Hydrogeology Journal
https://doi.org/10.1007/s10040-018-1877-0

REPORT

Hydrogeology of a weathered fractured aquifer system near Gitega, Burundi

Sara Vassolo[1] · Christoph Neukum[1] · Christian Tiberghien[1] · Matthias Heckmann[1] · Kai Hahne[1] · Désiré Baranyikwa[2]

Received: 1 March 2018 / Accepted: 24 September 2018

Abstract
The domestic water supply of Burundi is mainly based on some 25,000 springs that provide water through gravity systems. These systems have their natural limitation and cannot respond to future domestic water needs caused by the enormous annual population growth. An estimate of the quantity and quality of groundwater resources in the crystalline and metamorphic hard-rock environment, with strongly variable weathering features, is a prerequisite to ensure future water supply from groundwater resources. The hydrogeology of the Nyanzari aquifer system, which is used for the water supply of the city of Gitega in central Burundi, has been investigated with the aim of understanding aquifer characteristics. Results indicate that weathering of the metamorphic basement rocks has led to the development of two-staged aquifers: a deeper fractured aquifer in the saprock, covered by a shallow saprolite aquifer. This shallow aquifer is fed directly by precipitation and discharges at numerous small overflow springs along the valley edges. In general, the discharge of the springs shows seasonal variation patterns with maxima shortly after the rainy season similar to those of the hydraulic heads measured in the saprock aquifer. Groundwater management in the Nyanzari wellfield is partly unsustainable since abstraction is temporarily higher than recharge, even if, so far, periods of over-abstraction have been compensated by later rainy seasons. The lessons learned concerning the behaviour of the strongly weathered fractured aquifer system in Nyanzari will help to develop and manage comparable groundwater resources in Burundi.

Keywords Fractured rocks · Burundi · Over-abstraction · Overflow spring · Groundwater monitoring

Introduction

The domestic water supply of Burundi is mainly based on the about 25,000 springs (BRGM 2011) that provide water through local gravity systems. However, these are limited in quantity and cannot respond to future higher domestic water needs caused by the enormous annual population growth, estimated at 3.25% for 2017—ranking fourth worldwide, according to the "CIA World Factbook" (CIA 2016). Therefore, there is an urgent need for the country to search for other sources of supply, including surface water or other sources of groundwater. An estimate of the quantity and quality of groundwater resources in the crystalline and metamorphic hard-rock environment, with strongly variable weathering features, is a prerequisite to ensure that future water demand can be covered by these resources.

Weathering of crystalline and metamorphic rocks causes diverse changes in their physical properties and petrographic composition (Walther 1915; Larsson 1984; Chilton and Foster 1995; Oliva et al. 2003; Arias et al. 2016). Consequently, the hydrogeology of hard rock aquifers is strongly dependent on the overall development of weathering, its depth and its spatial distribution. Three main zones with different hydrogeological characteristics are distinguished in the weathering process: unweathered (fresh) bedrock, saprock showing initial weathering and fracturing, and saprolite that while maintaining the original rock structure has an increased permeability and water storage (Arias et al. 2016). Wyns et al. (1999) distinguish two sub-layers within the saprolite: (1) alloterite, which is mostly a clayey horizon at the top of the saprolite where the structure of the mother rock is lost due to weathering and volume reduction and (2) isalterite, where

✉ Sara Vassolo
saraines.vassolo@bgr.de

[1] Federal Institute for Geosciences and Natural Resources, Stilleweg 2, 30655 Hanover, Germany

[2] Institut Géographique du Burundi, Gitega, Burundi

Published online: 20 October 2018

the original structure is preserved and volume is not or only slightly changed. In plutonic rock, the base of the isalterite is frequently laminated and mainly constitutes the capacitive function of the aquifer (Dewandel et al. 2016). Groundwater occurrence, dynamic, and availability for water supply vary with the main controlling factors of weathering: petrography of the crystalline and metamorphic rocks, time for the development of rock alteration whenever weathering rate is higher than erosion rate, and climate (temperature; Lachassagne et al. 2011), which in turn control landscape and aquifer evolution.

Crystalline basement rocks are a major source of potable water throughout equatorial Africa. Howard and Karundu (1992) show that the basement rocks of a region in southwestern Uganda form a very weak aquifer, which is highly susceptible to over-production. Bakundukize et al. (2016) investigated the groundwater potential in the Bugesera region in northeast Burundi to understand the reason for hand-dug wells failures, whereby they concluded that although there are good prospects for water resources in the fractured/weathered basement as well as the lower part of the weathered overburden, a poor understanding of the hydrogeology is the main cause for hand-dug well failure. Walraevens et al. (2018) investigated the hydrochemistry of groundwater in the same region and demonstrate the control of aluminosilicates weathering on the hydrogeochemical evolution; furthermore, they reported anthropogenic pollution indicated by the presence of nitrate and sulphate in groundwater. Concerning natural groundwater quality problems due to high uranium concentration in northwest Burundi, Post et al. (2017) proposed a model in which weathering and evapotranspiration during groundwater recharge, flow in the underground, and discharge are the main controlling factors on elevated uranium concentration. Despite those studies focusing on the Bugesera region, the overall hydrogeology of Burundi is poorly understood so far.

The hydrogeology of the Nyanzari aquifer system, which is used for the water supply of the city of Gitega in the central part of Burundi, has been investigated aiming at understanding the system and quantifying its hydrodynamic behaviour. Major questions for future water supply and its management are related to the dynamic, availability, and interdependency of the used groundwater resources, e.g. groundwater from springs and wells. Based on soils and weathering features, classification of borehole logs as well as tracer and pumping tests, the aquifer system is characterized and a conceptual hydrogeological model is proposed, which is surely representative for many other locations with a similar geological setting in Burundi.

Geography, land use, vegetation, and climate

Burundi is a small (27,834 km^2, UNdata 2018) landlocked country on the eastern flank of the Western African Rift Valley (Fig. 1). With about 11.5 million inhabitants and an annual growth rate of 3.25% (CIA World Factbook, CIA 2016), it has one of the highest population densities in Africa—about 450 inhabitants per square kilometre (UNdata 2018).

Gitega is the second biggest city in the country and the capital of the Gitega Province and is located at an elevation of 1,705 m above sea level (asl) on the Central Burundian Plateau, some 100 km to the east of Bujumbura, the capital city. Geographically it lies on the north-western shoulder of the Birohe-Rugari-Songa Mountain range (1,700–2,000 m asl) that is separated by the Mutwenzi River from the Cene Mountains (2,000 m asl), the major mountain massif on the Central Plateau (Fig. 1).

According to the census from 2008, the commune of Gitega has a population of 150,000 inhabitants. The principal activities in the region are agriculture-related with livestock breeding (goats and sheep), grazing, and small-scale agriculture with banana, peanut, sweet potato, manioc, bean, corn, and coffee as the main production.

The region has a moderate climate with maximum annual temperatures in the range of 24.1 to 27.7 °C and minimum values between 11.9 and 14.8 °C for the period 1985–2013—Gitega airport station, data from the “Institut Géographique du Burundi” (IGEBU). The mean annual precipitation at the Gitega airport station for the period 1964–2013 is 1,178 mm with a distinct dry period from May to October and minimum rainfalls in June and July.

Geology, tectonic setting, and weathering zone

Geology

The geology of Burundi is characterized by rocks of the Mesoproterozoic Kibaran Belt. The Kibaran Belt extends SSW–NNE from southern Congo to south-western Uganda and is one of several, roughly parallel, Mesoproterozoic sedimentary basins that subsequently experienced metamorphic deformation (Tack et al. 1994).

The lithology of the Central Burundian Plateau, where Gitega is located, consists mainly of low to intermediate metamorphic pelitic to psammitic metasediments and extensive areas of intrusive rocks, according to the Gitega sheet of the “Geological map of Burundi” (Claessens and Theunissen 1988). The dominant lithostratigraphic units are the tectono-metamorphic complexes Kiryama and Vyanda (Fig. 2).

Most of the Nyanzari catchment, where the main wellfield providing water to the city is sited, is located within the Kiryama complex composed of undifferentiated

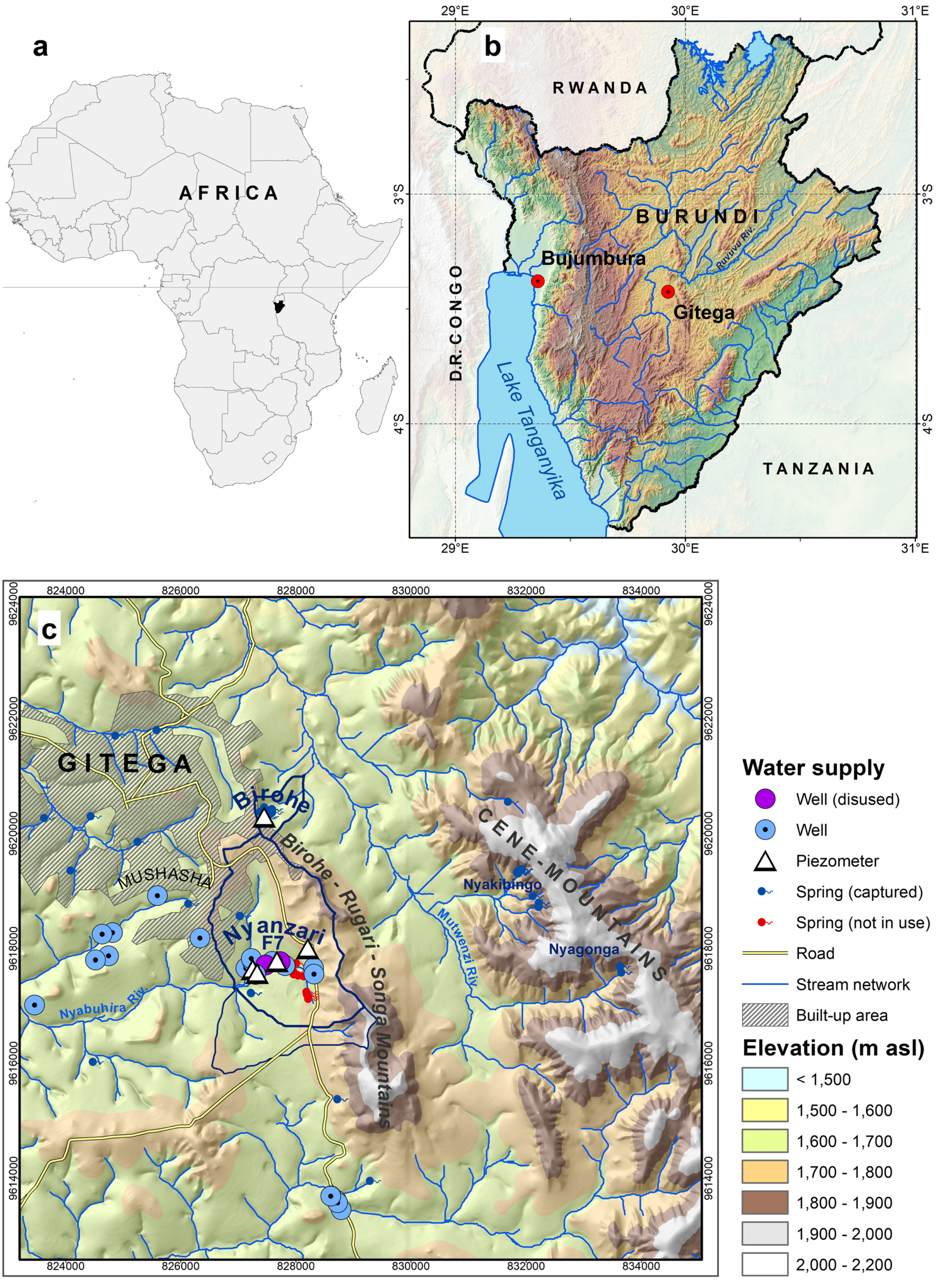

Fig. 1 **a** Location of Burundi in Africa and **b** location of Gitega in Burundi. **c** Overview on the Nyanzari and Birohe catchments with location of wells and springs

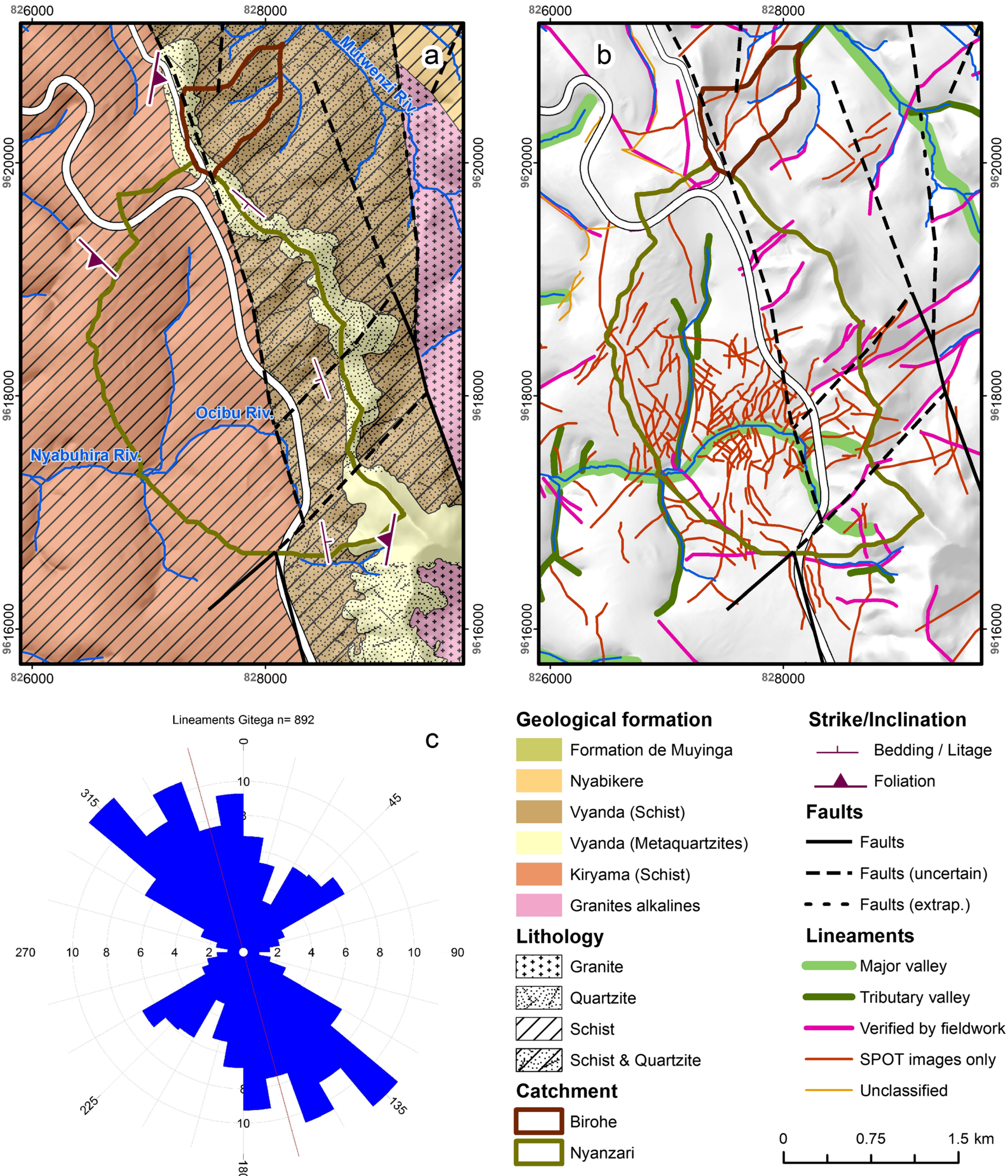

Fig. 2 **a** Geological map of Gitega after Claessens and Theunissen 1988. **b** Spatial distribution of lineaments in the Nyanzari and Birohe catchments mapped using multispectral SPOT satellite images. **c** Rose diagram (n = 892) with all mapped lineament directions derived from lineament mapping on multispectral SPOT satellite images

metamorphic rocks including metaquartzites and schists. The dominant rocks in the study area are schists intercalated with thin quartzitic banks.

The Birohe-Rugari-Songa Mountain range in the eastern part of the Nyanzari catchment belongs to the Vyanda complex. This complex is mapped as alternations of grey-to-red metapelites (phyllites) and banked grey metaquartzites (Claessens and Theunissen 1988). During fieldwork, the unit was found to consist purely of banked metaquartzites in the elevated parts of the Nyanzari catchment; although generally the quartzite outcrops found there are strongly fractured and weathered.

Tectonic setting

The Central Burundian Plateau is shaped by NE-oriented and elongated Precambrian fold-structures that controlled the development of the stream network. All major rivers flow perpendicular to the dominant ridges of the anticlines. The exposure of Mesoproterozoic rocks and the absence of Mesozoic and early Cenozoic sediments over almost the entire area of Burundi, except for some terraces at Lake Tanganyika, indicate prolonged periods of tectonic quiescence, profound weathering, denudation and peneplanation (Claessens and Theunissen 1988). With the onset of Cenozoic rifting, new faults developed and older ones were reactivated (Chorowicz et al. 1990).

The dominant orientation of the lineaments follows the main fracture direction of the Tanganyika graben (NW), whereas stress release fractures, developed as conjugated faults, are oriented perpendicularly. Lineaments strike predominantly NW–SE (130–170°) and NE–SW (050–060°).

For lineaments tracing in the study area, remote sensing techniques were applied. Multispectral data (SPOT satellite images) and appropriate image enhancement (high-pass filtering, histogram stretching) were most valuable for lineament identification. The methodology allows to detect, to a certain extent, also soil-covered NW- and NE-striking lineaments, which are related to the most recent rift-faulting. The lineaments become directly visible by the combination of spectral bands also using information of the infra-red part of the electromagnetic spectrum because the soil development shows gentle differences concerning composition along them (Fig. 2). These kinds of faults have been proven to exist in outcrops and in other areas of Burundi by means of TEM profiles, showing steps of normal faulting within the basement (Hahne 2014). The importance of these "buried" lineaments as pathways for groundwater flow becomes obvious at the highly productive Nyanzari well field south of Gitega, which is situated in an area of intersecting soil-covered lineaments (Fig. 5).

Weathering zone

Subsurface weathering and aquifer evolution in Burundi is characterized by (1) faults related to ancient (post-)Mesoproterozoic tectonics and the ongoing rifting associated with the East African graben system, (2) development of horizontal fractures and fissures in the wake of initial weathering during exhumation, (3) Mesozoic-Cenozoic denudation and planation surfaces and the development of respective deep weathering profiles, and finally (4) the shaping of the Holocene topography with particular focus on linear erosion features and anthropogenic stripping of soil and saprolite.

The Central Burundian Plateau is the remnant of an ancient planation surface, probably the late Tertiary Kagera surface (Rossi 1980) with a characteristic *demi-orange* relief. Repeated cycles of denudation and peneplanation have led to staged surfaces and locally to topographic inversion reinforced by lateritic ferricretes. These are ubiquitous and stand out as mesa-like hilltops or form distinct scarps at the steep lower slopes, where they often developed within saprolitic schist. The ferricretes, often over 6 m thick and occurring as both pisolithic layers and continuous vermiform ironstones, have a high potential to influence the infiltration and runoff regime. Field observations suggest that ferricretes rather abet infiltration than acting as a surface-sealing agent.

The aquifers of the Nyanzari catchment developed by weathering from the tectono-metamorphic complexes Kiryama and Vyanda. Field observations indicate high spatial variability of weathering and weathering depths for both geological units. Where lateritic ferricrete overlay the quartzite rocks of the Birohe-Rugari-Songa Mountain range, it has been completely weathered and several meters of pure white quartzitic sands occur. Only initial soil development on the mountain slopes suggest widespread erosion and removal of weathering layers, particularly the former protecting soil cover. Overall, the quartzite outcrops are highly fractured and fissured and represent an uncovered, highly conductive aquifer.

Weathered saprolitic metapelites ("schists") of the Kiryama complex often preserve original bedding and rock structure. Outcrops are observed at all relief positions—on hilltops, at roadcuts, on the foothills, and also at scarps on the lower slopes—often impregnated and overprinted by lateritic ferricretes. On slopes, the magnitude of the generally residual (soil) layer overlying the saprolitic weathered rock is estimated based on soil descriptions to amount up to 5 m thick. Topographic inversion and the likely spatial variability of prolonged weathering during peneplanation and subsequent denudation render any reliable regional approach regarding estimation of weathering depths and weathering grades highly speculative.

Lithology and weathering conditions along the valleys are only known from borehole descriptions (Tiberghien et al. 2014; Lahmeyer et al. 2005). The reports coincide in the description of a thick clay-rich residual-weathering layer that tentatively can be subdivided into an upper plasmic and a lower saprolitic zone. Consequently, borehole descriptions were reinterpreted according to idealized weathering schemes (Walther 1915; Larsson 1984; Acworth 1987; Tardy 1992; Wright 1992; Aleva 1994; Chilton and Foster 1995; The Geological Society 1995; Robertson et al. 1998; Lloyd

1999). Four weathering zones with related hydrogeological interpretation are distinguished from top to bottom (Fig. 3):

1. Collapsed clay-rich plasmic zone (only available along the valleys)

- Collapse of rock structure, homogeneous, dense 'plasmic' zone
- Formation of secondary (soil) structure
- Strong clay neoformation and clay enrichment
- Aquitard to porous aquifer with very low hydraulic conductivity

2. Saprolite (shallow aquifer)

- Strongly weathered and clay horizon at the top (alloterite)
- Intact rock structure: isovolumetric weathering below the top horizon (isalterite)
- Strong leaching: > 20% of minerals weathered
- Isalterite: fractured-porous aquifer with moderate to high hydraulic conductivity depending on clay content

3. Saprock (deeper aquifer)

- Strongly fractured rock
- Open fractures
- Slightly weathered and still identifiable minerals (e.g. amphibolite)
- Semi-confined fractured aquifer

4. Bedrock

- Fresh poorly fractured metamorphic rocks
- Aquitard

This conceptual hydrogeological model is quite similar and in accordance with other concepts of hard rock aquifer hydrogeology (e.g. Lachassagne et al. 2011, 2014; Dewandel et al. 2011).

Hydrogeology

Groundwater flow in the shallow aquifer: Birohe catchment

The springs used for water supply of Gitega emanate at positions where the moderate sloping hills meet the gentle slopes at the valleys. Artificial sources created by clay extraction pits at the edge of the valley (Heckmann 2016) show strong and rapid water influx even at slightly elevated positions (up to 1.5 m above the valley bottom). The ubiquitous outflow of groundwater along valley edges suggests either the presence of a shallow water-bearing layer, which involves the saprolite and maybe the uppermost part of the saprock (contact springs) or impounding and backing up of the shallow groundwater triggering discharge at depression springs. Discharge patterns of some larger springs used for water supply show seasonal variations with maxima shortly after the rainy season (data not shown).

In order to quantify groundwater flow velocity and flow direction, two tracer tests using sodium chloride were performed in the Birohe catchment in April 2013 (Fig. 4). The first test was designed to get a general idea on the groundwater flow conditions. Consequently, tracer was injected at a rather short distance (approx. 39 m) from the sampling source S25. For the second test, injection took place at a more representative flow distance of 88 m in the catchment of springs S26 and S119. Due to the construction of the springs' tapping, neither spring could be sampled individually. The breakthrough curves were assessed measuring the electrical conductivity of spring water by means of WTW Multimeters 340i and 3430, from which the sodium chloride concentration was calculated based on an electrical conductivity vs. salt content curve prepared beforehand. Spring discharges were measured using a portable ultrasonic flow meter (Prosonic Flow 93 T). The recovered sodium masses at the monitoring sites were calculated by integration of time variant sodium concentration and spring discharge.

For the tracer injections, holes with diameters of 0.75 m were excavated with 1.7 m (first experiment) and 1 m (second experiment) depths. In the first case, groundwater was found at the bottom of the injection hole. Due to the hardness of the underground at injection point 2, digging of more than 1 m was not possible and groundwater was not reached. Both injection points were dug at elevated positions close to a quartzite quarry where low-permeable weathering layers have been completely removed. The layer belongs to the upper part of the saprolite—alloterite according to Wyns et al. (1999)—with strong weathering and unpreserved structure of the mother rock. However, the fast infiltration of tracer solution indicates that the bottom of the injection points were situated in or closely to the isalterite layer. The tracer test conditions are summarized in Table 1.

During the first test, tracer was detected only at spring S25. The first indication of tracer was recorded 4 h after injection and the maximum concentration was obtained after 28 h. A total of 56% of the tracer mass were recovered after 8 days of measurement, when measurement stopped. Spring discharge at S25 rose from around 10 to 15 m^3/h during the tracer experiment.

The first indication of tracer in the second experiment was detected about 5.5 h after injection at springs S26 + S119. The maximum concentration was measured after 30 h. A total mass recovery of 14% was obtained. At S25 a slight increase of electrical conductivity was measured during the second experiment, but it cannot be differentiated between the first

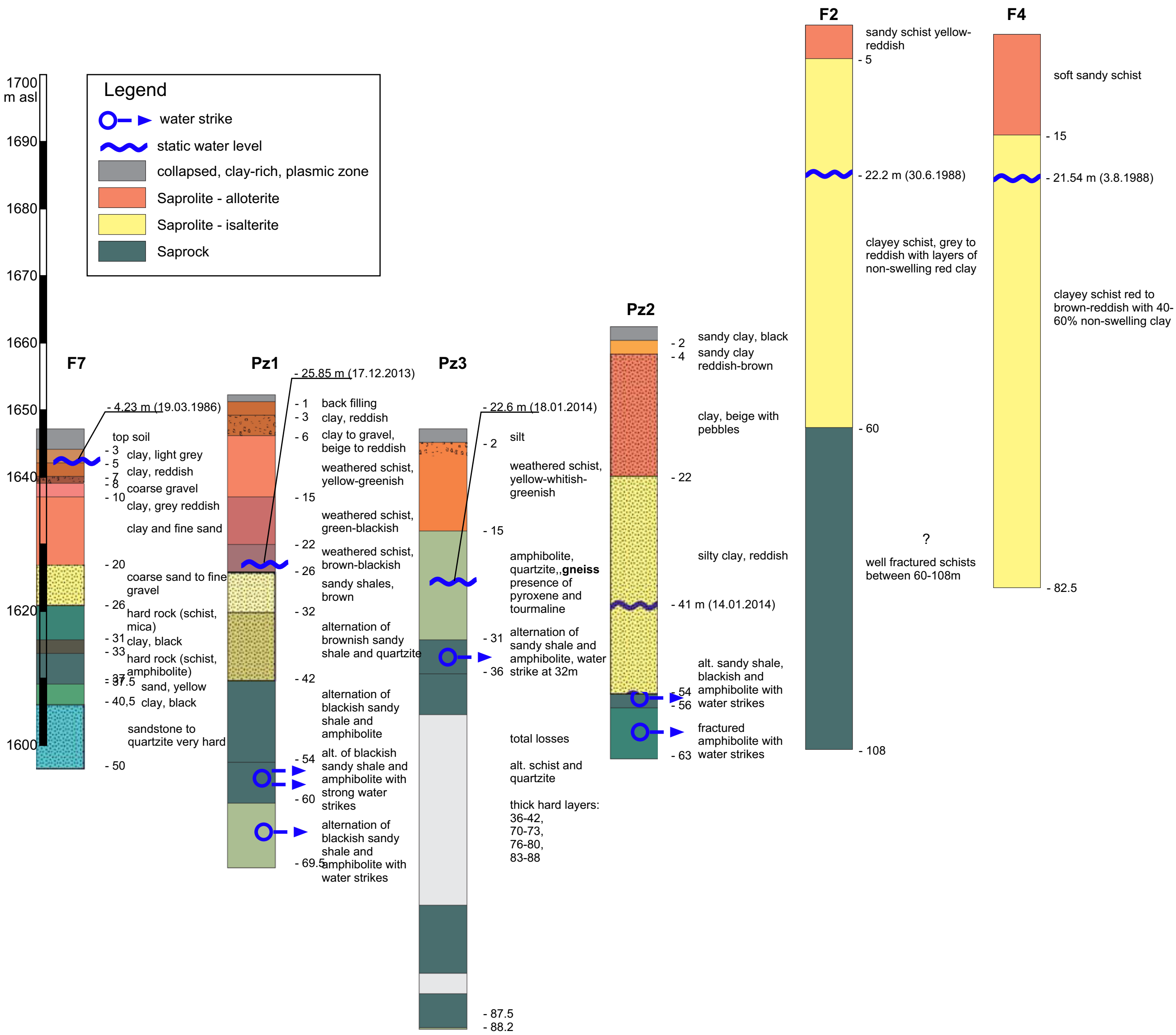

Fig. 3 Borehole stratigraphy at Nyanzari (borehole data from Tiberghien et al. 2014). Horizontal axis not to scale. For borehole locations see Fig. 5

and second test. The discharge at S26 + S119 rose from around 12 to approx. 16 m^3/h during the test.

Both tracer breakthrough curves are influenced by precipitation (Fig. 4). The breakthrough curve of the first experiment shows a narrow double peak at its maximum, which is probably caused by a precipitation event with more than 40 mm on the injection day. A secondary peak in the tailing of the curves is triggered by a later precipitation event which occurred during the test. The second breakthrough curve shows two major peaks. The first peak is attributed to the relatively high amount of tracer solution injected at the beginning of the experiment. The second peak is triggered by a precipitation event, which induced the flushing of the tracer by infiltrating precipitation water.

Groundwater flow velocities for peak tracer concentrations are 1.32 m/h for the first and 2.75 m/h for the second experiment. If only the very first peak of experiment one is considered, then the peak velocity calculates to 1.66 m/h. The difference in peak flow velocity between the tests might be due to the higher hydraulic gradient and the larger amount of solute injected in the second experiment. The increase of spring discharge on the precipitation events is rather low which indicates a high storage volume of the shallow aquifer. At the same time, tracer velocities and the increase of solute concentration on precipitation events are high, which indicates a high hydraulic conductivity.

Groundwater flow and dynamic in the deeper saprock aquifer: Nyanzari wellfield

The deeper fractured aquifer is tapped by the boreholes of the Nyanzari wellfield with water strikes between ~32 and >50 m

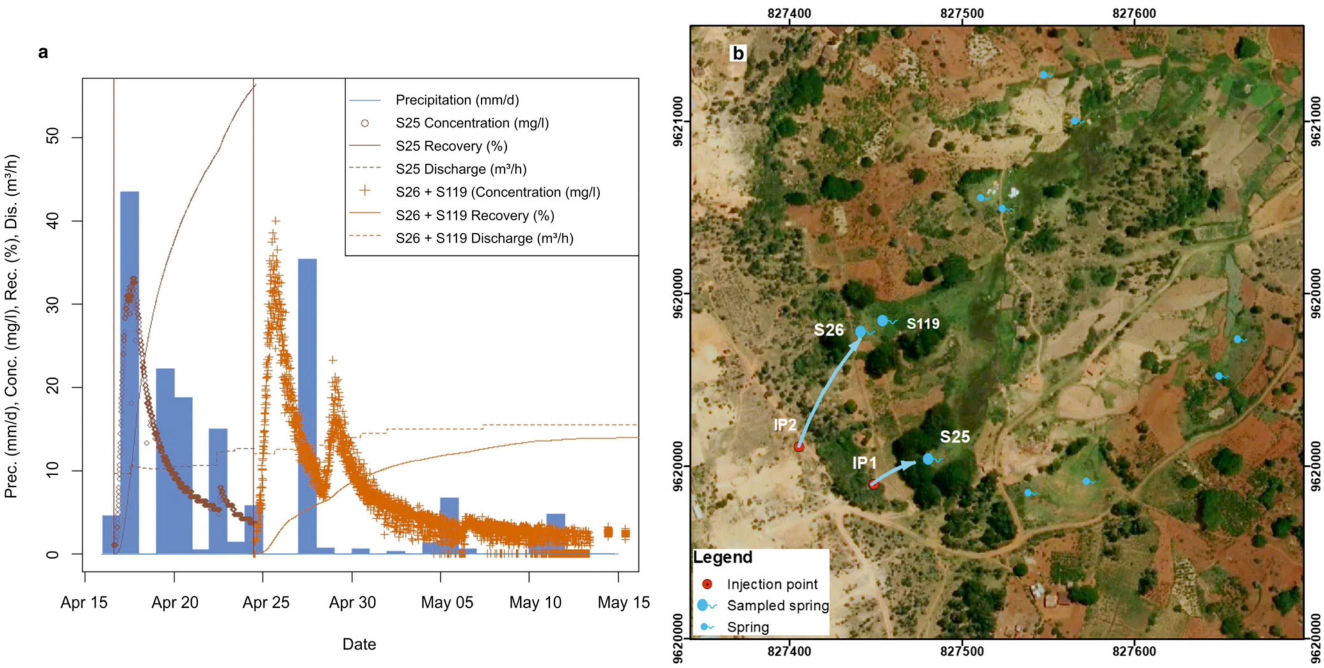

Fig. 4 **a** Tracer breakthrough curves with measured precipitation, spring discharges and tracer recovery. The vertical lines indicate the times of tracer injections. **b** Locations of tracer injection points, sampled springs and other springs in the Birohe catchment as well as traced groundwater flow path

below soil surface (Fig. 3). According to borehole descriptions, water strikes occur at fractures in the schist/amphibolite saprock.

The Nyanzari wellfield, about 5 km south of Gitega, was established in 1986 with the drilling of wells F7 and F8. Two further wells, F2 and F4, were drilled eastwards in 1988. To satisfy the growing water demand of Gitega, six additional wells were drilled in 2008 (F7.3, F7.5, F7.8, F7.12, F7.15, and F7.17). Operated by Régie de la Production et Distribution d'Eau et d'Électricité (REGIDESO), the Nyanzari wellfield provides about two thirds of the drinking water for the town of Gitega (Tiberghien et al. 2014).

The surface catchment of the Nyanzari wellfield (~5 km^2) comprises the watersheds of the Ocibu and Vyinkona streams and the Bikinga plain to the south. At present, water extraction occurs at F7, F2, F4, F7.3, F7.5, F7.8, F7.12, and F7.15 (Fig. 5). According to the records from REGIDESO for the period March 2013 to July 2017, the mean daily pumping rate from the wellfield sums up to 3,100 m^3, whereas F7.15 extracts 50% of the water (1,500 m^3/day).

To monitor the effects of the wellfield on the aquifer, a first data logger was installed in 2013 in an unused well named Itankoma located close to wells F2 and F4. Three piezometers (Pz1–Pz3) were constructed and equipped with a data logger

Table 1 Boundary conditions of the tracer tests within the Birohe catchment; points S25, S26 and S119 are sampling points common to both tracer injection studies

Characteristic	Injection 1	Injection 2
Tracer	NaCl	NaCl
Tracer mass (kg)	40	300
Volume of tracer solution (m^3)	0.2	1.5
Injection point	3°25′50.72″S / 29°56′47.94″E	3°25′50.02″S/29°56′46.54″E
Sampling points	S25 (3°25′50.25″S/29°56′49.06″E) S26 (3°25′47.85″S/29°56′47.78″E) S119 (3°25′47.64″S/29°56′48.19″E)	
Distance from injection point, horizontal (m)	S25: 37	S25: 78 S26: 76 S119: 89
Distance from injection point, vertical (m)	S25: 8.5	S25: 19.9 S26: 19.0 S119: 21.4

in 2014 by IGEBU/BGR. Time series of all these piezometers (Fig. 6) show strong seasonal variations (>10 m) because of a combined effect of pumping activities and recharge from precipitation. Clear indications of over-abstraction are seen in the hydrologic years 2013–2014 and 2016–2017 when groundwater recharge from precipitation with 1,100 and 960 mm/a, respectively, was not able to compensate groundwater abstractions as indicated by the lack of hydrograph recoveries after the rainy seasons. They contrast with the rapid recoveries seen in the hydrologic years 2014–2015 and 2015–2016 that result from a relatively high precipitation of 1300 mm/a. Reliable pumping data for the well field F7 (sum of wells F7, F2, F4, F7.3, F7.5, F7.8, F7.12, and F7.15) are available only for 2014 and 2015, and sums up to 1.21 and 1.15 million m^3, respectively. The relative small difference in the annual sum of abstracted groundwater compared to the strong variation of the inter-annual groundwater heads indicates a large sensitivity of the aquifer to the relationship pumping/groundwater recharge, probably due to a low aquifer storage.

At the time of establishment of the wellfield in 1986/1988, the first boreholes showed (semi-) confined conditions with hydraulic heads at about 5 m below soil surface. Hydraulic heads at the piezometers drilled in 2014 were 23 m (Pz3), 26 m (Pz1) and 41 m (Pz2) below soil surface suggesting a strong drawdown since installation of the wellfield. The drawdown in the wellfield and the recent drying-up of tapped springs upstream of the Ocibu Valley are strong indications for the interconnection of the upper and lower aquifers.

Five pumping tests had been conducted in F7.3, F7.8, F7.12, F7.15, and F7.17 in 2008, at the time of well construction. Although no data are available on borehole lithology, well construction, or details on the experimental setup, the data were analysed using appropriate methods (Table 2).

Recent pumping tests were performed at Itankoma and at the three piezometers installed between 2013 and 2014. For these tests, an electrical submersible pump with 5.5 kW and 400 V was used. Pumped water was discarded downstream in the nearby valleys. Water levels were measured manually by means of portable dipmeters.

All available test data were analysed by means of the software OUAIP from BRGM (2015). Transmissivity values vary

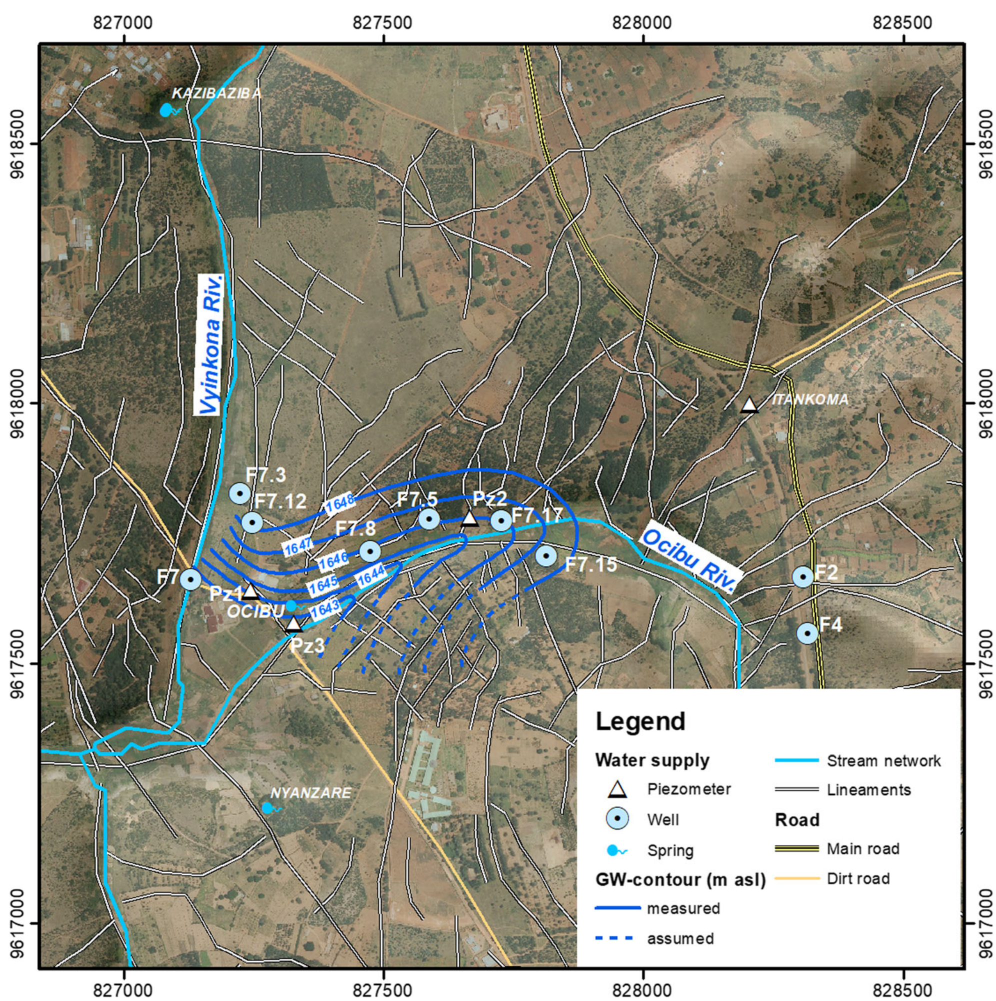

Fig. 5 The Nyanzari wellfield with location of pumping wells, piezometers and important springs. Groundwater contours are based on measurement taken at the time of the wellfield installation

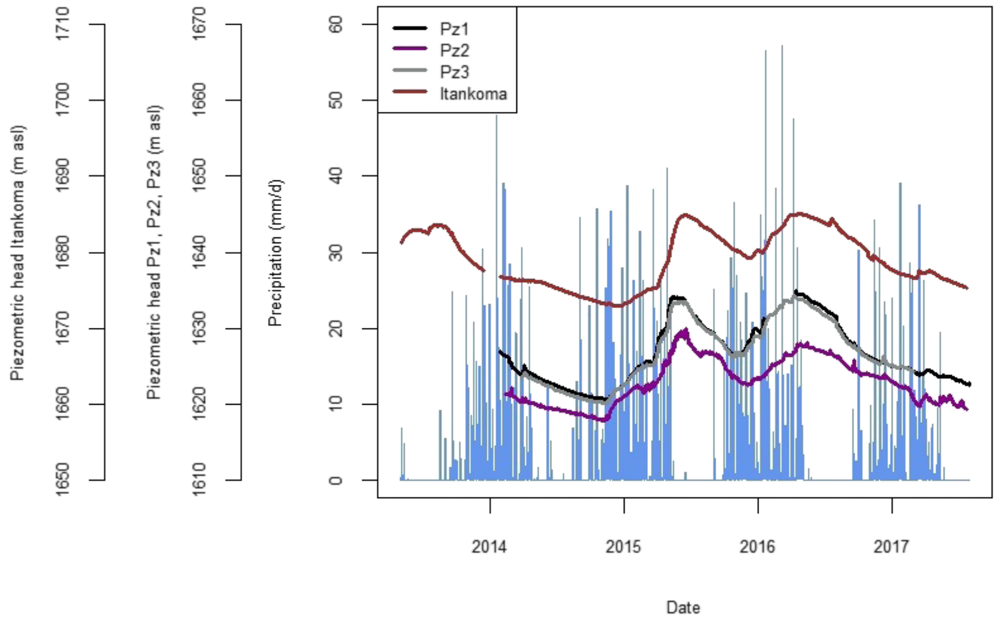

Fig. 6 Precipitation measured at Gitega airport station and piezometric heads recorded at the four piezometers available in the Nyanzari wellfield. Note the different Y-axis for Itankoma

between 4E-02 and 3E-04 m^2/s. Yields of fractured aquifers are highly variable because of the spatial heterogeneity of the fracture system, a generally low storage capacity of the fractures themselves, and a very low hydraulic conductivity of the massive rocks (Wright 1992). Accordingly, yields at the Nyanzari wellfield vary strongly between neighbouring wells (Table 2); furthermore, the estimated storage coefficients show an aquifer with confined conditions.

Estimation of groundwater recharge

The estimation of the groundwater recharge (R) for the Nyanzari catchment was done using the mass balance equation that reads:

$$R = P - \mathrm{ETR} - Q \pm \Delta\mathrm{SWS} \quad (1)$$

where P is precipitation, ETR real evapotranspiration, Q surface runoff, and ΔSWS the variation of soil water storage.

The potential evaporation (ETP) has been calculated using the Thornthwaite (1948) method at a monthly time step for the period 1982–2013. The fact that for the Gitega airport station, located 5.5 km to the NW of the wellfield, only daily precipitation and maximum and minimum temperatures were available for a long period of time at an acceptable quality in the IGEBU database led to the decision of using the Thornthwaite method, although it is known that it overestimates potential evapotranspiration in humid climates (Bakundukize et al. 2011).

The real evaporation (ETR) is then determined based on the ETP and the soil-water content, which in turn depends on the volume of soil water taken by the plants during the growing period and the water retention potential of the soil. Calculations were performed assuming soil water contents of 10, 50, 75, 100, 120, and 200 mm. The obtained values of PET varied between 660 and 839 mm/a with a mean of 741 mm/a and a standard deviation of 62 mm/a. Bakundukize et al. (2011) published the water content for soils in the Bugesera region in the north of Burundi. They are composed of weathered Precambrian metasediments and thus are predominantly clayey and used mainly for agriculture with shallow rooted crops. Assuming an overall retention potential of 30% (clay soils) and a root depth of 0.25 m, a maximum water storage content of 75 mm was estimated. This value was also adopted for Gitega because of the similarities concerning soils and soil occupation. The real evapotranspiration was calculated at monthly steps as follows:

If $P \geq$ ETP, then ETR = ETP.
If $P <$ ETP then:

- If $P + \Delta S \leq$ ETP, ETR = $P + \Delta S$
- If $P + \Delta S >$ ETP, ETR = ETP

The long-term mean real evapotranspiration calculates at 725 mm or 63% of the precipitation for the period 1982–2013 (Table 3). The long-term monthly minimum runoff (Q) has been published as 6% of the precipitation for the Ruvubu catchment area (IGEBU 2010), where the well field is located (Table 3). The average recharge for the given period of time in the Nyanzari catchment can be now estimated using the mass balance equation (Eq. 1), a value of 446 mm/a or 39% of precipitation is obtained.

The groundwater recharge for the hydrologic years between 2013 and 2014 and 2016–2017 was estimated at 450,

Table 2 Results of constant discharge tests conducted in the wellfield. *Q* pumping rate, *T* transmissivity, *S* storativity

Well	Well depth (m)	Pump depth (m)	Date	Drawdown (m)	*Q* (m^3/h)	Method	*T* (m^2/s)	*S*
F7.3	89	87	01.05.2008	8.50	55	Theis	6.0E-03	–
F7.8	95	71	10.05.2008	50	23	Theis	3.0E-04	–
F7.12	52	41	05.05.2008	16	55	Theis	2.5E-03	–
F7.15	75	96	31.03.2008	2.8	49	Hantush	4.0E-02	–
F7.17	109	104	17.05.2008	0.95	18	Theis	2.0E-02	–
Itankoma	123	105	12.09.2013	13	2	Theis	6.0E-05	–
Pz1	69	67	18.12.2013	0.7	15	Theis	6.0E-03	5.0E-05[a]
Pz2	63	60	15.01.2014	9.5	10	Gringarten	1.0E-02	5.0E-05
Pz3	88	35	18.01.2014	2.8	17	Gringarten	9.0E-04	4.0E-04

[a] Storativity is calculated from drawdown measurements at well F7

643, 666, and 371 mm/a, respectively. The low recharge calculated for the hydrologic years 2013–2014 and 2016–2017 explain the over-abstraction effects, which have been described in section 'Groundwater flow and dynamic in the deeper saprock aquifer: Nyanzari wellfield'.

Summary and conclusions

Weathering of the metamorphic basement rocks of the Nyanzari catchment has led to the development of two staged aquifers: a deeper fractured aquifer in the saprock, covered by a shallow saprolite aquifer. The shallow aquifer discharges at numerous small overflow springs along the valley edges where the concave hill slope meets the valley bottom causing a pronounced break in slope.

This shallow aquifer is fed directly by precipitation and shows locally varying discharge patterns with time lags of up to 1 month between rainfall and spring discharge. In general, the discharge of the springs show seasonal variation with maxima shortly after the rainy season and very similar to the variations of the groundwater head observed in the wells and piezometers.

Mechanisms triggering the springs may be twofold: (1) clay-rich weathering residues in the valley bottoms act as an hydraulic barrier for emanating groundwater at contact springs and/or (2) saturation of the subjacent low-permeability weathering zones results in the impounding and backing up of the shallow groundwater triggering discharge at depression springs. In valleys and on lower slopes, saturation of the saprolite and weathering layers with an elevated clay content and a reduced hydraulic conductivity back up interflow and percolation water and trigger discharge through springs and channels. Borehole data located in valleys confirm the presence of such clay-rich weathering residues that act as an aquitard and produce (semi-) confined groundwater conditions for the lower fractured aquifer of the saprock. The observed low permeability results from a high clay content produced during advanced weathering of schist and the collapse of the isovolumetric weathered saprolite in the plasmic (clay) zone of the valley bottoms (Fig. 7).

Borehole descriptions of the piezometers drilled in 2013/2014 show that the lower fractured aquifer in the wellfield area has water strikes between ~32 and > 50 m below soil surface corresponding to fractures in the schist/

Table 3 Determination of monthly mean recharge (*R*) for Gitega for the period 1982–2013 (mm)

Parameter	Month												Total	% *P*
	Sept	Oct	Nov	Dec	Jan	Feb	March	Apr	May	June	July	Aug		
P	46	98	157	145	162	140	157	164	67	5	5	11	1,157	100
ETP	79	77	71	71	73	75	74	75	72	66	66	73	873	76
Δ*S*	0	20	75	75	75	75	75	75	70	9	0	0		
ETR	46	77	71	71	73	75	74	75	72	66	14	11	725	63
Q	3	6	9	9	10	8	9	10	4	0	0	1	69	6
R	0	15	77	65	79	57	74	79	0	0	0	0	446	39

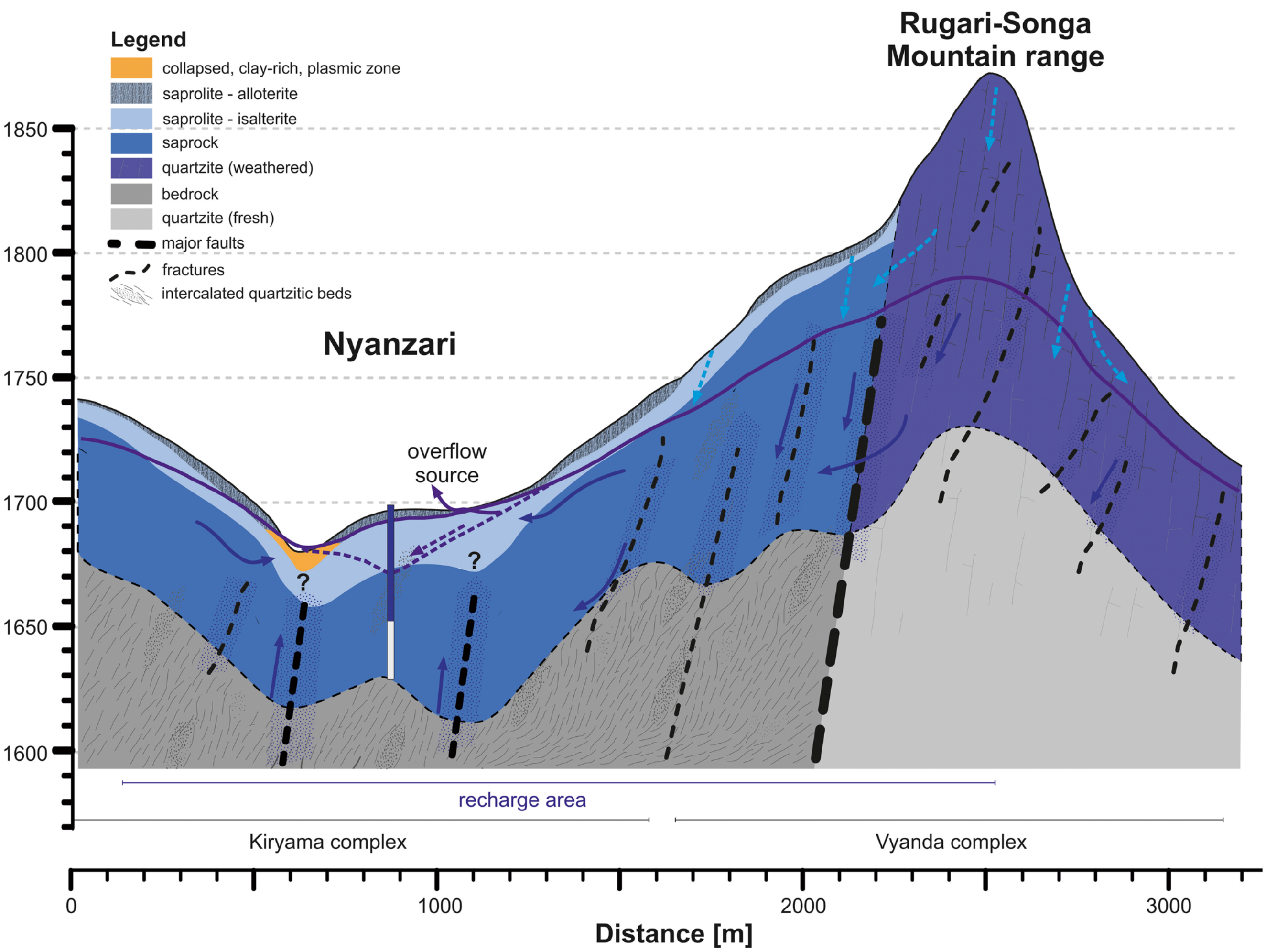

Fig. 7 Conceptual hydrogeological model of the aquifer system in the Nyanzari and Birohe catchments

amphibolite saprock. Fractures and fissures associated with tectonic faults, horizontal fractures, foliation or the original sedimentary bedding planes as well as occasional quartzite intercalations, are the main pathways for groundwater flow. Highly variable yields between wells confirm the spatial heterogeneity and discontinuity typical for fractured aquifers.

The concurrent drawdown in the wellfield and the drying out of springs since the wellfield installation are strong indicators for the interconnection of the upper and the lower aquifer. In some places, particularly at upper topographic positions where no separating clay layer exists, the two may form only one single aquifer and the exposed strongly fractured quartzite that allows for a good infiltration might rapidly replenish the low-lying schist saprock aquifer. Consequently, recharge areas of both aquifers are spatially overlapping. This hypothesis is supported by the relatively low mass recoveries in the tracer tests. There is a fast flow component towards the springs, but probably also a slower component to the deeper part of the aquifer represented by the "lost" solute mass.

Groundwater management in the Nyanzari wellfield is temporarily unsustainable since abstraction in some years is higher than recharge, even if, so far, periods of over-abstraction have been compensated by posterior rainy seasons. The sensitivity of groundwater heads measured in the wells is probably due to the low storage volume of the saprock aquifer. Further continuous monitoring of groundwater heads combined with interpretation of measurement results is probably the most simple and effective way to manage the Nyanzari wellfield on a sustainable level. Additionally, the lessons learned concerning the behaviour of the strongly weathered fractured aquifer system in Nyanzari will help to develop and manage comparable groundwater resources in Burundi.

Acknowledgements The authors express their gratitude to Désiré Miburo for his support during field work and Torsten Krekeler for the execution of the tracer tests.

Funding information We appreciate the financial support from the German Federal Ministry of Economic Cooperation and Development (BMZ), project No. BMZ PN 2009.2040.5.

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