE bank (Fig. 6), creating a distinct break in the landscape. The existence of the evergreen vegetation suggests availability of nutrient rich groundwater all year. Because it is a fractured aquifer, this must be associated with a sudden change in rock permeability such as the contact between a permeable fault swarm with a hydraulic barrier. The linkage to the hot spring is speculative.Skarn, granite, gneiss, pegmatite, and quartz veins were found in addition to the mere gneisses documented in the existing geological map. Gneisses along the Rupice Valley are folded and strained, indicating a complex structural geology meriting further studies.

Hot spring chemistry

Sediment temperatures ranged over a stretch of 100 m length and 3 m width from 47 to 62°C, and in one spot up to 67°C, whereby the surrounding water temperature was 64.5°C. Water temperature was always below the temperature of the underlying sediments. Table 1 contains the results of the water chemistry analyses of the three samples. The quality of the results was checked by calculating the balance between positively and negatively charged species using PHREEQC. The electrical balance error was 4.36, 0.99 and 3.43% for Mosa P1, Mosa P2 and Mosa P4, respectively, and are therefore within an acceptable range.

The three samples do not differ much from each other in their chemical compositions. Differences can be seen for pH, redox potential (electromotive force: EMF, and standard hydrogen electrode: SHE), dissolved oxygen content (O_2), and temperature, which is explained by contact with atmospheric air. The redox potential (SHE) is close to zero, i.e. tends to reduce species rather than to oxidize them. This is in conformity with the low oxygen content of 0.42 mg/L (6.42% saturation with respect to atmospheric oxygen) and the fact that nitrate is below the detection limit. The water is dominated by sodium, chloride, and sulfate (Fig. 7). Considerably low are the concentrations of calcium, magnesium and total dissolved inorganic carbon (TIC) while fluoride (8.63 mg/L) and phosphate (1.72 mg/L) are elevated. The high phosphate concentration might be a reason for the algae growth in the flow channel, which rapidly decreases with the dilution of phosphate due to cold water entering the discharge channel.

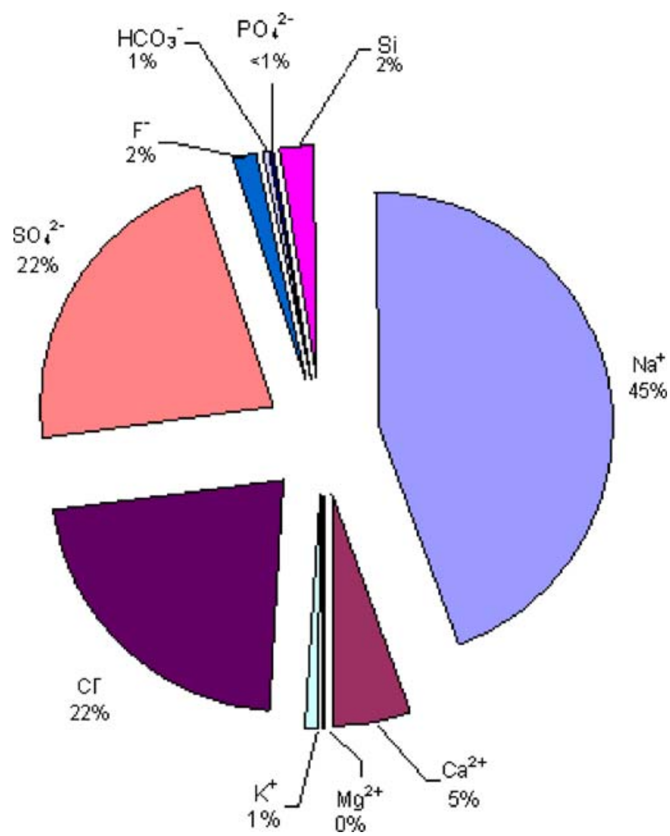

Fig. 7 Main species contained in the Nhambita Hot Spring in meq%

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Table 2 Radon and isotopes of Nhambita Hot Spring (sample Mosa P1)

Radon ^{222}Rn	Tritium ^{3}H	^{14}C corrected	Deuterium ^{2}H	^{18}O	Sample date
10.6 Bq/L (=0.29 nCi)	<0.3 TU	24.47‰	–34.7‰	–6.0‰	24.10.2006
			–34.3‰	–5.61‰	23.08.2007

Additional chemical parameters were determined only in Mosa P1 (Nhambita Hot Spring) and are compiled in Table 2. The radon concentration of 0.26 nCi/L is considerably low (following the German definition a mineral water can be called "radon containing" if it contains ≥ 18 nCi radon).

Discussion

Assuming a geothermal gradient of 21.1°C per 1,000 m and a mean annual temperature of 24°C, a groundwater with a temperature of about 60°C has seen a depth of about 1,700 m (60–24=36; 36/21.1 x 1,000 m=1,706 m).

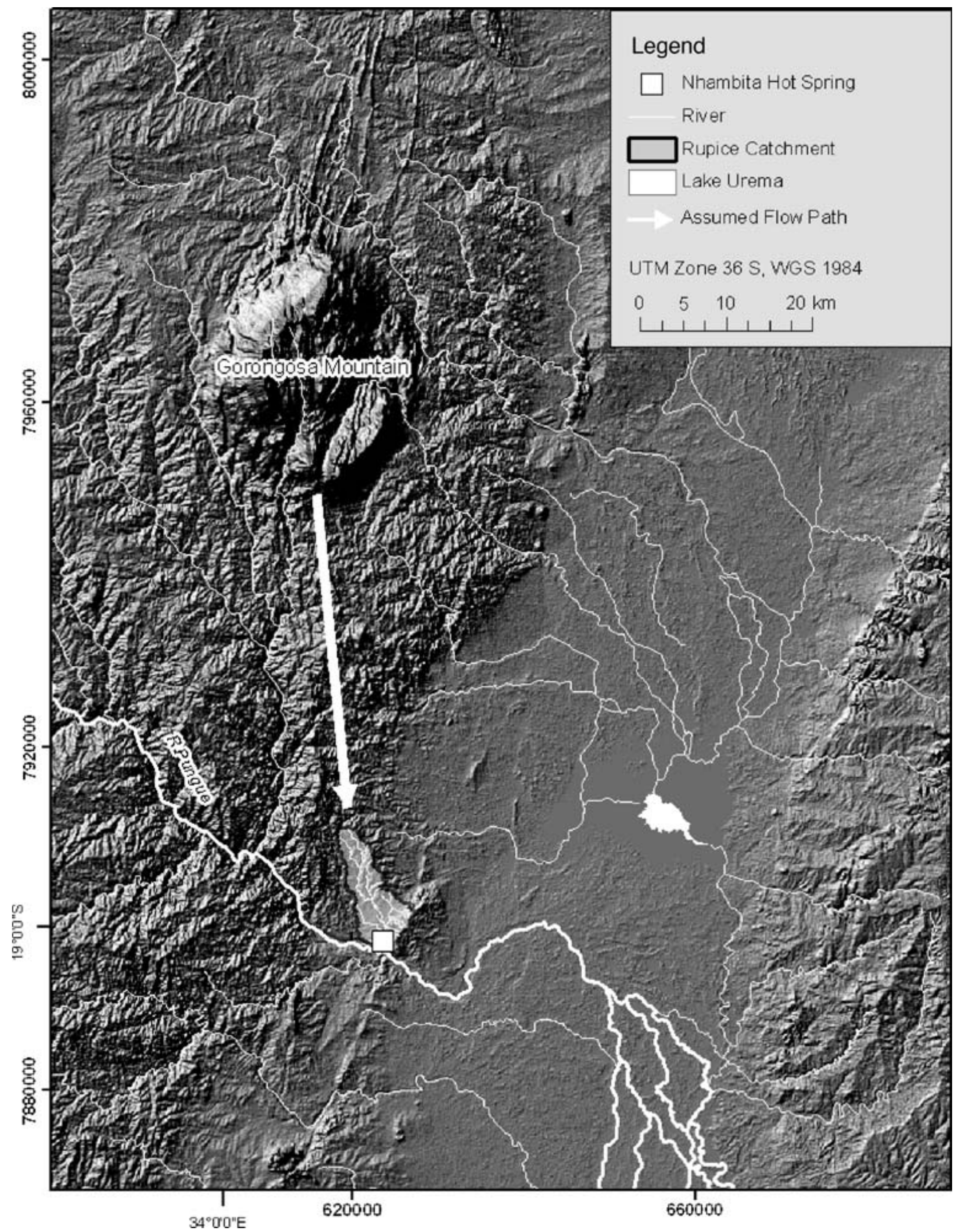

Fig. 8 Map of hypothetical recharge path from Gorongosa Mountain to Nhambita Hot Spring, (*hill shading* derived from NASA SRTM90)

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In reality, the depth might be deeper, because cooling takes place during the uplift of the water. The silica geothermometer represents the temperatures at which equilibrium with chalcedony or quartz from surrounding rocks took place during the formation of the thermal water, which is calculated from the silica content in water. According to Arnorsson (1975), geothermal waters below 120°C are in equilibrium with chalcedony and saturation with respect to quartz occurs at above 180°C (Arnorsson 1975). From the measured silica concentration of 43 mg Si/kg (92.1 mg/kg SiO_2), the silica geothermometer calculates to 132 and 105°C as the temperatures at which equilibrium is established with chalcedony and quartz, respectively. It is therefore speculated, that the Nhambita thermal water was saturated with chalcedony at 132°C and therefore must originate from more than 5,000 m depth. Data on geothermal heat flows in Mozambique are scarce and not representative for the study area; so therefore the source of the heat remains speculative. Another explanation could be the existence of a mantle plume in the area of Gorongosa Mountain.

From the major fault directions, it is speculated that groundwater is recharged north of the Pungue River in the area of Gorongosa Mountain or the Barue Midlands. This would require the existence of a deep, connected fault system parallel to the Urema Rift. Assuming Gorongosa Mountain or an area 10 km to the north of the spring in the Barue Midlands as the recharge area, one obtains for the subsurface flow path a gradient of about 0.035. Assuming high permeability in fault zones, this is sufficient to drive the groundwater along the flow path to the discharge point close to the Pungue River even over a depth of several thousand meters.

The origin of the Nhambita Hot Spring cannot be from seawater because both ratios Br/Cl and I/Cl are 2.5×10^{-3}, while seawater has a Br/Cl ratio of 3.5×10^{-3} and an I/Cl ratio of 0.0027×10^{-3} (due to the scavenging effect of iodine with organic matter in ocean sediments). Therefore, all three halogens have its origin in water dissolving silicate rocks, which is comparable with Br/Cl and I/Cl obtained from investigations of groundwaters in silicate rocks in Namibia (Boneß et al. 1991). Because silica minerals dissolve fairly slowly, these ratios are indicators for a very long subsurface residence time of the Nhambita Hot Spring water in a silicate-rich rock formation. This once more supports the hypothesis of Gorongosa Mountain as being the recharge area of Nhambita Hot Spring (Fig. 8).

Quality characterization

At least 38 thermal springs were identified and geochemically characterized in Mozambique (Martinelli et al. 1995). Figure 2 shows that several geothermal springs occur west of the city of Beira and three close to the study site. From the chemical analyses published in Martinelli et al. (1995), spring No. 35 (referred to as Rupizi) appears identical to Nhambita Hot Spring with respect to temperature, TDS, calcium, sodium, and chloride. There was no evidence in the fieldwork of this current study for other hot springs east of the Nhambita Hot Spring (referred to as Chichere No. 36 and 'unlabeled spring' in Martinelli et al 1995). The coordinates in the map of Martinelli et al. 1995 appear biased and no coordinates of the analyzed springs are provided making it impossible to re-visit these sites. Furthermore, the Chichere spring in Martinelli et al (1995) is marked with 60°C in the map but 47°C in tables II and III of that publication. Since discussions with elders of the Nhambita community did not confirm any further historical or existing spring locations, it is assumed that the information in Martinelli et al. (1995) might be faulty or may correspond to the locations of the former hot water dug wells. Tinley (1977) has mapped one hot spring in the Urema Rift in GNP near the Tambarara Community, which, however, could not be found in the field.

The Nhambita spring water has a discharge temperature of 62°C and is therefore, according to Mozambican standards, considered to be thermal water—the EC is 1,680 μS/cm, while the TDS is 989 mg/L. In some

Table 3 SI (saturation index) calculated by PHREEQC and LLNL database for Mosa P1

Mineral	SI	Formula
Fluorapatite	15.56	$Ca_5(PO_4)_3F$
Cronstedtite-7A	11.63	$Fe_2Fe_2SiO_5(OH)_4$
Trevorite	11.38	$NiFe_2O_4$
Magnetite	11.11	Fe_3O_4
Hematite	10.92	Fe_2O_3
Polydymite	10.48	Ni_3S_4
Andradite	7.11	$Ca_3Fe_2(SiO_4)_3$
Hydroxylapatite	6.51	$Ca_5(OH)(PO_4)_3$
Goethite	4.89	FeOOH
Ferrite-Ca	3.86	$CaFe_2O_4$
Ferrite-Mg	2.62	$MgFe_2O_4$
Minnesotaite	2.37	$Fe_3Si_4O_{10}(OH)_2$
Whitlockite	2.37	$Ca_3(PO_4)_2$
Ni_2SiO_4	2.17	Ni_2SiO_4
$MnHPO_4$	1.82	$MnHPO_4$
Greenalite	0.94	$Fe_3Si_2O_5(OH)_4$
Quartz	0.3	SiO_2
$Fe(OH)_3$	0.21	$Fe(OH)_3$
Barite	0.19	$BaSO_4$
Tridymite	0.14	SiO_2
Chalcedony	0.06	SiO_2
Witherite	–0.13	$BaCO_3$
Cristobalite(alpha)	–0.18	SiO_2
Fluorite	–0.31	CaF_2
Coesite	–0.42	SiO_2
Millerite	–0.53	NiS
Cristobalite(beta)	–0.54	SiO_2
Ferrosilite	–0.54	$FeSiO_3$
SiO_2(am)	–0.76	SiO_2
Vaesite	–0.86	NiS_2
Calcite	–0.94	$CaCO_3$
Strontianite	–1.07	$SrCO_3$
Aragonite	–1.09	$CaCO_3$
Talc	–1.26	$Mg_3Si_4O_{10}(OH)_2$
Anhydrite	–1.39	$CaSO_4$
Fayalite	–1.54	Fe_2SiO_4
Gypsum	–1.55	$CaSO_4:2H_2O$
Siderite	–1.69	$FeCO_3$
Monohydrocalcite	–1.94	$CaCO_3:H_2O$
Bunsenite	–2	NiO

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countries, it is common to define a mineral water by the criteria TDS >1 g/L. Accordingly, the Nhambita Hot Spring would not be a mineral water.

The mineral content of the Nhambita water is characterized by the major ions sodium, sulfate, and chloride with elevated concentrations of fluoride, phosphate, and nickel. The water is low in TIC (HCO_3^-, CO_2, CO_3^{2-}) which is a clear indication that the water was not in contact with active volcanism. The water is low in natural toxic elements like arsenic, lead, cadmium, mercury, beryllium, selenium, antimony, and uranium. As expected, the hot spring water does not contain any pathogenic microorganisms.

Table 3 shows saturation indices (SI) calculated with the software PHREEQC and the database LLNL (Lawrence Livermore National Laboratory, database version V8.R6230). Fluorapatite is highly oversaturated with SI= 15.56; however, this mineral is known as a mineral which tends to stay in solution. Contrarily, fluorite, a mineral which tends to precipitate, is undersaturated with SI=–0.31. Without going into detail, it must be expected that some of the minerals being oversaturated will precipitate with system changes (cooling, pressure decrease). This might be an issue for any future utilization of the hot spring water. The same applies to calcite which is undersaturated (SI=–0.94). Thus, the water is not in calcite carbon dioxide equilibrium and tends to be aggressive to metal pipes. The water is in equilibrium with chalcedony, which is in agreement with the earlier discussed silica geothermometer.

Mean residence time

The Nhambita Hot Spring does not contain tritium and so has no significantly young components, and therefore is more than 40 years old. This also corresponds to the low amount of dissolved organic carbon (DOC, 0.3 mg/L). From the $\delta^{14}C$ concentration of 24.47‰ ± 0.14 in Nhambita Hot Spring water the corrected mean residence time of the geothermal water in the subsurface is calculated to be 11,310±45 years. The calculation of the mean residence time does not account for exchange processes in the subsurface, sulfate reduction, and methane genesis. So far there is no evidence for such processes. The determined $\delta^{13}C$ of –12.54±0.3‰ indicates that the water is in equilibrium with terrestrial carbonates. The stable water isotopes (Table 2) support this very long mean residence time, because the mean values from Harare, Zimbabwe, with $\delta^{18}O$ –4.82 and $\delta^{2}H$ –25.89‰ for the period 1990–2001—International Atomic Energy Agency – Global Network of Isotopes in Precipitation (IAEA/WMO 2006) database—are higher than the Nhambita spring stable water isotope data. The low values of the Nhambita Hot Spring indicate a lower temperature at the time of recharge, which is in agreement with the significant lower temperatures at the end of the last ice age 11,000 years ago. In such cases, seasonal effects and even long-term climate changes have no impact on the water quality of the deep discharge system.

Conclusion and suggestions

As part of the long-term monitoring it is necessary to read the pressure in the geothermal system quasi continuously. Therefore, at least one monitoring well should be drilled (in addition to the pumping well) and equipped with a pressure transducer and a data logger. A number of key parameters need to be determined on a monthly basis, e.g. EC, temperature, pH. Water samples for a bacteriological check have to be taken every three months for analysis in the laboratory. It is recommended to take samples for complete analyses every second year. There is evidence for more discharge in the downstream area but it is not clear so far whether this water comes from the same source. One or two permanent weirs should be installed downstream of the Nhambita Hot Spring. Reading can be done manually since anyhow maintenance is necessary on a regular basis. It is suggested to drill a series of shallow wells along the Nhambita channel in order to obtain more information about groundwater discharge and its quality. In terms of inundation control it would be very important to obtain a precise digital terrain model of the area of interest (area size $1\times0.6\ km^2$). It would further be important to monitor the response of the catchment to precipitation events and to compile a map of land use within the catchment. For water quality control, the preliminary water analyses (performed in this study) should be repeated twice in a year to cover the rainy and dry season. In addition, one sample for strontium (rock and hot spring) and sulfur isotope analyses should be taken to improve the understanding of the hot water source. Boron and pesticides—after compilation of a target list—should be included in the analysis. ^{14}C analysis should be repeated once. The result for phosphate should be checked with another analytical method (e.g. ion sensitive electrode).

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References

Arnorsson S (1975) Application of the silica-geothermometer in low temperature hydrothermal areas in Iceland. Am J Sci 275:763

Boneß M, Heumann KG, Haack U (1991) Cl, Br and I analyses of metamorphic and sedimentary rocks by isotope dilution mass spectrometry. Contrib Mineral Petrol V107:94

COBA, Profabril (1977) Esquema geral da bácia do Rio Pungoe [General scheme for Pungoe River basin], vol VI. Direcção Provincial de Serviços Hidraulicos. Lisboa, Portugal

DNA (1986) Explanatory notes to the hydrogeological map of Mozambique, scale 1:1Mio. National Directorate of Water, Maputo, Mozambique

EPA (Environmental Protection Agency) (2002) EPA standard http://www.epa.gov/safewater/contaminants/index.html, June 2003 edn. Cited 15 February 2008

Espirito Santo TR (1955) Ensaio para o estudo do clima da provincia. Aplicação da nova classificação do Thornthwaite [Initiation for a climate study of the province]. Imprensa Nacional de Moçambique. Lourenço Marques, Provincia de Moçambique

 DOI 10.1007/s10040-008-0343-9

IAEA/WMO(2006) Global network of isotopes in precipitation: the GNIP database. http://isohis.iaea.org. Cited 02 July 2008

Lächelt S (2004) The geology and mineral resources of Mozambique. Direcção Nacional de Geologia Moçambique, Maputo

Martinelli G, Dongarra G, Jones MQW, Rodriguez A (1995) Geothermal Features of Mozambique: country update. In: Proceedings of the World Geothermal Congress, Florence, Italy, May 1995, pp 251–273

Owen R (2004) GM SAFMA hydrogeology condition and trend report: the millennium ecosystem assessment. MSc Thesis, Mineral Resources Centre, University of Zimbabwe, Mount Pleasant, Zimbabwe

Pik R, Marty B, Hilton DR (2006) How many mantle plumes in Africa? The geochemical point of view. Chem Geol 226:100

Tinley KL (1977) Framework of the Gorongosa Ecosystem. University of Pretoria, South Africa

WHO (World Health Organization)(2004) Guidelines for drinking water quality, vol 1, 3rd edn. WHO, Geneva. http://www.who.int/water_sanitation_health/dwq/guidelines2/en/. Cited 21 May 2008