Numerical Groundwater Model of the Nyanzare well field at the town of Gitega, Burundi

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<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>a.s.l.</td>
<td>Above sea level</td>
</tr>
<tr>
<td>AWC</td>
<td>Available Water Capacity</td>
</tr>
<tr>
<td>BC</td>
<td>Boundary condition</td>
</tr>
<tr>
<td>BGR</td>
<td>Bundesanstalt für Geowissenschaften und Rohstoffe</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>ETP</td>
<td>Potential Evapotranspiration</td>
</tr>
<tr>
<td>FE</td>
<td>Finite Element</td>
</tr>
<tr>
<td>FK</td>
<td>Field Capacity</td>
</tr>
<tr>
<td>GPES</td>
<td>Gestion et Protection des Ressources en Eau Souterraine au Burundi</td>
</tr>
<tr>
<td>IGEBU</td>
<td>Institut Géographique du Burundi</td>
</tr>
<tr>
<td>PCG</td>
<td>Preconditioned Conjugate Gradient</td>
</tr>
<tr>
<td>PWP</td>
<td>Permanent Wilting Point</td>
</tr>
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</table>
0 Summary

The majority of the water supply for Gitega city, located in the center of Burundi, is derived from the Nyanzare well field which produces around 5000 m³/day. Rapid decline of the water level has been measured in the last years, meaning that the well field is over pumped. A good management of the well field is needed, if supply is to be ensured.

To provide for a groundwater management tool, a 3D numerical groundwater flow model of the Nyanzare catchment was developed. The model was set up using the finite element software SPRING. It contains the relevant lithological units of the highly inhomogeneous valley as well as lineaments that act as preferential flow paths leading to great efficiency in some of the pumping wells.

A transient recharge calculation was carried out taking into account recent spatial and climate data of the area. Recharge rates average around 300 mm/year for the assumptions made. The model was successfully calibrated using water level data from four observation wells collected for the period 01.2013 till 01.2016. The resulting flow field in the valley was applied to determine average flow velocities and to establish protection zones around each well. Based on the 50-days travel time, protection zones reach a maximum of 125 m for well F7.15 alongside the preferential flow path of the valley. The other wells were calculated to have 50 days travel time distances of 50 m or less.

A strategy for sustainable use requires an assessment of available groundwater resources combined with changes in socio-economic and climatic conditions. Several scenarios were tested to simulate the effects of (1) increased water demand after the installation of a new supply well and (2) the variation of pumping intervals. Furthermore, a decline in recharge caused by (3) stresses from climate change and (4) the expansion of build-up areas spreading further into the catchment area was simulated. Results show that scenario (3) is the most hazardous, since less precipitation as a result of climate change leads to a recharge rate significantly reduced. Therefore groundwater withdrawal should be especially controlled when a series of low precipitation years occurs, due to the fact that the overall capacity of the aquifer appears to be low and water levels react rapidly to overuse.
1 Introduction

1.1 Context

The cooperation project “Management and Protection of Groundwater Resources in Burundi” (GPES) of the BGR and the Institut Géographique du Burundi (IGEBU) focuses on groundwater quantification, quality and its vulnerability to pollution.

The GPES project has different main objectives. One of them is the assistance for setting up the protection zones of the Gitega city water supply catchments. The Gitega study area is located in the centre of Burundi to the south-east of the city of Gitega. The majority (about 2/3) of the city’s water demand is currently covered by the Nyanzare well field south of Gitega city. Due to population growth, the water demand for the second largest city of Burundi is currently increasing. At the same time, progressive urbanization, clay mining, agriculture, coffee industry, and fuel depots represent a growing risk for drinking water quality.

For the definition of the protection zones, some research studies were completed to understand the hydrogeological context. To be able to manage the main well field for water supply, it was decided to introduce a numerical groundwater model as a management tool.

1.2 Objectives

A numerical groundwater model is built to characterize the hydrogeological situation of Gitega providing a better understanding of the system and its behaviour. Because of the aquifer’s heterogeneity, the irregular shape of its boundaries, and the complicated interaction between them, a numerical model is needed to reproduce and visualize the flow processes.

The main objectives of this study are to provide technical information for the determination of protection zones and to support a sustainable management of groundwater abstraction for the Gitega well field.

Specific objectives are:

- Estimation of groundwater resources for a sustainable development
- Estimation of groundwater flow velocities to evaluate travel times, which is essential for the determination of groundwater protection zones
- Provide a well field management tool. The numerical model can project the response of the aquifer (water levels) to the implementation of any management alternative.
The numerical model is also a tool for predicting the response to stress including reduced recharge and increased withdrawal. Various scenario calculations need to be performed taking into account future changes in climate, land use and demand.
2 Conceptual model

2.1 Hydrogeological overview of the Gitega region

The study area is located in the Central Plateau of Burundi. The region is characterized by rounded hills of ancient formations composed of heterogeneous metamorphic rocks such as schist, (meta)quartzite, phyllite and locally granite. Between them, narrow valleys are filled with layers of decomposed schist and clay. Within the Nyanzare catchment, the valleys and the Nyabututsi-Rango Hills in the west are characterized by layers of weathered schist, whereas strongly fractured and weathered quartzite saprolite/saprock is exposed all along the Birohe-Rugari-Songa Mountain Ridge in the east. Saprolite and saprock describe different stages of chemically weathered rock. Saprock, as the first stage, consists of partially weathered and even unweathered minerals, the parent rocks mineralogical and structural characteristics are still assured. Saprolites are more altered; weatherable minerals have been pseudomorphed by clays or oxides/oxihydroxides (Taylor & Eggleton 2001).

The difference in altitude between the main valley and the quartzite mountain ridge is up to 300 m. The generalized conceptual model of the weathering zones, lithostratigraphic sequences, faults and presumed groundwater flow is illustrated in Fig.1.

Lineaments of different categories have been identified by remote sensing methods (Hahne 2014). They strike in NW-SE-direction (130°-170° and 110°-120°) as well as in NE-SW direction (050°-060°) and for the most parts can be considered open to groundwater flow (Hahne 2014).

Over the past decades several boreholes were drilled and pumping wells were installed in the Nyanzare valley for the water supply of Gitega City. These wells are F7 (1986), F2, F4 and F8 (1988), F7.3, F7.5, F7.8, F7.12, F7.15 and F7.17 (2008). F8 was never installed and F7.17 is currently not operated. By the turn of the year 2012/2013, the GPES project installed three observation wells in the valley to monitor the well field that taps a productive aquifer supplying pumping rates of up to 5000 m³/day.

Pumping tests performed in 2008 revealed quite different transmissivities for the well field (Table 1). The highest transmissivity was measured for F7.15 and F7.17. These wells are situated close to the main valley lineament.
Table 1: Results from analytical evaluation (Theis) of pumping test in the Nyanzare well field in 2008 (Tiberghien et al. 2014)

<table>
<thead>
<tr>
<th>Measured Well</th>
<th>T (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F7</td>
<td>4.7E-04</td>
</tr>
<tr>
<td>F7.3</td>
<td>6.0E-03</td>
</tr>
<tr>
<td>F7.5</td>
<td>8.3E-03</td>
</tr>
<tr>
<td>F7.8</td>
<td>3.0E-04</td>
</tr>
<tr>
<td>F7.12</td>
<td>2.5E-03</td>
</tr>
<tr>
<td>F7.15</td>
<td>4.0E-02</td>
</tr>
<tr>
<td>F7.17</td>
<td>2.0E-02</td>
</tr>
<tr>
<td>F2</td>
<td>8.6E-05</td>
</tr>
<tr>
<td>F4</td>
<td>2.0E-04</td>
</tr>
</tbody>
</table>

The aquifer is assumed to be dominated by preferential flow paths along open fractures in the alternating schist and amphibolites bedrock. Therefore not a homogenous porous matrix but a more differentiated situation can be anticipated.

Tracer tests in the Birohe catchment - to the north of the Nyanzare catchment - showed rather fast flow rates that averaged at 1-2 m/h (Vassolo & Krekeler 2013). The hydraulic conductivity of the fractured quartzite aquifer derived from these tests is between $K_{test1} = 1.5E-4$ m/s and $K_{test2} = 2.5E-4$ m/s (Vassolo & Krekeler 2013). The results indicate a heterogeneous aquifer containing interconnected highly permeable fractures.

A considerable difference in water levels can be observed between the present state and the time of first well drilling and installation in the 1980's, where water levels used to be at about 5 m below the ground surface. Currently, water levels in the observation wells are found at depths between >20 m (Pz1, Pz3) and >40 m (Pz2). However, at permanent operation no steady state condition has been reached.

Shallow groundwater discharges at many small overflow springs along the edges of the valley, which is probably supplied by interflow coming from the hills surrounding the Nyanzare valley (Fig. 1). Flow measurements at the springs OCIBU, Nyanzare and Kazibaziba show accumulated discharge rates of 21-33 m³/h (Tiberghien 2015). Discharge rates of additional locally used springs are not known.

A more detailed contemplation of the conceptual model can be found in Heckmann (2016).
Figure 1: Conceptual model of the Nyanzare valley (Heckmann 2016)
2.2 Simplification of the geological model

The geological situation of the study area is complex and yet not fully understood. For a modelling approach, these conditions must be considerably simplified. Four major lithological units were identified (Tab. 2) and incorporated into the model as horizontal layers with different hydraulic parameters (hydraulic conductivity, effective porosity).

The top layer of the valley is a ductile, clay-rich zone, which is a product of decomposed schist. The largest thickness of the layer is found more or less along the axis of the valley, thinning out towards the hillsides. Due to a high clay content, the permeability of this zone is rather low. It is followed by a weathered schist (saprolite) layer with lower clay content, which is part of the aquifer system in the valley. It is thickest along the valley and slightly thins out towards the hillsides and quartzite mountains.

The main aquifer of the Nyanzare catchment is composed of fractured schist (saprock) containing amphibolites. The layer thickness is lower towards the centre of the valley, although permeability is significantly higher at the main valley lineament. The groundwater flow is controlled by open fractures and fissures, whereas the rock matrix is supposed to have a moderate hydraulic conductivity and low storativity. This can be taken into account in the model by a high-permeability zone alongside the valley lineament that allows for preferential flow. Only the two main out of four categories of lineaments identified by Hahne (2014) are considered in the model. They represent the 1st-order and 2nd-order valleys and are recreated by different zones of higher permeability.

The top layer of the Birohe-Rugari-Songa Mountains in the western part of the catchment consists of weathered and fractured quartzite saprock transferring water towards the valley.

Both, the underlying unaltered schist and the quartzite bedrock can be ignored in the hydrogeological model, since no major groundwater exchange is expected from these layers.

Table 2: 3D model layers

<table>
<thead>
<tr>
<th>Model Layer</th>
<th>Lithology</th>
<th>Properties</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clay zone</td>
<td>clay-rich plasmic zone, low hydraulic conductivity</td>
<td>0 - 26 m</td>
</tr>
<tr>
<td>2</td>
<td>Schist saprolite</td>
<td>weathered schist, moderate hydraulic conductivity</td>
<td>25 - 35 m</td>
</tr>
<tr>
<td>3</td>
<td>Fractured schist</td>
<td>strongly fractured rock, locally high hydraulic conductivity</td>
<td>40 - 75 m</td>
</tr>
<tr>
<td>4</td>
<td>Fractured quartzite saprock</td>
<td>weathered quartzite ridge, low to moderate hydraulic conductivity</td>
<td>40 m</td>
</tr>
</tbody>
</table>
Each layer is assigned preliminary values for hydraulic properties and thickness, which are revised during a calibration process (Chapter 3.5). The effective porosity and storativity of the schist and its decomposed clay-rich products are considered to be rather low. Groundwater flow occurs mainly within faults and joints.
3 Numerical model

Numerical methods represent the flow domain by a limited number of discrete nodes and cells (forming a grid with several overlying layers). A set of equations are then derived to relate the nodal values of the dependent variable such that they satisfy the governing equations, either approximately or exactly.

3.1 Software

The program SPRING 4.2 by Delta h Ltd. was chosen to carry out 3D groundwater flow simulations (single phase) in the Nyanzare catchment. SPRING is based on the numerical finite element method (Delta h 2015). Finite elements offer flexibility in grid design, elements can be shaped to boundaries and structures, layers can thin out and expire over the model domain. Another advantage of the FE methods is that they are able to simulate point sources/sinks at nodes.

The governing equations for partially saturated conditions (attenuation factor 0.5, 5 iterations for the free-surface boundary) were solved by means of an iterative PCG (preconditioned conjugate gradient) solver. For accuracies, the maximum value of the residual, which is the error of the approximation, was set to 1.0E-10. The iteration difference, which is the accepted error between two iteration steps, is 1.0E-8 m. For storage coefficient at confined conditions, fluid compressibility was set at a constant value of 4.4E-10 (ms²)/kg and the matrix compressibility at 2.4E-8 (ms²)/kg, which lies in the range of values for jointed or weathered solid rock.

3.2 Model assumptions

For a groundwater model, a series of assumptions and simplifications have to be made. The basic needs of a model are:

3.2.1 Geometry and Finite Element Grid

In the first place, the geometry of our model is defined by the topographical catchment. This catchment was expanded towards the east by about 150 m in order to include areas where inclined faults in the quartzite Birohe-Rugari-Songa Mountains might contribute to the groundwater recharge of the catchment (see Fig. 1). A Digital Elevation Model (DEM) of the study area with a resolution of 10 m was provided by IGEBU. It defines the ground surface that is represented by the upper grid layer of the model. Thickness and spatial distribution of the underlying layer boundaries were interpreted from field investigations and well profiles (Tiberghien et al. 2014).
The model grid has a maximum surface grid spacing of 50 m x 50 m (x-y-direction). Grid spacing in z-direction depends on the layer thickness. Each lithological layer (Tab. 2) was sub-divided into two equal grid element layers. Thereby, the withdrawal in the wells can be placed at a node in the middle of the aquifer in order to have a centred withdrawal from the aquifer layer. The domain surrounding pumping and observation wells, lineaments or other basic structures was refined several times, reducing the grid spacing to a minimum of 1 m in order to minimize the approximation error and to achieve a more accurate estimation of hydraulic head or drawdown at well scale.

A grid dependency test was conducted to eliminate effects of numerical dispersion on the results. It revealed no considerable effects on the calculated flow field.

3.2.2 Material properties

The initial hydraulic properties of the aquifer and all other model layers take into account standard values for the given lithology (e.g. Spitz & Moreno 1996) on the one hand and pumping tests that were conducted in 2008 and evaluated by analytical methods (Tiberghien et al. 2014) on the other hand.

Due to rock weathering in the study area, the hydraulic properties of the schist aquifer are differentiated throughout the model domain. Generally, it can be assumed that a deeper weathering zone developed in the valleys and lineament zones compared to well-drained material on the steep slopes, plains and hill/ridge tops. Hydraulic conductivity is therefore assumed to be higher in lower topographic positions of the catchment.

Figure 2: 3D view of the model: from above (left), and from the side showing subjacent layers (right)
3.2.3 Initial conditions

The definition of initial conditions means specifying the head distribution throughout the system (model domain) at the beginning of the calculation, which is needed for both initialization of the steady-state simulation and recharge estimation.

The initial distribution for groundwater levels of the main aquifer was taken from a groundwater surface regionalization by Heckmann 2016. Based on groundwater level measurements, the depth to water table for the fractured aquifer is estimated at 15 m below ground at the topographically lowest point of the valley.

The regionalized heads are used as initial condition for the pre-pumping steady-state simulation. The heads obtained from this simulation are then used as initial condition for a pumping steady-state simulation (with a constant recharge and pumping rate), whose results provide the heads to be used as initial condition for the transient simulation (with varying recharge and pumping rates).

The extrapolation of the groundwater level to the whole model area followed the regionalised Chanel Network Base Level that was later elevated in the hilly areas to 75 % of the difference between the interpolated level and topographical elevation (Heckmann 2016). For a conservative approach in the recharge calculation, the regionalized water level distribution was lifted by 15 m in the whole catchment area, reducing thus the depth to water table to a minimum close to 0 m in the valley. In this way, losses due to capillary rise in areas with shallow groundwater are allowed for.

3.3 Recharge calculation

For groundwater recharge calculation the soil moisture balance method was applied, which is implemented in the SPRING 4 software (Delta h 2015). The calculation of transient recharge rates is based on the theoretical concept described in DVWK 238/1996 "Determination of evaporation from land and water areas" that applies in the first place to natural undeveloped areas. Since a groundwater model usually also includes built-up areas, recharge in these areas are estimated by the Schroeder and Wyrwich (1990) method. The code is designed to calculate the spatial distribution of groundwater recharge over time using a gridded data structure. Required input data involves spatial and time-dependent components.
3.3.1 Spatial distributed input data

All elements of the upper grid layer were classified according to specific soil type, land use and degree of sealing. Additionally, the surface height from the DEM and the initial heads were given to each node of the upper model layer.

According to the soil type, which was distinguishing between sand soils and loam/clay soils, the following parameters were defined:

- **Permanent wilting point (PWP):** The permanent wilting point describes the water content of the soil below which plants cannot grow further and wilt. In the model, the PWP values for sandy and clay soils remained at default, which is 3 % and 4 %, respectively.

- **Field capacity (FK):** The field capacity is the maximum water content that a soil can hold under natural conditions. The part of the field capacity that can be absorbed by plants through the roots is called the available water capacity (AWC). The usable field capacity is thus obtained from the difference between field capacity and the permanent wilting point (AWC = FK - PWP). For sandy soils, the mean field capacity was set to a standard value of 10 mm/dm. For clay soils, mean field capacity was assumed at 30 % of the volume, which is the upper limit for clay soils suggested by Bakundukize et al. (2011) after Thornthwaite & Mather (1957).

Land use was classified into farm-/grassland, deciduous forest, mixed forest, coniferous forest and build-up areas (Fig. 3). Depending on the land use, which was interpreted from the digitalized topographic map of Gitega, the following parameters were defined:

- **Effective root depth:** The effective root depth is about 50 – 60 % of the maximum root depth. It features the soil volume in which the soil water balance is affected by intensive plant water consumption. Effective root depth on farm/grassland was set to 1 m, on all types of forests to 3 m.

- **The degree of sealing** determines the amount of precipitation that turns into surface runoff. Due to the fact that the build-up areas in the study area are dominated by small domestic buildings having no drain system (sewage water system) and very little paved zones, the degree of sealing was assumed to be 25 % on living areas, 80 % on industrial sites (Fig. 3).

A digital elevation model (DEM) of the area is used to calculate the slope and relief energy in each cell in order to estimate the direct runoff by which infiltration is reduced.

The regionalized hydraulic heads calculated by Heckmann (2016) define losses by capillary rise and evaporation. In the lowest part of the valley, water levels are assumed at ground
level while for the rest of the catchment, the distance to water table increases with topographical elevation. These levels remain static for the recharge calculation. Even though the water level for the deep groundwater is currently measured at 15 m or more below ground, near-surface groundwater can be observed at numerous springs in the catchment. For conservative assumptions in our standard case, near-surface groundwater was assumed to be affected by capillary rise and evaporation that reduce the infiltration or recharge towards the main aquifer.

A sensitivity analysis on the input parameters for recharge calculation was conducted in Chapter 3.6.2.
3.3.2 Time-dependent input data

For climate data, daily values of precipitation and temperature (January 2013 – January 2016) were entered together with potential evapotranspiration (ETP) values, which can be
derived from readily available meteorological conditions (Eq. 1) whenever direct measurements are not available. ETP, as required by the model, defines the amount of evaporation, if an unlimited water source is available. Due to the limited values existing in the meteorological data base, potential evaporation was calculated using the empirical Thornthwaite equation (1948) by means of an online tool by SDSU (2015):

\[
ETP = 16 \left( \frac{L}{12} \right) \left( \frac{n}{30} \right) \left( \frac{10T}{I} \right)^\alpha
\]

Eq. 1

\[T\] – monthly average temperature (°C)
\[L\] – average day length (hours) depending on latitude
\[n\] – number of days in the month

\[I = \sum_{i=1}^{12} \left( \frac{T_{n(i)}}{5} \right)^{1.514}\]

\[\alpha = (6.75 \cdot 10^{-7})I^3 - (7.71 \cdot 10^{-2})I^2 + (1.792 \cdot 10^{-2})I + 0.49239\]

Thornthwaite provides monthly potential evaporation (mm/month) that was later on converted into daily values for the climate input file. The calculated mean ETP during the observation period accounts to 909 mm/a.

Measured and calculated climate data for the observation period is illustrated in Appendix 1.

3.3.3 Results

According to the modeling results, the mean groundwater recharge for the Nyanzare catchment during the observation period (2013-2015) amounts to 1 864 000 m³ per year. For a model area of 6.12 km², the average recharge rate is 305 mm/a, which is 25.6 % of the measured total annual precipitation. The time distribution of the calculated average recharge is shown in Fig. 4 and the spatial distribution in Fig. 5. The resulting recharge data file was implemented into the model as a transient specified flux boundary condition (Neumann) assigned to each grid element of the upper layer.

Groundwater recharge for the Nyanzare catchment had been calculated before based on climate data of the last 30 years by Tiberghien (2015). For the topographical catchment area of 5.6 km², a total recharge rate of 1 466 500 m³ per year had been estimated leading to 264 mm/a or 23 % of precipitation (Tiberghien 2015), which is a very similar order of magnitude to the calculated as described above.
Figure 4: Variation of recharge in time. Values are accumulated and averaged over the model area.

Figure 5: Resulting recharge distribution for the Nyanzare catchment. The recharge values for each cell are averaged over the climate time series of 2013-2015.
3.4 Boundary conditions

3.4.1 Wells

For steady-state calculation a total pumping rate (nodal specified flux, Neumann boundary condition) of 4347 m³/day was assigned to the active wells. This value represents the pumping rate in April 2004, when all wells (except for F7.17) were operating at a relatively high level that can still realistically be maintained. Due to periodical stops of certain pumps, this representative extraction rate exceeds the average real pumping rate in the examined period (Fig. 6) by about 16 %.

In the transient simulation, nodal extraction rates were varied at 10-days intervals accordingly to the actual performance data of the wells.

![Figure 6: Pumping rates of wells in the Nyanzare valley](image)

3.4.2 Discharge

Since the subsurface discharge of the catchment through the valley is not known, head-dependent flux (Cauchy boundary condition) was established at the lowest part of the model boundary. These "drain" nodes were defined to enable exfiltration from the aquifer whenever a certain water level or pressure head is reached. With a Cauchy BC, the calculated flux across this boundary responds to changes in hydraulic head within the aquifer adjacent to the boundary (Franke et al. 1987). The head of the boundary, extending 120 m along the model border, is defined at 15 m below ground or z = 1615 m a.s.l. The discharge rate depends on the difference in hydraulic heads between this defined head value and the
changing hydraulic potential of the aquifer. Thus, flux is a function of head in the aquifer - as head rises, flux across the boundary increases, and as head falls, flux decreases. A constrain was added to ensure that no flow goes into the model area when hydraulic heads fall below the defined boundary condition. The leakage coefficient, specifying the connectivity between the aquifer and the BC, was assumed and adjusted during calibration.

Overflow springs could not be implemented into the model since their occurrence is a very local phenomenon and could not be represented by the regional model.

3.5 Calibration

Aim of the calibration is to arrive at a model that can adequately reproduce a time series of field-measured hydraulic heads with parameters that best represent all field-measured conditions.

For model calibration, both steady-state and transient conditions were examined. An initial steady-state model was calibrated to meet the observed head values from early well installations in the 1980’s in order to simulate the conditions before well extraction (pre pumping).

In the transient calibration, time series of recharge and pumping rates were incorporated and measured piezometric heads (from observation wells) were used for calibration. Transient aquifer response to the pumping allows calibration to both hydraulic conductivity and storage parameters.

In the calibration process, all input values may be changed within realistic ranges in order to meet the desired measurement values of the observation wells as precisely as possible. Here, the trial and error method was used, since not only hydraulic parameters but also the conceptual model (layer structure and boundary conditions) were edited and adjusted during the calibration process.

3.5.1 Results

Initial heads were established from a steady-state calculation prior to water extraction from wells. The measured depth to water table for the wells build first in 1986 (F7 & F8) and 1988 (F2 & F4) were used for calibration. The modelled hydraulic head distribution before pumping is shown in Fig. 7. The modelled values approximately recreate the measured water levels found during well construction, which are listed in Tab.3. Though the aquifer was already utilized, the measured water levels at the drilling operations in 2008, when the majority of the
Nyanzare well field was installed, are within a reasonable offset to the simulated static hydraulic heads. The steady state model has a coefficient of determination $R^2$ of 0.92.

The calculated head distributions in the domain is influenced by the layered and differentiated structure of the model, the spatial distribution of recharge and the head-dependent flux BC that regulates discharge. The main aquifer is confined throughout the valley. Because of steady-state conditions and the mass balance principle, the flux discharged through the leakage boundary at the eastern side of the valley equals the recharge rate.

Table 3: Borehole data including the measured water depth at installation and modelled water depth before pumping ($R^2 = 0.92$)

<table>
<thead>
<tr>
<th>Well name</th>
<th>Year of installation</th>
<th>DEM Elevation (m a.s.l.)</th>
<th>Well Depth (m)</th>
<th>Water depth at installation (m)</th>
<th>Modelled water depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F7</td>
<td>1986</td>
<td>1639</td>
<td>50.0</td>
<td>4.2</td>
<td>1.5</td>
</tr>
<tr>
<td>F8</td>
<td>1986</td>
<td>1639</td>
<td>48.0</td>
<td>3.5</td>
<td>2.3</td>
</tr>
<tr>
<td>F2</td>
<td>1988</td>
<td>1703</td>
<td>108.0</td>
<td>22.2</td>
<td>24.7</td>
</tr>
<tr>
<td>F4</td>
<td>1988</td>
<td>1700</td>
<td>82.5</td>
<td>21.5</td>
<td>21.9</td>
</tr>
<tr>
<td>F7.3</td>
<td>2008</td>
<td>1641</td>
<td>89.5</td>
<td>9.5</td>
<td>3.1</td>
</tr>
<tr>
<td>F7.5</td>
<td>2008</td>
<td>1652</td>
<td>85.7</td>
<td>11.0</td>
<td>13.7</td>
</tr>
<tr>
<td>F7.8</td>
<td>2008</td>
<td>1648</td>
<td>94.7</td>
<td>10.0</td>
<td>10.4</td>
</tr>
<tr>
<td>F7.12</td>
<td>2008</td>
<td>1644</td>
<td>52.3</td>
<td>3.8</td>
<td>5.9</td>
</tr>
<tr>
<td>F7.15</td>
<td>2008</td>
<td>1659</td>
<td>95.6</td>
<td>20.3</td>
<td>20.8</td>
</tr>
<tr>
<td>F7.17</td>
<td>2008</td>
<td>1656</td>
<td>108.9</td>
<td>16.5</td>
<td>17.6</td>
</tr>
<tr>
<td>Itankoma</td>
<td>2008</td>
<td>1700</td>
<td>172.0</td>
<td>22.0</td>
<td>20.6</td>
</tr>
</tbody>
</table>

Subsequently, steady-state calibration was performed for which mean extraction rates were applied as specified flux (Neumann) boundary conditions. Figure 8 shows the steady-state hydraulic head distribution at a total pumping rate of 4347 m$^3$/d. From the steady-state modelling results, the depletion due to nowadays water extraction is about 20 m in the Nyanzare valley. This is in the same range as the currently measured water levels in the observations wells.
Figure 7: Hydraulic head distribution of the main aquifer (isolines) and depth to water table in the Nyanzare valley without water extraction through pumping wells. For calibration, measured water levels of the earliest wells (black symbols) installed in the 1980’s were used
There are indications for the existence of a NW oriented fault located close to the wells F2, F4, and Itankoma. The fault is outlined on the geological map ‘Carte Géologique de Burundi, Gitega’ (Claessens and Theunissen 1988) although it could not directly be verified in the field (Heckmann 2016) and was not documented in the remote sensing lineament mapping by Hahne (2014). A strong indication for a major fault is a distinct morphological break in slope towards the foothills of the Songa Mountain Range (Heckmann 2016). The documented location of the fault approximately coincides with the trace of the RIG 3 road. Steep hydraulic head gradients between the three wells in the East (F2, F4, and Itankoma) and the remaining group of wells in the western and middle part of the Nyanzare valley indicate a low permeability zone (barrier) in-between those areas. The mapped NW-SE striking fault could be affecting the efficiency of lateral flow, due to clay smearing from weathered schist.
material. Still, a sufficient hydraulic conductivity must be present to enable the productivity of the wells F2 and F4, which are operated since 1988. This might be explained by the fact that faults often function as combined conduit-barriers to enhance fluid flow along the fault and impede fluid flow across the fault (Caine et al. 1996, Faulkner et al. 2010, Bense et al. 2013). These characteristics can be observed when the fault core is filled with clay material reducing permeability whereas the surrounding damage zone has secondary fractures enhancing permeability. This approach was implemented in the model by placing a narrow high conductivity zone along the course of the fault zone accompanied by a barrier towards the main valley (Fig. 9), where higher clay contents might have effectively reduced the lateral permeability of the fault zone.

![Hydraulic conductivity zones of the main aquifer](image)

Figure 9: Hydraulic conductivity zones of the main aquifer
In the model, the fault had to be located tens of meters towards the east of the location indicated in the geological map to be able to reproduce the heads measured in F2, F4, and Itankoma.

The calibration of the transient model involved the variation of boundary conditions, hydraulic parameters, and the spatial distribution and thickness of lithological layers and hydraulic features. The computed hydrographs that produced the best possible fit to the available observation data from the piezometers (GI-Pz01, GI-Pz02, GI-Pz03, and Itankoma) are illustrated in Fig. 10. The hydraulic parameters obtained from the modelling process are summarized in Tab. 4 and illustrated in Fig. 9.

Table 4: Hydraulic parameters resulting from calibration

<table>
<thead>
<tr>
<th>Zone/Lithology</th>
<th>Differentiation</th>
<th>Hydraulic conductivity K (m/s)</th>
<th>Anisotropy $K_H/K_V$</th>
<th>Effective Porosity (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay zone</td>
<td></td>
<td>5.0E-07</td>
<td>10</td>
<td>0.03</td>
</tr>
<tr>
<td>Schist saprolite Valley / low slope</td>
<td></td>
<td>1.0E-05</td>
<td>10</td>
<td>0.04</td>
</tr>
<tr>
<td>High slope area</td>
<td></td>
<td>1.0E-06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fractured schist saprock 1st order valley lineament</td>
<td></td>
<td>3.5E-03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd order valley lineament</td>
<td></td>
<td>5.0E-04</td>
<td>1</td>
<td>0.04</td>
</tr>
<tr>
<td>Valley / low slope</td>
<td></td>
<td>9.0E-05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High slope</td>
<td></td>
<td>1.0E-06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault zone (conduit vs. barrier)</td>
<td></td>
<td>5.0E-04; 1.0E-07</td>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td>Fractured quartzite saprock</td>
<td></td>
<td>1.0E-06</td>
<td>10</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Figure 10: Calibration of the water levels in observation wells GIPz01, GIPz02, GIPz03, and Itankoma. Bold colours mark the measured values (data loggers), light colours mark computed values (model output).
The head dependent flux defined by a Cauchy BC, allowing outflow out of the model domain, can be seen in Fig. 11. Precipitation periods are followed by increased outflow rates as a result of rising water levels in the aquifer. The significant increase of outflow in mid-2015 is partly reinforced by a dropping pumping rate due to a stop of well F7.12 during November 2014 and February 2015 (Fig. 2).

Figure 11: Model outflow at the Cauchy boundary condition and precipitation rate during the observation period

3.6 Limitations of the numerical model

For a numerical groundwater model, simplifications are needed in order to deliver reasonable processing and simulation times. Furthermore, assumptions have to be made to enable and manage limited data. This leads to uncertainties and deficits of the model.

3.6.1 Boundary condition at catchment outflow

In order to simulate catchment outflow in an optimal way, the head-dependent boundary would have to be transient and derived from field measurements. It is clear that high precipitation and recharge rates not only affect the water levels in the Nyanzare catchment, but also the adjacent catchments and transition zones. Therefore, the head boundary allowing flux out of the catchment would have to be constantly adjusted. A considerable increase in discharge rate during the rainy seasons can be seen in Fig. 11.

Especially the simulation of the rising groundwater levels during summer 2015 would need a transient hydraulic head condition for groundwater outflow from the model that varies with the actual water levels – particularly for observation wells GI-Pz1 and GI-Pz3 that are closer to the Cauchy boundary. Since there are no measured time-series for the water levels at the
points of catchment outflow and the discharge rate itself is not known, it is difficult to calibrate the hydraulic conductivity and head level of the drain. The steady-state assumption therefore overestimates outflow during and after rainy seasons, when water levels naturally rise.

3.6.2 Sensitivity analysis on recharge calculation

Major uncertainties in the recharge calculation are:

- The Thornthwaite method for ETP calculation uses only very limited climatic inputs (latitude, temperature) and therefore applications of this method to short-time periods can lead to significant errors (Grace & Quick 1988).

- For conservative assumption, the initial head distribution was assigned at surface level in the lowest part of the valley. Hence, there is likely an overestimation of losses due to capillary rise (and evaporation). Furthermore, this input data is static and does not adjust to varying head values.

- The regionalization and categorization of spatial data such as land use and soil type implicates a strong simplification or potential misinterpretation.

- Properties including the field capacity of soils and the root depth of different vegetation types can have a certain range of variation. For conservative assumptions, values were chosen in such a way that they are detrimental to a high infiltration and recharge rate.

A sensitivity analysis was computed in order to evaluate the effects of the different parameters involved in the recharge calculation. Sensitivity is measured by monitoring changes in the average recharge rate and the resulting head levels in steady state simulation.

At first, the calculated potential evapotranspiration (ETP) - averaging at 908 mm/a in the observation period was altered by up to ±30 % to account for uncertainties implemented in the Thornthwaite method. Results show a strong (almost linear) correlation between ETP and recharge rate (Fig. 12). As expected, mean recharge (R) decreases with increasing ETP and vice versa.
Furthermore, the sensitivity analysis includes several parameters for groundwater recharge calculation that had to be assumed or estimated. It was performed manually by varying the parameters initial head distribution, degree of sealing, field capacity and root depth within a reasonable range. All input variables and results are listed in Appendix 3. Other input data for recharge calculation such as the assignment of soil type and land use classes as well as measured climate data are considered definite and were not altered.

During the analysis only one input variable was altered at the time, keeping the others according to the standard case. All parameter attributions in the standard case except for the degree of sealing in urban areas conform to the worst case end of the parameter ranges (Fig. 13). The input variable regionalized groundwater level is only sensitive up to 5 m below ground. Beneath this level, no capillary rise occurs that reduces effective infiltration. The effect on the mean recharge rate is at almost 8%. The most sensitive single parameter is the field capacity of clay soils, which was varied between 15% and 30% (Bakundukize et al. 2011 after Thornthwaite & Mather 1957), the best case result in recharge exceeding the worst case result by almost 18%. The degree of sealing in urban areas affecting the losses due to surface runoff was varied between 12.5% and 50% leading to a maximum variation in recharge of almost 10%. However, the effective root depth of both vegetation types has only little impact on the calculated recharge rate.

Combined best case (highest recharge) assumptions result in a mean groundwater recharge rate of 387 mm/a, which represents a difference of 35% compared to the result of worst case (lowest recharge) assumptions of 286 mm/a. Following a conservative approach, the defined standard case (305 mm/a) is oriented more towards the worst case.
In steady state calculation, the effect of the varied recharge rate is linear to the calculated head values, which are illustrated exemplary for the locations of the observation wells (Fig 14).

Figure 13: Box plot featuring the sensitivity of calculated recharge to the variability of selected input parameters. The upper line marks the best case result for the observed range, the lower line marks the worst case result, and the middle line represents the result for the average value of the range. The combined evaluation on the right side shows the joined effect of all best and worst case assumptions. It can be seen that the standard case recharge rate (dashed line) is founded on worst case assumptions for almost all parameters (except for degree of sealing in urban areas)
Figure 14: Groundwater head level vs. recharge rate at varied input data
4 Protection zones

Protection zones were calculated using path lines that follow the movement of water trough integration of the flow field (Delta h 2015). Path lines are calculated based on the flow velocity $v_a$, which is derived from the Darcy velocity $v_f$. The flow velocity is the actual interstitial velocity referring to the mesh flow area. It is obtained by:

$$v_a = v_f / n_{eff}$$  \hspace{1cm} \text{Eq. 2}

$v_a$ = Field velocity  
$v_f$ = Darcy velocity  
$n_{eff}$ = Pore volume relevant to flow (effective porosity)

The velocity field is acquired from a steady-state calculation. The path lines start at the centre of the wells following the particles backwards (in direction opposite to flow). Figure 15a shows the path lines flowing towards the pumping wells, marking the actual catchment of the well field in the Nyanzare valley. It can be seen that not the whole recharge of the model area contributes to the wells catchment areas. The rest discharges towards the leakage boundary condition (15b). It can be concluded that, assuming a steady state condition, not the total amount of the catchment recharge is available for a sustainable use of the well field. However, the area captured by the well field depends on the pumping rates and the produced gradients toward the wells.

For the determination of protection zones surrounding the pumping wells, the travel time within the aquifer was narrowed down to 50 day. The path lines start at the centre of the wells moving further in direction opposite to flow for 50 days. From the tips of the path lines 50 days isochrones were constructed to create a potential “Protection Zone II” around each well (Fig. 16) according to the directives DVGW (2004). The 50 days travel time zones reach a maximum distance of 125 m at the very productive well F7.15 alongside the high-conductivity zone of the valley lineament. For the rest of the operated wells the radius for the 50 days travel time is at or below 50 m.
Figure 15: Computed flow lines (steady-state) starting at (a) the pumping wells operated at a high rate (standard case) and (b) at the leakage boundary condition for catchments outflow. 12 flow lines run from each starting point. 15(a) shows the underground catchment area of the currently operated pumping wells. The rest of the model area discharges towards the leakage boundary condition (at steady state conditions)
Figure 16: Protection zones from 50-days travel time lines
5 Future scenarios

The calibrated model can be used to predict the response of the aquifer to stress including reduced recharge and increased withdrawal. Several potential scenarios concerning the development of the Gitega area were compiled. They take into account future changes in climate, land use, and demand. Of course, no exact forecast on the actual future development can be made, not to mention all influencing factors that go along with it.

5.1 Scenario 0 (pumping at long-term mean recharge rate)

At first, the current maximum average pumping rate that provides a sustainable use of the Nyanzare catchment was identified. This approach requires an extraction rate which can be supported by the long-term recharge and the local flow field so that water levels remain steady. The quantification of water resources strongly depends on the method for recharge calculation and the assumptions that are made here. If total extraction exceeds mean recharge, a constant decline cannot be prevented. As for recharge, a yearly rate of 1,864,000 m³ was calculated for the whole catchment area (see Chapter 3.3). If only the catchment area of the operated well field (Fig. 15a) was considered, recharge is reduced to a rate of approximately 1,585,600 m³/year. This is the maximum supply that can be obtained from this area including withdrawal from springs and domestic wells. The reference value of pumping rates (see Chapter 3.4.1) used for steady state calculations - which is 1,587,845 m³/year - already complies with the total mean recharge rate of the well field's catchment area. However, the used reference value for pumping rate represents a very conservative estimate that does not include phases of interrupted pump operations in single wells.

At transient scenario simulations, such a constantly high pumping rate (without recurring interruptions in well operation), groundwater levels at first show an almost constant decline for about 8 years and mean head values in the valley decrease by about 50 m. This does not happen in the transient calibration since average pumping rates are about 16 % lower during the observation period, due to several technical failures on the pumps. In the following years, the resulting higher head gradients reinforce groundwater flow towards the lowered head level in the valley until a new equilibrium is reached that coincides with the steady-state solution.

All further scenarios will focus on the potential development of the well field, land use and climate in the Gitega area.
5.2 Scenario I (new well F7.17)

Despite attempts to rehabilitate the very productive well F7.17, it had to be decommissioned and backfilled in 2013 due to technical problems. Since the demand of water from the Nyanzare well field is rising, a new well next to the old F7.17 is currently intended. In order to account for this, the well F7.17 is reactivated in the model with a permanent pumping rate equivalent to the adjacent well F7.15, which has a similar transmissivity according to pumping test analysis (Tiberghien et al. 2014). All other wells remain at their previous extraction level (reference rate April 2014).

For this scenario, precipitation, potential evaporation, temperature, and extraction rates for the other wells were adopted from the standard case.

Results

The results from recharge calculation within the catchment area of the well field have already shown that the maximum extraction rate is approximately reached when all existing wells are simultaneously operated without F7.17. Adding a withdrawal rate of 600 m³/day (or 25 m³/h) at the position of F7.17 would sum up to a total extraction of 4947 m³/day. In steady-state simulations the additional withdrawal lowers the water level in the valley by approximately 3 m compared to the standard case (Scenario 0). Additionally, the lowered piezometric surface enlarges the catchment area of the well field driving in water from the western part of the valley.

Any long-term pumping rate higher than in Scenario 0 would lead to an overuse of the Nyanzare well field. A withdrawal rate of 1200 m³/day (50 m³/h), analogous to the mean pumping rate in F7.15, combined with an continuing extraction of 4347 m³/day for the existing wells, exceeds the calculated mean recharge. Results show a rapid decline of heads in transient simulations. The hydraulic head in the valley drops by about 50 m within 3.2 years, which causes the withdrawal nodes of several wells (F7.5, F7.8, F7.12, F7.15, and new F7.17) to fall dry. Though the water levels in the valley start to recover after that (by reinforced groundwater flow towards the lowered head level in the valley and a virtually died down catchment outflow), an increase of total pumping rate by the introduction of another productive well can’t be supported by the aquifer in the long-term.

5.3 Scenario II (change in pumping schedule)

At the moment all pumps of the F7 well field are operated non-stop (24 h a day, 7 days a week), provided that no technical defects cause a shut-down. For the future a limited operation time per day is intended. For this, a transient, short-term simulation is supposed to
reveal differences in the reaction and behaviour of the aquifer, if the same daily rate of groundwater is extracted within 12 hours compared to 24 hours.

Results

No major differences can be observed from alternated pumping intervals during a day. A limited operation time of 12 h followed by 12 h of rest shows a water level variation of 0.3-0.4 m throughout the day. Over a period of one year the general reaction of the aquifer is exactly the same for 12 h and 24 h operation time. Therefore, different pumping intervals with the same daily extraction rate offer neither benefit nor any disadvantage to the aquifer head levels. Although, from a well field management perspective, a permanent operation at a lower rate should be recommended.

5.4 Scenario III (less recharge due to climate change)

Precipitation is variable throughout the years. With global climate change a decrease in average precipitation is conceivable. To account for a period of water stress, the measured climate data of 2005 with extraordinary low precipitation of 795 mm/a was assigned to be the standard for the Nyanzare catchment. Compared to the long-time average (1150 mm/a for the time period of 1982-2013) precipitation is reduced by 31 %. These precipitation values were used as input data for a re-assessed recharge calculation analogous to Chapter 3.3.

Results

In the year of 2005, potential evaporation quantities remain more or less the same while total precipitation is reduced by 33 % compared to the observation period of 2013-2015. A reduction in precipitation leads to a proportionally more dramatic reduction in recharge. The average recharge for this scenario results in 473 083 m³/year (77 mm/a), which is only ~ 25 % of the standard case (305 mm/a). This amount is equal to 10 % of 2005 precipitation (795 mm). Current pumping rates cannot be retained in this case. Complete dry out of the wells – when hydraulic heads fall below the extraction nodes of the model – is reached very quickly (< 3 years) in transient simulations, if total pumping rates remain constant at 4347 m³/day.

If low precipitation years should reoccur, well management would have to be dramatically adjusted towards lower pumping rates that are in the range of the estimated new recharge rates. In this extreme case this would mean a reduction by 75 %. A long-lasting non-sustainable use cannot be maintained, due to low storativity of the aquifer.
5.5 Scenario IV (expansion of urban area)

Due to population growth and migration into cities, the urban area of Gitega is expected to expand during the next years and decades. If no measures are taken, the expansion will probably also reach into the catchment area for the Nyanzare well field. This will affect the recharge due to changes in land use towards more build-up areas and therefore affect the ratio of surface runoff and infiltration. Therefore, new assignments for the input data land-use and degree of sealing were used (Fig. 17) for a re-assessed recharge calculation analogous to Chapter 3.3.

Results

An expansion of build-up areas and the simultaneous increase in sealed surfaces results in a reduction of groundwater recharge on these surfaces. For the situation pictured in Fig. 17, calculation shows an average recharge rate of 276 mm/a or 23 % of precipitation. This represents a reduction of almost 10 % compared to the standard case (Scenario 0). The adjusted distribution of recharge in the catchment is shown in Fig. 18. A continuing water withdrawal of 4347 m³/day would lead to an over-use of the aquifer and a long-term decline of the water levels. The steady-state water levels in the valley and lower slope area are decreased by 2-3 m compared to the standard case. For expanded build-up areas as shown here, it is recommended to reduce the average pumping rate accordingly by 10 %.

On the other hand, pit latrines can be a major source of bacterial contamination in drinking water wells. Expanding urban areas would bring these closer to the Nyanzare well field. Calculation of path lines show a travel time of 3 years from the outskirts of the urban area to well F7. Traveling times towards other wells are significantly longer. Since pathogenic microorganisms die within a much shorter period of time, no danger of bacterial contamination from these areas can be expected for the Nyanzare well field. Nevertheless, more resistant water contaminants still constitute a potential risk for groundwater quality.
Figure 17: Extend of the land-use class *build-up area* for the current situation (pink hatching) and potential future growth in the Scenario IV (orange hatching)
Figure 18: Distribution of the modified recharge rate in Scenario IV
6 Conclusion and Recommendations

The modelling results lead to the following conclusions and recommendations:

- The recharge for the Nyanzare catchment was calculated using conservative assumptions regarding water losses by capillary rise as well as high field capacity of the clay soils. However, not the entire amount of recharge flows towards the operated well field and is available for extraction.
- For uncertainty reduction in recharge calculation, input parameters were identified that cause significant uncertainty in the output (evapotranspiration, field capacity of clay soils, water level prone to capillary losses, degree of sealing in urban areas) and should therefore be the focus of attention in further research on groundwater recharge in the Nyanzare catchment.
- A piezometer should be installed at the model outflow to be able to measure groundwater level changes over time and thus estimate the outflow rate. This would enhance the model results.
- To ensure a sustainable groundwater management, the long term total withdrawal at the well field should be below 1 600 000 m³/year.
- Well productivity at the Nyanzare well field greatly depends on effective fracture connectivity. Analogously, the calibration process reveals different zones of permeability for the fractured aquifer, the most conductive (and productive) part spreading along the main valley. Hydraulic conductivity appears to decrease towards the slopes and hills surrounding the Nyanzare valley.
- Indications were found for the existence of a north-south hydraulic barrier between the lower part of the valley, where the Nyanzare well field is located, and the eastern part, where the wells F2 and F4 are founded. This is visible by high hydraulic head gradients between those two areas. Concurrently, a NW-SE running fault must enable a preferential flow to supply the long-standing water extraction in F2 and F4. Therefore, the fault - that is documented in the geological map of Gitega (Claessens & Theunissen 1988) - must provide combined conduit-barrier characteristics.
- Geophysical investigations should be implemented to better understand the NW-SE fracture/lineament between the Nyanzare well field and F2/F4. Furthermore, tracer tests execution should help to measure the flow velocity in the fracture.
- The calibration based on the observed water levels was problematic due to limited data on the catchments outflow. In nature, water levels (with or without withdrawal) vary with recharge rates. Since there are no measurements of water levels at the points of catchment outflow and the sub-terrestrial discharge rate itself is not known, the boundary condition had to be assumed constant. This assumption overestimates...
the model outflow rate during and after rainy seasons, when water levels naturally rise. Therefore the rising water levels within the catchment cannot be recreated correctly.

- For the determination of protection zones, 50 day isochrones were defined around each pumping well, which according to DVGW (2004) corresponds to the “Protection Zone II”. The calculated 50 days travel time zones reach a maximum of 125 m for F7.15 alongside the valley. For the rest of the operated wells the distances for the 50 days travel time are at or below 50 m. The size of the zones relies heavily on the hydraulic conductivity of the matrix and the pumping rate that creates a hydraulic gradient driving fluid flow.

- Recent pumping capacities of the existing wells already reach the limit of water availability in the catchment. Frequent technical malfunctions in the past have preserved the aquifer from larger water level decline. Withdrawal should be especially controlled when low precipitation years occur frequently, because recharge rate decreases significantly and the overall storativity and specific yield of the aquifer appear to be low.

- Future developments may carry risks of an unsustainable use of the groundwater resources in the Nyanzare catchment. Growing water demand (by population, agriculture, and industry), modifications in land use, and the uncertainty of climate development due to climate change bear risks for the aquifer. Scenarios were calculated to predict head changes related to the specific stress under study.
  - The introduction of a new well next to the former F7.17 to enhance well field production is not recommended. If the construction of a new well is inevitable, the maximum pumping rate for a new well should stay below 25 m³/h (600 m³/day), if the remaining wells continue at current operation rates of 4347 m³/day.
  - If a series of low precipitation years occurs, the pumping rate of the well field must be reduced accordingly to avoid drying out of the pumps. Since evapotranspiration remains at a high level, recharge is reduced to a greater percentage than the difference in precipitation.
  - The anticipated level of expansion of build-up areas will result in a reduction of groundwater recharge, which was calculated at 10 % of the recent recharge rate. In this case, it is recommended to reduce the average pumping rate accordingly by 10 %, which is apparently opposed to the increasing water demand of a growing population.
  - Pit latrines can be a major source of bacterial contamination in drinking water wells. Calculation of flow lines show a travel time of 5 years from the actual urban
areas to well F7. Expanding urban areas – as shown in Scenario IV - could reduce travel times towards well F7 to 3 years.
7 References


Hahne K (2014) Lineament mapping for the localisation of high groundwater potential using remote sensing, prepared by IGEBU & BGR: 52 p, Hanover

Heckmann M (2016) Groundwater Vulnerability Map (COP) for the Nyanzari catchment, Gitega, Burundi. Report No6, 95 p, Hanover


Thornthwaite CW, Mather JR (1957) Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance. Drexel Institute of Technology, Laboratory of Climatology, 10(3), 311 pp


Tiberghien C (2015) Estimation de volumes d'eau prélevables de l'aquifère cristallin du champ captant de Gitega et de sa recharge, 29 p, Gitega

Appendix 1 Climate data of the observation period (2013-2015) at the Airport Gitega. Missing data was filled by monthly average values derived from long-term observation (1986-2013).
Appendix 2 Sensitivity analysis on calculated ETP (SDSU 2015 after Thornthwaite 1957) for recharge calculation based on the soil water balance method

<table>
<thead>
<tr>
<th>ETP Variation</th>
<th>Recharge rate</th>
<th>GIPz1</th>
<th>GIPz2</th>
<th>GIPz3</th>
<th>Itankoma</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m³/a</td>
<td>mm/a*</td>
<td></td>
<td></td>
<td>(m a.s.l.)</td>
</tr>
<tr>
<td>30%</td>
<td>1.386.047</td>
<td>226.55</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>20%</td>
<td>1.534.369</td>
<td>250.79</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10%</td>
<td>1.693.106</td>
<td>276.74</td>
<td>1615.99</td>
<td>1616.12</td>
<td>1616.12</td>
</tr>
<tr>
<td>5%</td>
<td>1.777.520</td>
<td>290.54</td>
<td>1617.02</td>
<td>1617.19</td>
<td>1617.02</td>
</tr>
<tr>
<td>0%</td>
<td>1.864.048</td>
<td>304.68</td>
<td>1618.01</td>
<td>1618.29</td>
<td>1618.17</td>
</tr>
<tr>
<td>-5%</td>
<td>1.952.246</td>
<td>319.10</td>
<td>1619.16</td>
<td>1619.4</td>
<td>1619.22</td>
</tr>
<tr>
<td>-10%</td>
<td>2.042.414</td>
<td>333.83</td>
<td>1620.26</td>
<td>1620.55</td>
<td>1620.3</td>
</tr>
<tr>
<td>-20%</td>
<td>2.230.626</td>
<td>364.60</td>
<td>1622.56</td>
<td>1622.93</td>
<td>1622.56</td>
</tr>
<tr>
<td>-30%</td>
<td>2.430.065</td>
<td>397.20</td>
<td>1624.99</td>
<td>1625.46</td>
<td>1624.95</td>
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</table>
Appendix 3 Sensitivity analysis on various estimated parameters for recharge calculation based on the soil water balance method

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Recharge rate</th>
<th>Hydraulic head level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m³/a</td>
<td>mm/a*</td>
</tr>
<tr>
<td>Water level (m below ground)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 m</td>
<td>1 864 048</td>
<td>304.68</td>
</tr>
<tr>
<td>2.5 m</td>
<td>1 996 776</td>
<td>326.37</td>
</tr>
<tr>
<td>5 m</td>
<td>2 010 520</td>
<td>328.62</td>
</tr>
<tr>
<td>10 m</td>
<td>2 010 558</td>
<td>328.63</td>
</tr>
<tr>
<td>15 m</td>
<td>2 010 558</td>
<td>328.63</td>
</tr>
<tr>
<td>20 m</td>
<td>2 010 558</td>
<td>328.63</td>
</tr>
<tr>
<td>Effective field capacity of clay soil (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 %</td>
<td>1 864 048</td>
<td>304.68</td>
</tr>
<tr>
<td>25 %</td>
<td>1 929 589</td>
<td>315.39</td>
</tr>
<tr>
<td>20 %</td>
<td>2 009 105</td>
<td>328.39</td>
</tr>
<tr>
<td>15 %</td>
<td>2 121 314</td>
<td>346.73</td>
</tr>
<tr>
<td>Effective root depth (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 m</td>
<td>1 864 048</td>
<td>304.68</td>
</tr>
<tr>
<td>2 m</td>
<td>1 871 563</td>
<td>305.91</td>
</tr>
<tr>
<td>1 m</td>
<td>1 883 341</td>
<td>307.83</td>
</tr>
<tr>
<td>Farm-/grassland</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 m</td>
<td>1 864 048</td>
<td>304.68</td>
</tr>
<tr>
<td>0.7 m</td>
<td>1 874 646</td>
<td>306.41</td>
</tr>
<tr>
<td>0.4 m</td>
<td>1 885 086</td>
<td>308.12</td>
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<tr>
<td>Degree of sealing in urban areas (%)</td>
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<td></td>
</tr>
<tr>
<td>50.0 %</td>
<td>1 749 506</td>
<td>285.96</td>
</tr>
<tr>
<td>37.5 %</td>
<td>1 799 007</td>
<td>294.05</td>
</tr>
<tr>
<td>25.0 %</td>
<td>1 864 048</td>
<td>304.68</td>
</tr>
<tr>
<td>12.5 %</td>
<td>1 938 842</td>
<td>316.91</td>
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<tr>
<td>Combined</td>
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<td></td>
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<tr>
<td>Worst case</td>
<td>1 749 506</td>
<td>285.96</td>
</tr>
<tr>
<td>Standard case</td>
<td>1 864 048</td>
<td>304.68</td>
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<tr>
<td>Best case</td>
<td>2 368 188</td>
<td>387.08</td>
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</tbody>
</table>

* Total recharge rate is standardized on the model area of 6 118 053 m²