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Hydrogeological and hydrogeochemical investigation of a Precambrian basement aquifer in Bugesera Region (Burundi)[1]

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Water, also known as blue gold, is vital to human life and to the survival of water-related biodiversity and natural ecosystems. Burundi, like many Sub-Saharan countries, is still far from achieving the Millennium Development Goal which is related to achieving secure access to safe drinking water and adequate sanitation. Recent figures indicate a global drinking water coverage of 83% and 55% in urban and rural areas, respectively. Several attempts have been made to resolve the issue of drinking water supply in those areas that fall outside of this coverage by tapping groundwater resources. However, supply problems persist, mainly due to poor knowledge of hydrogeological conditions and limited financial investment. The present study makes a significant contribution to former by extending scientific understanding of the hydrogeological framework and the hydrogeochemical environment of a basement aquifer in the Bugesera region, one of the most water-scarce areas in Burundi.

Bugesera region, which covers an important part of northeastern Burundi and southeastern Rwanda, is one of the numerous depressions known in the inter-lacustrine zone of East Africa. Despite a large complex of interconnected swamps and small lakes, there is a marked lack of natural springs in this region. For domestic needs, the local population, for whom a lack of drinking water is a form of "damnation", relies heavily on groundwater which is tapped through hand-dug wells. Where such hand-dug wells are not operating, the population resorts to the surface water of lakes and marshlands that is often polluted. The study area mainly consists of a depression surrounded by a more rugged landscape to the South and East. It covers an area of 1050 km^2 and stretches over 5 main watersheds: Kanyaru 9, Nyavyamo, Cohoha South, Cohoha North and Rweru.

1 This is the report of PhD research carried out at Ghent University, under the supervision of Kristine Walraevens.

The main source of groundwater recharge in the study area is precipitation. The long-term average groundwater recharge, estimated using the soil moisture budget technique for a period of 35 hydrologic years (1974/75-2008/2009), is 218 mm/year calculated by the Thornthwaite Monthly Water-Balance Model (TMWB model) (McCabe & Markstrom, 2007). The latter, which is on a monthly basis, using Hamon's PET (185 mm/year), was found to perform very well, as it fairly approximates average recharge values obtained on a daily basis with Penman-Monteith PET (243 mm/year) for the period 1999-2009 where a complete set of climatic parameters is available. This study clearly demonstrates that the use of small time steps in recharge calculations, which better corresponds to the reality in nature, leads to an increase in the level of recharge recorded. Four evapotranspiration calculation methods, namely Hamon (1963), Hargreaves, & Samani (1982), Thornthwaite & Mather (1957) and a modification of the original Thornthwaite method (Camargo *et al.* 1999 in Pereira & Pruitt, 2004) were evaluated in comparison to the reference Penman-Monteith equation (Allen *et al.*, 1998) for the period 1999-2009. The results of evapotranspiration calculations show that the Hargreaves method aberrantly overestimates evapotranspiration by 51% with a RMSE of 48 mm/month and should be avoided in the study area. This study draws attention to the risk of generating inaccurate estimates of recharge by using inappropriate PET methods. The calculation of groundwater balance in the study area shows that groundwater exploitation, which represents only 0.16% of the recharge, is still underdeveloped despite the scarcity of drinking water. The important baseflow explains the existence of the perennial complex of marshlands and lakes. A comparison of the volume of water available (3,806,000 m^3/year) to the water demand (3,334,000 m^3/year) shows an apparent surplus of 14% which is mainly due to the springs concentrated in the southern and eastern highlands and which flow round-the-clock.

The study area, which is entirely situated in the Western Domain of the Karagwe-Ankole Belt, Tack *et al.*, 2010 is predominantly underlain by Precambrian crystalline rocks consisting of metasedimentary rocks and magmatic intrusions. They form five geological formations: (1) the Undifferentiated Complex, which occurs in the centre of the depression, is mainly composed of granitic and pegmatitic intrusions; (2) the Formation of Murehe (or Mugendo) girdles the Undifferentiated Complex; it is made up of pelitic and quartzitic metasediments intruded by granites, pegmatites and quartzitic veins; (3) the Formation of Ngozi occupies the South-West of the study area where it forms an L-shaped set of metasediments and metavolcanites with sporadic dykes of pegmatites; (4) the Formation of Ruganza, which is mainly composed of quartzites, underlies the Formation of Ngozi in the South-West; (5) the Formation of Nyagisozi (or Nyabihanga) forms a NE-SW elongated feature made up of psammites to psammoschists (micaceous sandstones) with intercalation of conglomerates. Cenozoic formations comprise various types of soils and alluvium in valley bottoms and lower terraces. The hydrogeological structure was inferred from the re-interpretation of two existing batches of vertical electrical soundings (VES) which were constrained by available geological and lithological information. The interpretation of the VES shows sequences of 3 to 6 geoelectrical layers organised in different sequences which, overall, **show an upwards fining of weathering**

materials reflecting the upwards increasing degree of the weathering process. The hydrogeological model of the study area shows that the aquifer tapped by the hand-dug wells is hosted by the weathered overburden and consists of a mixture of clay, sand, gravel and rock fragments in variable proportions (with a resistivity between 28-150 Ωm), which is topped by a clay-rich layer (with a resistivity between 3-28 Ωm) acting as the (semi-) confining layer. The top soil is formed by a wide variety of materials which are characterised by a wide range of resistivities (7-600 Ωm). The weathered overburden is underlain by the fractured weathered basement (150-500 Ωm) which may form the prolongation of the aquifer. The weathered/fractured basement overlies the fresh basement which is characterised by high values of resistivity (>500 Ωm). The Undifferentiated Complex Formation, which is characterised by the highest thicknesses of the two components of the aquifer, i.e. weathered overburden and the weathered/fractured basement, has the highest groundwater potential compared to the two metasedimentary formations: Murehe and Nyagisozi in which VES were performed.

The hydraulic parameters were evaluated based on the analysis of 41 constant-rate pumping tests conducted during two field campaigns, from September to December in 2007 and from July to October in 2008. Pumping and recovery test data were analysed using different analytical methods, namely: Theis (1945), Hantush (1960), Cooper & Jacob (1946), Papadopoulos & Cooper (1967), double porosity method and the specific capacity method (Kruseman & de Ridder, 1994). The results of the pumping test data analysis show a widespread conformity of the aquifer response to the analytical Hantush method (27 pumping and recovery tests), thus confirming the proposed hydrological model which reveals leaky conditions. In the western part of the study area, most of the pumping tests conform to the double porosity model and this reflects the tectonic fracturing associated with the North-South trending fault along which the River Kanyaru flows. Overall, the transmissivity varies between 1 m^2/d and 377 m^2/d with an average of 33 m^2/d, whereas the hydraulic conductivity ranges between 0.1 m/d and 166 m/d with an average of 14.8 m/d. Specific capacity values calculated for the 41 pumping tests are in the range of 6.6-1134 m^2/d with an average of 113.6 m^2/d. The wide variability is typical of basement aquifers, as reported by several authors. The hydraulic parameters obtained using the Hantush, and Cooper & Jacob methods, both for the pumping and recovery phases are generally closely comparable. The spatial distribution of hydraulic parameters confirms the high groundwater potential of the Undifferentiated Complex Formation (T = 2.1-377 m^2/d, K = 0.3-166 m/d, S_c = 6.6-1134 m^2/d) in comparison to the metasedimentary formations of Nyagisozi (T = 5.7-60 m2/d, K = 1.6-41 m/d, S_c = 24-222 m^2/d) and Murehe (T = 1-30 m/d, K= 0.2-34 m/d, S_c = 7-104 m2/d).

The groundwater flow system was reconstructed based on 157 piezometric measurements and 126 topographic elevations of springs located in the southern highlands. An analysis of the groundwater flow pattern shows a local component towards the perennial and ephemeral streams and a regional component flow from the southern and eastern highlands towards the complex of marshlands and lakes which forms the main discharge area. Analysis of the inter-annual variation of groundwater levels shows a decreasing trend between 1991 and 2006, whereas between 2006 and 2008, a maximum is observed in 2007. This pattern of groundwater level fluctuation is in agreement with the amount of recharge calculated for each hydrologic year, the highest groundwater level corresponding to high recharge. Analysis of the seasonal variations of groundwater levels for 2008 shows a trend which closely follows that of the monthly rainfall. However, it was observed that peak of groundwater levels occur at different times in northeastern (May), central (April) and southwestern pasts (June). This important observation is related to the duration of travel of the recharge across the unsaturated zone and confirms the high hydraulic conductivity which characterises the Undifferentiated Complex Formation situated in the central part of the study area.

A simple steady state groundwater flow model of Bugesera region was successfully developed and calibrated using the finite difference code Visual Modflow 3.0 (Waterloo Hydrogeologic Inc., 2002). Considering the low level of groundwater exploitation in the study area, steady state conditions were assumed. Taking into account the defined hydrogeological model, 3 layers, comprising the top clay-rich layer, the weathered overburden and the weathered/fractured basement were considered. The model domain was discretised into a grid consisting of 225 rows and 278 columns with a spatial resolution of 180 m * 180 m for each grid cell. The calibration of the model through a trial and error process has enabled the achievement of a satisfactory match between the observed and calculated piezometric levels with a RMSE of 5.24%. The groundwater flow model shows that the average hydraulic conductivity for the weathered overburden is 0.30 m/d instead of 0.66 m/d, deduced from pumping tests which appear to have been overestimated. The simulated groundwater flow confirms both the local flow towards the myriad of V-shaped valleys where ephemeral and perennial streams flow, and the regional flow towards the marshlands and the lakes. The potentiometric map generated by the model is closely similar to the piezometric map constructed manually based on groundwater level measurements. The groundwater balance shows a small discrepancy (0.01%) between the inputs and outputs of the model, which confirms a good convergence of the model.

The hydrogeochemical study is based on the analytical results of 143 water samples collected from wells (66), springs (61) and lakes (16). **The spatial distribution of different hydrochemical parameters shows a general increasing trend from the highlands where water samples, mainly from springs, show low mineralisation (TDS = 26-152 mg/l) and low pH (field pH = 4.6-6.6) towards the depression of Bugesera where higher values of mineralisation (TDS = 44-3229 mg/l) and pH (field pH = 5.6-7.7) are observed.** The classification of water types based on the dominant in and representation of water samples on a Piper diagram (Waterloo Hydrogeologic Inc., 2002) highlights the existence of clusters which clearly show an evolutionary sequence from the lowly mineralised springs, mainly of NaCl types (19%), towards a suite of water types along the flowpath which are dominated by $NaHCO_3$ (49 %) and $CaHCO_3$ (13%). The anthropogenic pollution is underlined by the occurrence of $NaNO_3$, $CaNO_3$, KNO_3 and $NaSO_4$ types even in spring water. The main hydrogeochemical factor controlling groundwater evolution in Bugesera region is the weathering of aluminosilicates. The evaporative concentration, the leaching of evaporitic salts and the anthropogenic pollution play a secondary role. This important finding is buttressed by the predominance of $NaHCO_3$ and $CaHCO_3$ water types (62%), the stability diagrams which show that all water samples are in thermodynamic equilibrium with the weathering products of aluminosilicates (gibbsite and kaolinite) and the cross-plots which confirm an increasing trend of the alkaline and alkaline earth cations ($Na^+ + K^+ + Ca^{2+} + Mg^{2+}$) released from the weathering of aluminosilicates along the flowpath. The poor correlation between the concentrations of SiO_2 and Na^+, Ca^{2+}, Mg^{2+}, K^+, HCO_3^- and TDS confirms the incongruent character of the weathering of aluminosilicates which causes part of the silica released from the weathering of silicates to be retained in the formation of clay minerals.

This study clearly shows that Bugesera region has genuine groundwater potential which could be circumscribed and tapped in order to provide enough drinking water to the inhabitants of the area. Thus, this study recommends further investigations and measures, including, geophysical investigations coupled to reconnaissance drillings, the installation of a network of piezometers to monitor the groundwater level variation, measurement of the discharge rate and water level fluctuation in the complex of marshlands and lakes, monitoring of groundwater quality and further pumping tests in order to refine the distribution of hydraulic parameters in the study area.

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