

# A Preliminary Hydrological Assessment for Sustainable Groundwater Abstraction Using VES, MRS, SR and MODFLOW: A Case of Namanve Industrial and Business Park, Mukono District, Uganda

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## Abstract

The increase in demand for water supply in Uganda as a result of high population growth, agricultural and industrial expansion has triggered unplanned groundwater development and use in many parts of the country. This has put the future yield and sustainability of groundwater abstraction in some of these parts into question. This paper investigated a hydrogeological assessment for sustainable groundwater abstraction in Kampala Industrial and Business Park, Namanve. The main aim was to establish the behavioral response of the groundwater system to increased abstraction. This investigation was done using pre-existing groundwater/ borehole data from the area to generate the various aquifer parameters in the area: Aquifer geometry, hydraulic properties and finally the hydrogeological conceptual model of the area. These values were further adjusted during the modeling processes to suit the current hydraulic heads in the area. Modeling under non-pumping and pumping scenarios to match the current static water levels monitoring were done. The final modeling results demonstrated that an average recharge of 42 mm year<sup>-1</sup> m/day maintains the natural equilibrium of non-pumping and the model result with pumping scenario shows that the current estimated groundwater abstraction of 2871 m<sup>3</sup> day<sup>-1</sup> in the area did not cause any significant effect on the groundwater levels in the area. Significant effect on the water levels was however, realized after increasing the current abstraction rate by 500%. The sensitivity of the model was tested by systematically changing one parameter or input values at a time and it was found that the model is highly sensitive to changes of transmissivity of the aquifer system and the recharge rate. The model is however associated with a number of uncertainties resulting from the simplification and assumptions made to the complex field conditions, poor quality data and lack of detailed subsurface characterization of the aquifer system. Although it appears to be a preliminary model in nature, its results gave a good insight to policy makers as regards the issue of sustainable groundwater resources management in the study area.

**Keywords:** Hydrological-assessment; Sustainability; Vertical-Electric-Sounding (VES); Magnetic-Resonance-Sounding (MRS); MODFLOW; Groundwater abstraction; Mukono District; Uganda

## Introduction

Groundwater is defined by Freeze and Cherry [1] as the subsurface water that occurs beneath the water table in the soils and geologic formations that are fully saturated. It is one of the key subsurface natural resources in the world, and serves as important source of water supply for various purposes e.g. domestic, agricultural, and industrial purposes. This is due to mainly its abundance, with roughly stable quality and it is inexpensive to exploit [2]. Recent figures from the United States Geological Survey (USGS) [3] indicate that groundwater provides an estimated 22% of all fresh water supplies in the world, 37% of the water for agricultural, commonly used for irrigation, 37% of public water supplies, 51% and 90% of safe drinking water for urban and rural population respectively. Generally, groundwater has a fundamental importance of meeting the increasing urban, rural, industrial and agricultural water requirements especially in arid and semi-arid areas where surface water is increasingly becoming more scarce and seasonal due to the effects of climate change.

Uganda, like other African countries that majorly depend on groundwater occurring in the low yielding crystalline rock aquifers which are facing sustainable groundwater supply problems [4-6]. Despite the fact, ambitious developments plans, urbanization and rapid population growth that requires increased volumes of water supply are ongoing in many parts of the country. Groundwater source is one of the key targets to meet water demand for such developments e.g. more than 30 urban water supplies in the country are currently using groundwater [7], industrial and irrigation ground water uses have also increased in many parts of the country.

A situational study in Kampala Industrial and Business Park-Namanve located 12 Km along the Kampala-Jinja high way in Mukono District has showed that; groundwater from drilled boreholes is a significant source of water supply to most industrial establishment in the area alongside National Water and Sewerage Cooperation (NWSC) piped water supply that covers a very limited part of the Industrial park [8]. By June 2015, the time of this study, regulated groundwater abstraction in this area had risen to about 30 permits from about 03 permits in a year 2000 [9]. Currently, groundwater in this area may appear to be abundant, though the increasing rate at which it's being exploited possess a concern on aspects related to its management for sustainable use purposes. It upon this background that a groundwater abstraction sustainability assessment has been done in the study area in order to understand the groundwater system and the likely impacts of increasing groundwater abstraction on the system.

Geophysical methods (e.g. electrical resistivity, Magnetic Resonance Sounding (MRS) and seismic refractions) alongside borehole drilling

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logs have been used to provide information on groundwater availability in the area. Electrical resistivity method; being the commonest methods employed in various hydrogeological studies within the crystalline basement rocks e.g. Vertical electrical sounding and correlation of geoelectric data with aquifer parameters [10,11] were used to determine the depth to bedrock and zones of saturation in the subsurface. Hydraulic characteristics of the subsurface aquifers e.g. Transmissivity ( $T$ ), Hydraulic conductivity ( $K$ ) and Specific yield ( $S_y$ ) are important properties for groundwater flow and supply evaluation and were calculated from pumping tests performed on boreholes in the study area [5,6,12]. The resulting information was put together with other hydrological information in the area to develop a hydrogeological conceptual model. The conceptual model was further converted into a computer based mathematical model or a numerical groundwater model [13,14]. The numerical model was then used to describe groundwater flow, water balance conditions and predicting how aquifers may respond to various pumping stresses scenarios and other environmental factors related to groundwater resource management [15,16].

### Study area setting

Kampala Industrial and Business Park-Namanve is located about 12 km in the east of Kampala city along the Kampala-Jinja high way, it lies on the northern shores of Lake Victoria and is shared by two central districts of Uganda, namely Wakiso and Mukono (Figure 1). The study focused on an area of about 15 sqkm bounded by ridges in the west, east and the north while the south is a low lying valley area. The area is peri-urban characterized by high population, variety of commercial businesses and a number of industrial establishments.

### Relief and climate

The study area lies on the altitude between 1,158 m and 1,219m above mean sea level. It has moderate to high relief with some landform features e.g. small hills and ridges. The streams in the area generally drain North wards and the main river in the area is River Namanve [17]. The vegetation in the area is predominantly of the tropics but has been cleared for various commercial developments and a few patches are left. The rainfall is evenly distributed over the area with an annual amount between 1200-1600 mm [18].

Namanve Industrial Park is characterized by a bimodal pattern with most rainfall falling in March to May and September to November. There is normally a short drier spell between the two rainy seasons during mid-June to mid-July. The longest dry season sets in during early December through to early March. July is the driest month of the year as indicated by the average monthly rainfall distribution in Figure 2 (National Agricultural Research Organization- NARO-Mukono zonal area and the source of data was from the Directorate of Water Resources Management - 2014) The annual maximum temperature of the area is about 25°C to 27.50°C and annual minimum temperature is between 15 -17.5°C [19].

The study area is specifically comprised of the Kampala Suite granites that consist of variably deformed granitoids and orthogenesis and lies between the Paleoproterozoic Buganda group in the south and various tonalite-trondhjemite-granodiorite/granite (TTG) of gneisses in the north. Being compact and weathering resistant rocks, they usually form hills, that are particularly evident in the study area and rise up to about 110m above the Lake level and they are rounded and covered with laterite soils. The structures in the area include tight folds on ENE axes in the east which varies to the west, with a decrease in intensity and a lowering of the metamorphic grade to the south.

### Hydrogeological settings

Groundwater in the area occurs in both shallow aquifers contained in the porous weathered mantle and the deeper fractured bed rock aquifers. The weathered mantle comprises of weathered rocks (saporolite) or sandy-clays consisting of micas, feldspars and quartz grits while the fractured bed rock is made up disintegrated granitic gneisses. Groundwater levels in the area are usually shallow between 5-8 meters [20]. The shallow weathered mantle aquifers and the deeper fractured bedrock aquifers are usually hydraulically interconnected [5,6].

### Materials and Methods

#### Materials

Groundwater occurs in the crystalline rock aquifers in various continents of the world that include Africa, Asia and South America [2]. Crystalline basement rocks are known to form the oldest rocks of igneous origin such as granitoids and gneisses. The age of these rocks ranges between 2.75-2.55Ga and have little or no primary porosity [21]. Groundwater in these rocks is normally present in the fractures or the overlying weathered overburden.

Chilton and Foster [22], estimated that crystalline basement aquifers account for over 40% of the groundwater supplied in the SSA, volcanic rock aquifers that occur mostly in East Africa account for about 6%, the consolidated sedimentary rock aquifers that occur extensively in countries like Chad, DRC and Mozambique account for about 22% and finally the river/alluvial sediment aquifers located along the major river beds have unknown but significant contribution.

Boreholes that are drilled up to the fractured bedrock where the permeability is high and where the storage can be provided by the overburden usually have better yields as compared to the boreholes in the weathered mantle [6]. However, Taylor and Howard [5] observed that fractures in the crystalline basement rocks that form aquifers are sometimes discontinuous and inherently possess low storativities that prolonged or intensive groundwater abstraction from these aquifers depends upon leakage from the more porous overburden.

As presented in Table 1, aquifers are in the crystalline rocks across some few African counties have been noted to be heterogeneous and anisotropic with generally low estimates of transmissivities that commonly vary over three or more orders of magnitude both spatially and vertically [23-26].

**Studies in the crystalline basement rock aquifers in Uganda:** Geo-hydrological studies in southwestern Uganda in Nyabisheke catchment using well testing, packer testing, collection of water samples for major and minor ions and environmental isotope analysis demonstrated that the crystalline basement rocks of the catchment form a very weak aquifer which is highly susceptible to over pumping hence causing decline in groundwater levels [26]. The studies further suggest that in areas where good hydraulic interconnection between the bedrock and regolith exist, it is likely that the aquifer within the overlying regolith may be transmitting the majority of the vadose-zone recharge and therefore may provide the key feature of groundwater resource development.

**Nature of aquifers in the crystalline basement rocks of Uganda:** Precambrian crystalline rocks of Uganda have been subjected to long term weathering which is evident from the thick mantle of weathered rock that overlies the bedrock [27]. Aquifers occur in the fractured bedrock and at the base of unconsolidated overburden where coarser

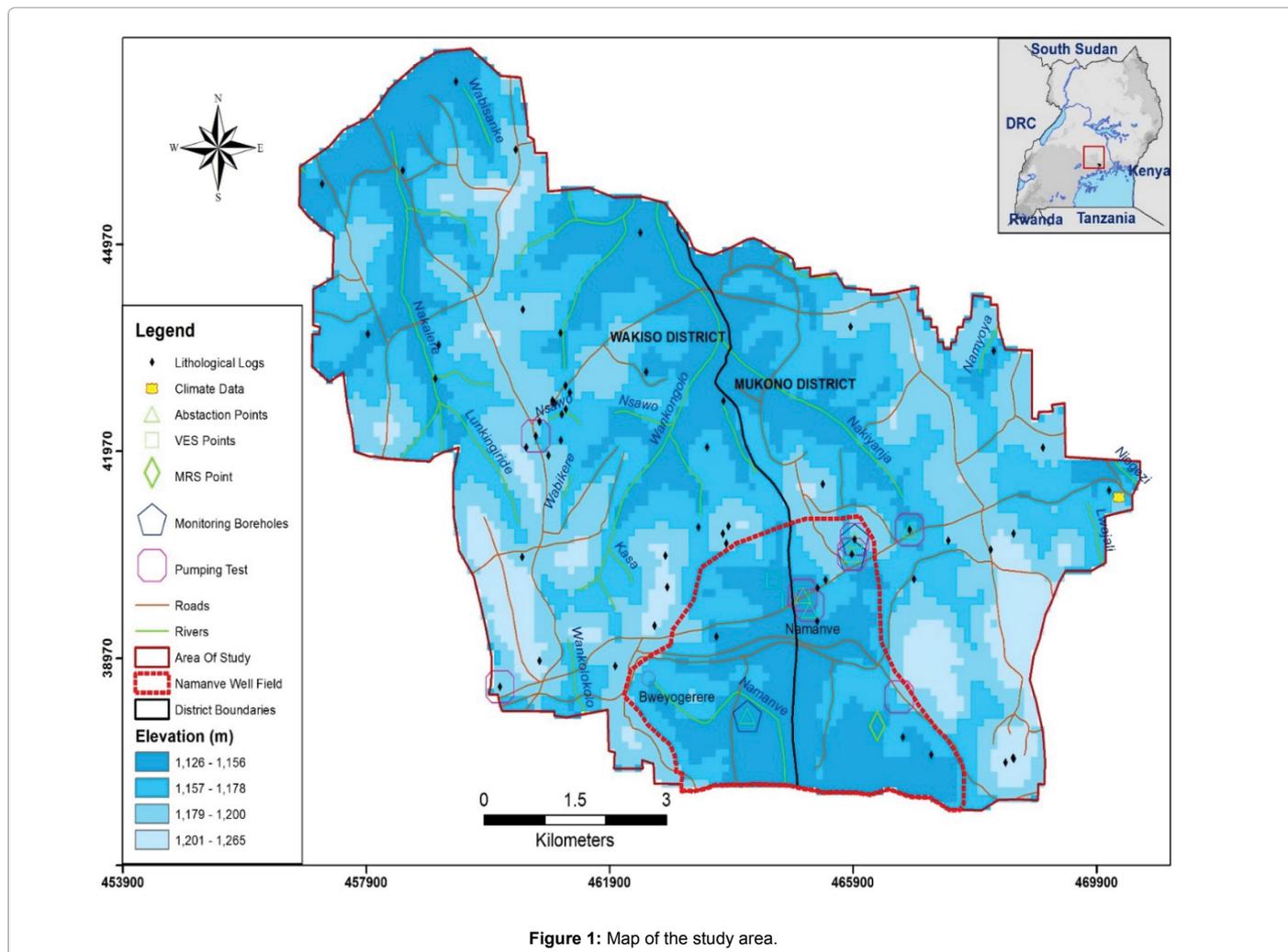


Figure 1: Map of the study area.

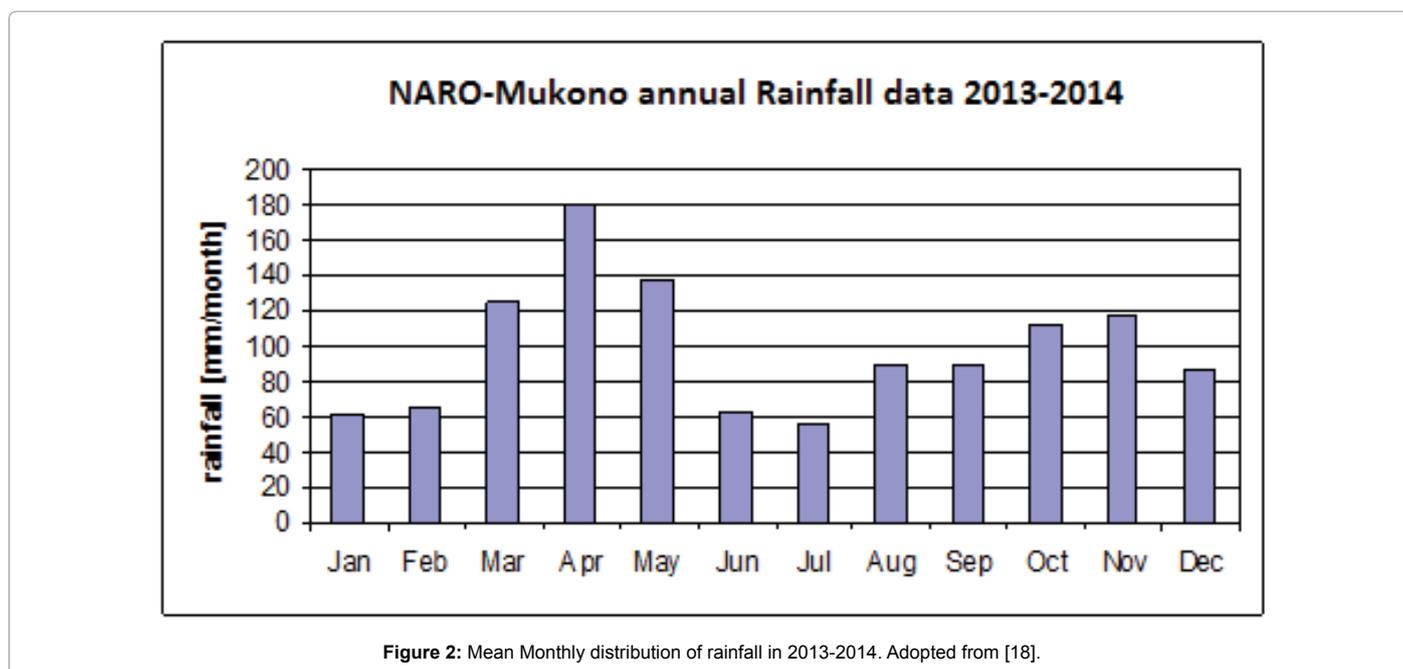


Figure 2: Mean Monthly distribution of rainfall in 2013-2014. Adopted from [18].

Location	Coordinates		MRS loop Shape & Size	Azimuth (°N)	Lamor Freq.(Hz)	Signal to Noise Ratio	Average # stack	θ_MRS (%)	T2*	Tickness(m)		Measured SWL (m)	Measurement	
	UTI_E (m)	UTI_N(m)								From	To		Date	Duration (d)
Ageri	476181	22886	8 square: 62 5 m	45	1439.52	5.77	400	8	167	4.5	20.6	6.29	28/03/2014	2
Egum	474098	227367	8 square: 62 5 m	45	1440	3.93	400	6.4	148	10.3	33.4		30/03/2014	2
Baracer	477788	221298	square:125m	None	1440.52	4.43	300	4.6	149	0.5	42.8	1.37	01/04/2014	3
Otong P/S	409700	333782	8 square: 62 5 m	35	1442.14	3.51	450	7	172	3.3	16.6	5.35	09/04/2014	2
Roofig	466324	37989	8 square: 62 5 m	215	1423.81	1.56	600	6.1	68	4.3	28.4		18/04/2014	2
Nsekanambo	229220	9958093	8 square: 62 5 m	175	14110.8	1.67	650	4.9	125	1.4	22.9	2.82	25/04/2014	4
Awal Obaro	429027	342154	8 square: 62 5 m	130	1442.61	1.86	400	2.6	142	2.1	10.3	5.4	11/04/2014	2
Pagwaya	328962	278913	square : 125m	None	1438.96	4.39	350	4.2	179	15.2	72	27.4	13/04/2014	2
Kabolwa	324495	223252	8 square: 62 5 m	335	1437.81	3.05	500	2.3	143	5	47.5	8.26	29/04/2014	3
Blowoza	547477	65172	8 square: 62 5 m	80	Too noisy site							15/03/2014	1	
Nkokonjeru	491452	28444	8 square: 62 5 m	170	Too noisy site							16/03/2014	1	

**Table 1:** Summary of the Synthesis of MRS measurement and interpretation for the 11 sounding sites in Uganda [41].

bedrock fragments predominate [28]. The occurrences of groundwater in these aquifers depend on the thickness of the weathered zone normally 10-90 m [6] and this zone is anisotropic characterized by permeability and porosity that vary with depth [22]. Porosity and permeability of the bed rock depend mainly on the nature of the formation and the extent of fracturing [6]. Recharge in Uganda amounts to approximately 10% of annual rainfall in the zone of deep weathering in central Uganda [29,30] whereas it is as little as 1% of annual rainfall in the zone of stripping in western Uganda [5]. This therefore suggests that the ability of the weathered crystalline rocks to provide adequate yields of water supply in Uganda depends on both the climatic conditions and aquifer properties.

**Hydrogeological conceptual model:** Generating a hydrogeological conceptual model for the fractured rock system e.g. the crystalline basement rock system requires a gross simplification or detailed description of the aquifer properties controlling the groundwater flow [31]. Fractured material is represented as an equivalent porous medium (EPM) by replacing the primary and secondary porosity and hydraulic conductivity distributions with a continuous porous medium of equivalent or effective hydraulic properties.

According to Yuri et al. [32], the EPM approach has been frequently applied to simulate flow in fractured media due to its ease of use. This practice results in some severe limitations such as hydraulic head averaging and an inability to handle preferred fluid pathways. When fractures are few and far between and the fractured block hydraulic conductivity is low, the EPM approach may not be appropriate.

In Uganda, the hypothesis of EPM has been successfully applied in the crystalline basement rocks of Pallisa district to construct a conceptual and numerical Model covering the full extent of the Pallisa as applied in groundwater abstraction and contamination [33] hence it was considered applicable in the study area moreover of similar hydrogeological environment.

**Aquifer system to increased groundwater abstraction:** Over abstraction of groundwater has negative effects on aquifers and the environment in general e.g. drop in groundwater levels and deterioration

of groundwater quality [34]. Sustainable groundwater abstraction must be balanced by recharge that ensures stable groundwater levels and quality. In areas where there is groundwater over abstraction, boreholes drilled may either fail at the time of drilling or cease to provide adequate quantity and quality of water within a short time of their construction as a result of decline in groundwater levels and deterioration of the water quality respectively. The cause of these effects is normally linked to reduced recharge, poor borehole yields in relation to water demand, seasonal variations e. g. draughts and the general increased groundwater demand [35].

As described by Carrera-Hernandez and Gaskin [36], the advantage of MODFLOW is that it provides different modules to undertake groundwater flow simulations in confined and unconfined aquifers as well as in aquifers with variable confinement with both constant and variable transmissivity values. The modules provided by MODFLOW can be used to simulate the effect on an aquifer system caused by different stresses such as the presence of extraction and injection wells, of areal distribution of recharge, evapotranspiration or of different hydrological features.

## Methods

Resistivity is one of the geophysics method commonly applied in groundwater studies to delineate hydro-stratigraphic units [10]. The method was applied in the study of horizontal and vertical discontinuity in the electrical properties of the subsurface and also in the detection of three-dimensional bodies of anomalous electrical conductivity.

Horizontal profiling in resistivity were detected while Vertical Electric Sounding (VES) data acquisition on depth investigations were made. The results of horizontal profiling and VES for both horizontal and vertical variations in the electrical properties of the ground were noted.

The generated VES data (mainly apparent resistivity and depth variations) were interpreted using computer software to generate models of the subsurface rock units as a function of depth.

In this research study, identification of hydro-stratigraphic units was undertaken using two composite approaches outlined below.

- i. Correlation of the available borehole logs from the study area; and
- ii. Analysis and interpretation of VES data obtained from the area.

**Analysis and interpretation of Geophysics Data-Vertical Electric Sounding (VES):** For the present study, geophysical survey results (VES) data obtained using Schlumberger configuration AB/2 distances (usually 200-300m) within the study were provided by private consulting companies' e.g. Draco drilling Company and Aquatec Enterprises. This data was lateral inverted using 1x1Dv3 Interpex software program. This program models VES data into layers usually the overburden on top, followed by weathered/ highly-fractured rock, then slightly-fractured rock and lastly the hard bedrock. Examples for comparison of VES and borehole log models are presented in Figures 6, 7 and 8.

MRS has been applied for estimating aquifer storage properties that are used for calculating groundwater reserves and recharge in the crystalline basement rocks in many parts of the world including Africa. It is a non-invasive geophysical method that measures a subsurface signal directly linked to the presence of groundwater within a given area. The details of the method and its principles are thoroughly described in Legchenko, Valla, Lubczynsky and Roy's studies [37,38]. The resulting MRS geophysical parameters are the initial amplitude which is linked to the water content ( $\theta_{MRS}$ ) and the decay time ( $T_2^*$ ) which is linked to the mean size of the pores that contain water [39] and the main aquifer storage properties estimated by MRS is the aquifer specific yield  $S_y$  obtained from MRS free water content [40]. The interpreted MRS results at this site were parametrized using pumping test data for a borehole adjacent to the sounding site hence aquifer storage coefficient  $S_y$  and Transmissivity  $T$  were estimated [41].

**Aquifer hydraulic parameters:** Aquifer tests results particularly

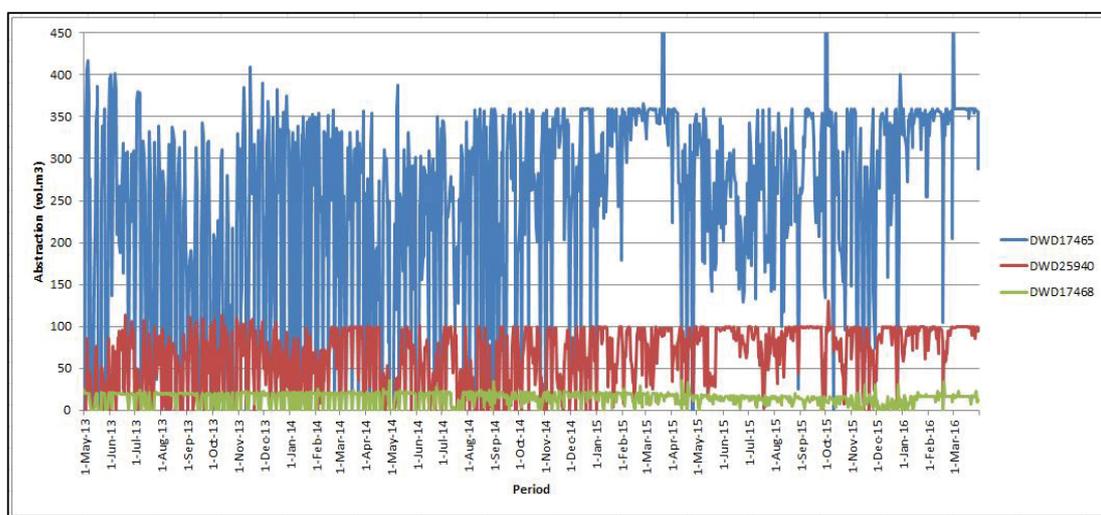


Figure 3: Variation of abstractions ( $m^3/day$ ) at 3 boreholes for a period of 3 years (2013-2016).

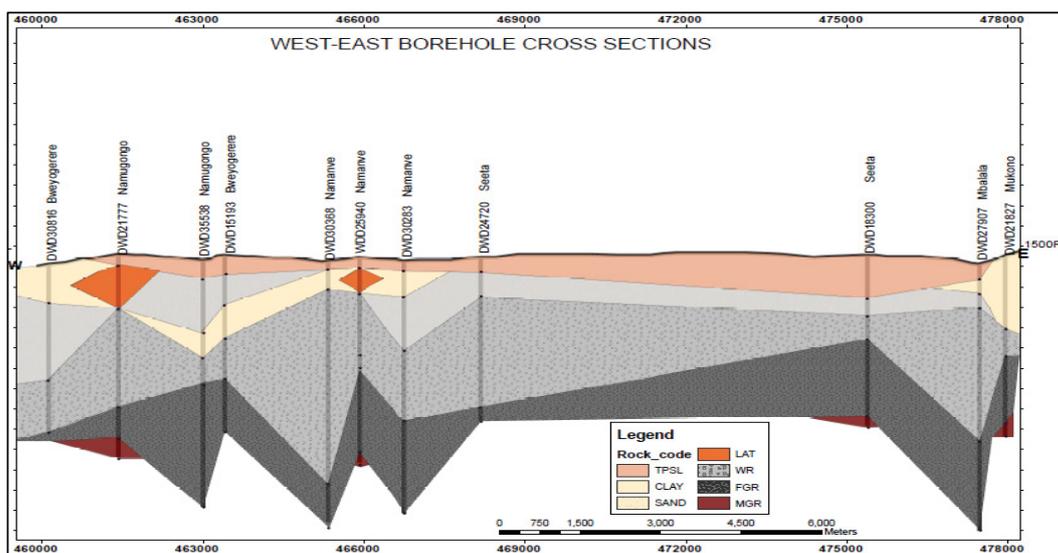


Figure 4: A 2D display of the stratigraphy of the study area using borehole drilling logs.

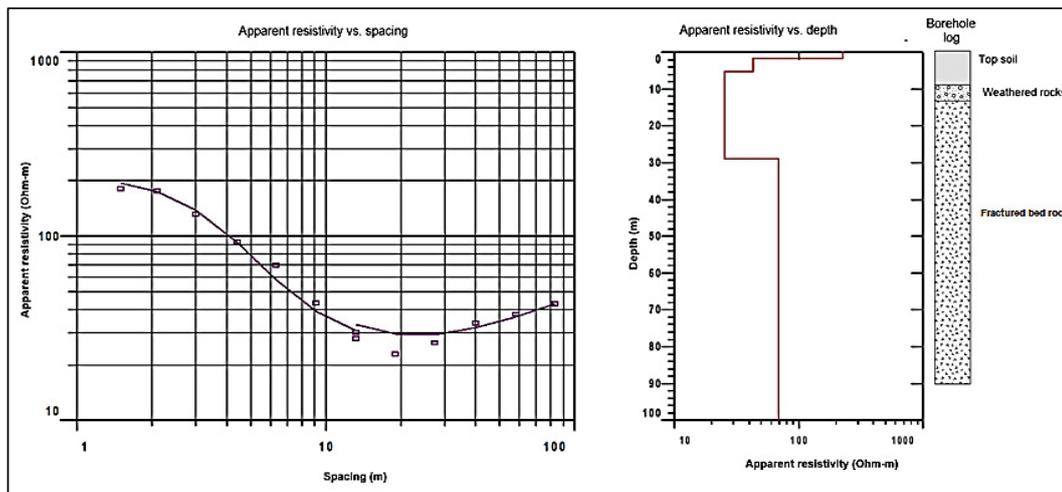


Figure 5: Correlation of apparent electrical resistivities with drill logs of borehole DWD 30368-Namanve.

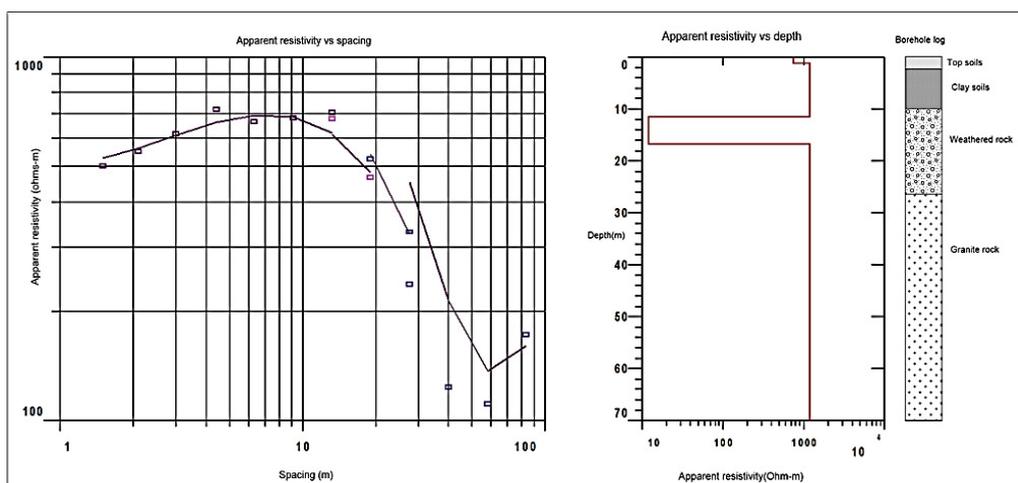


Figure 6: Correlation of apparent electrical resistivities with drill logs of borehole DWD 30283-Namanve.

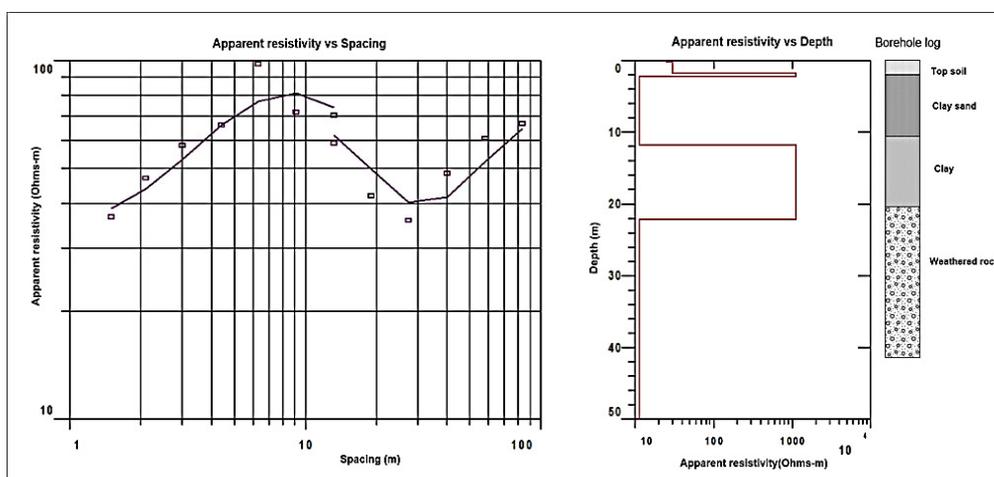


Figure 7: Correlation of apparent electrical resistivities with drill logs of borehole DWD 29736-Namanve.

pumping test data have been used by many authors to estimate the aquifer hydraulic parameters in crystalline rock environments [12]. The principle of a pumping test involves applying a stress to an aquifer by extracting ground water from a pumping well and measuring the aquifer response to the stress by monitoring drawdown as a function of time. The longer the duration of the test, the larger the volume of the aquifer involved hence the more representative aquifer data [42] straight line approach is one of the preferred method because it is flexible in different hydrogeological conditions and has been used successfully by many authors in different environments [43]. Computer software AQTESOLV has also been used as a main alternative for analysis of pumping test data in many research studies [6,12,27]. In this method, records of pumping test data e.g. draw down, saturated thickness of the aquifer, time of pumping test data are fed in the software and the software produces curves with estimated/ calculated hydraulic parameters like  $T$ ,  $K$  and  $S_y$ .

**Correlation of borehole logs:** Boreholes across the study area were selected and their logs were correlated to generate a stratigraphic a 2D cross section model (Figure 5) that represents the major hydro-stratigraphic zones in the study area [22].

ArcGIS v.10 software was used to correlate the large number of borehole logs considered in the cross section. Drilling logs related to the selected boreholes were fed into the software and were used to create and guide the dimensions and the vertical stratigraphy of the cross section. The generated cross section model was used to determine the average thickness and continuity of each stratigraphy layers in the area. The cross sections revealed both vertical and lateral variations of the lithology in the area, rock units penetrated by most boreholes, depth of occurrence and thickness of the saturated/ aquifers layers in the area hence a detailed interpretation of the underlying stratigraphic sequence and the extent of the saturated layers (aquifers) occurring in the area.

**Evaluation of the hydraulic parameters of the aquifer system:** Aquifers behave differently to groundwater withdraw because of the difference in the hydraulic characteristics e.g. transmissivity, hydraulic conductivity and storage coefficient. The difference in the hydraulic characteristics is mainly due to the geologic heterogeneity of the subsurface. Detailed knowledge of the distribution of the aquifer hydraulic properties is thus a prerequisite is such a study. In practice,

several investigation techniques e.g. aquifer tests, groundwater flow simulations may be employed to estimate the distribution of hydraulic properties of an aquifer system. In this study, aquifer tests (Pumping test) method was used. Pumping test data used in the study consisted of 01 set of multiple well test at Roofing Rolling Mills Uganda Limited-Namanve area and 09 single well pumping tests (without observation wells) (Table 1). The data was collected from boreholes distributed in Namanve, Seeta, Mukono and Mbalala area. AQTESOLV TM/Pro v4.5 software was used to analyze and interpret the pumping test data.

**Hydrogeological conceptual model of the study area:** A conceptual model is defined as hypothesis of how a system or process operates and consists of a set of assumptions that reduce the real system to simplified versions that are acceptable. Hydrogeological conceptual models are normally formulated to aid better understanding of the site hydrogeological conditions and define groundwater problems affecting a given area so that a numerical model with a suitable computer codes may be selected for further understanding of the problems [44]. The nature of the conceptual model determines the dimensions and design of the grid involved in numerical modeling. Failure of numerical model to give accurate result is often attributed to errors in the conceptual model. It is therefore critical that a conceptual model form a valid representation of the important aspects of a given groundwater system [31]. In this study, the hydrogeology of the area was conceptualized by incorporating the relevant information in the area e.g. drilling logs, geophysics, pumping tests and monitoring data for groundwater levels and weather events. Several simplifying assumptions e.g. on topography, geology, hydrology and climatic conditions were however applied to complete this conceptual model.

**a) Conceptual model boundaries:** Conceptual model boundary establishment is normally based on the site-specific knowledge acquired from geology, topography and flow system prevailing in the area. For this study, topography, surface water divides and borehole locations were used in defining the boundaries of the model domain.

**b) Terrain:** The general terrain of the study area was conceptualized to be of low relief with minor landforms features e.g. hills and ridges that diminish towards the southern part of the study area. Minor Streams occur in the lowest relief areas/ valleys and most of them drain northwards away from Lake Victoria. The commonly exposed lithological units within the study area was mainly lateritic soils and the

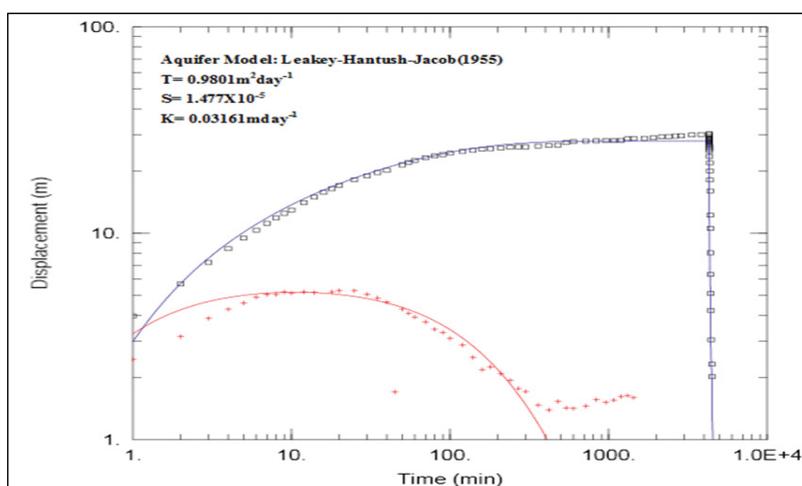


Figure 8: Roofing Rolling Mills Borehole 2, Leakey aquifer solution- Huntush Jacob.

Kampala Suite granites that consist of variably deformed granitoids and orthogenesis [45].

**c) Stratigraphy/hydro-stratigraphy of the area:** Based on the analysis of the available subsurface data (resistivity data, drilling logs) together with the general geological knowledge gained from the reconnaissance visit made to the study area, the general stratigraphy of the area may be described as follows:

- i. Weathered overburden that combines top soils and other thin profiles e.g. laterites, clays and sands. The thin profiles are quite ubiquitous in their occurrence and were completely missing in some borehole logs [46]. The average thickness of this unit (weathered overburden) is expected to range between 12 to 40 meters.
- ii. Fractured bedrock formation that is usually granitic and slightly weathered in nature comes follows below and it has an estimated thickness between 9 to 30 meters.
- iii. The massive and hard granitic rock formation forms the base of the stratigraphic column and its thickness could not be estimated but it occurs at an estimated minimum depth of about 55-70 meters.

The first two stratigraphic units are normally saturated (form aquifers) at varying depth and the total average thickness of the saturated zone within the two aquifers was estimated to be about 48 meters with 17 meters in the weathered overburden and 31 meters.

**d) Hydraulic properties of the stratigraphic units:** Hydraulic conductivity and transmissivity are key components of the groundwater conceptual model. The pumping test data analysis generally presented very low and highly varying hydraulic conductivities and transmissivities as a major characteristic of crystalline rock environments [22]. The average mean hydraulic conductivity and transmissivity of the deeper fractured rock aquifers was estimated to be  $0.1756 \text{ m day}^{-1}$  and  $3.275 \text{ m}^3 \text{ day}^{-1}$  respectively. The specific storage of the aquifer deduced using MRS soundings together with pumping test results is  $4 \times 10^{-3}$ .

**e) Recharge:** Factors contributing to groundwater recharge in the area include rainfall, evapotranspiration and soil type. The recharge in the area is assumed to occur mainly from rainfall/seasonal floods generated from the topographic elevated ridges surrounding the area. Results and conclusions made from previous recharge studies in Uganda that employed various methods e.g. soil moisture balance, water level fluctuation, isotope methods, chloride balance, flow modelling and base flow separation [12,26,28,30] were applied in this study. Most of these studies show that upon reaching the land surface, most of the incoming rainfall (70-90%) is recycled to the atmosphere by evapotranspiration and the remainder stays at the land surface and contributes to surface flow via runoff and to groundwater recharge via infiltration through the unsaturated zone. Taylor and Howard [28] showed that groundwater is recharged by heavy rainfall and that recharge events are effectively restricted to periods of heavy rainfall so that the magnitude of recharge is controlled more by the number of heavy rainfall events ( $>10 \text{ mm d}^{-1}$ ). Owor et al. [12] further concluded that the magnitude of observed recharge events is better related to the sum of heavy rainfalls exceeding a threshold of  $10 \text{ mm day}^{-1}$ , than to that of all daily rainfall events. Since there is a big variation of rainfall received in the different parts of Uganda, the estimated annual groundwater recharge rates in different parts of Uganda are highly variable but amounts to approximately 10% of annual rainfall in the zone of deep weathering i.e. central Uganda whereas its approximately 1% of annual rainfall in the zone of stripping in western Uganda [29,30].

**f) Groundwater discharge:** The study area is so close to Lake Victoria and one would assume a certain level of groundwater –

Lake water (G-S) interaction. It was however practically impossible to establish the hydraulic connection of the two system though [47] through Darcy flow calculations concluded that direct contributions from groundwater to Lake Victoria comprise  $<1\%$  of the total lake inflows. Considering the small size of the study area, the Groundwater-Lake water interaction and the discharge from the aquifers through seepages along the river banks were considered to fall under the natural groundwater flow from the area.

There are no available study details of the unsaturated zone in the study area but, it is assumed that the influence of evapotranspiration is limited to a depth of few meters above the water table and has very minimal effects on the saturated zone hence it's not considered as discharge component.

**g) Groundwater flow system:** The conceptualization of how and where water originates in the groundwater flow system and how and where it leaves the system is critical to the development of an accurate model [48,49].

As pointed out by different researcher's [6] regional groundwater flow in the crystalline rock environments is mainly controlled by regional structures for instance faults and lineaments while local flows are controlled by the topography, geology and sometimes degree of fracturing. The mean annual rainfall fed groundwater recharge in the entire Uganda was estimated to be  $120 \text{ mm/year}$ . Basing on this information and the 3 year daily rainfall record of the study area (Figure 3), the mean annual rainfall recharge of the study area was estimated to be  $112 \text{ mm/year}$ .

The direction of groundwater flow in the area was, however, deduced using calculated hydraulic heads obtained from the initial groundwater levels of each borehole at the time it was drilled. Ground water in the area generally flows from the Northern to the Southern direction. The calculated hydraulic heads were also used in setting the initial conditions for the numerical groundwater modeling. Hydraulic heads were calculated by subtracting Static water level depth (mbgl.) from borehole depth (m).

**h) Graphical representation of the conceptual model in the real world:** In this aspect, Anderson and Woessner [31] suggested that the conceptual model should be simplified as much as possible while it still remains complex enough to represent the system behavior. In Figure 10, the simplifying assumptions were considered that represented the hydrogeological conceptual model of the area as:

- i. The geological formations of concern are considered horizontal.
- ii. There is no groundwater inflow from the adjacent sub-basins.
- iii. The aquifer system is fully penetrated and saturated.
- iv. A 48 m of average aquifer thickness was considered.

The generated conceptual model is regarded as an approximation of the field conditions though useful in obtaining the preliminary hydrogeological information of the area subjected to refinement

**Determining the sustainability of groundwater abstraction:** The solution for this problem was implemented using numerical modelling approach where simulations of various abstraction and recharge scenarios were performed. The response of the groundwater system to rainfall recharge and abstraction (pumping from boreholes) was presented in form of hydraulic head variations/changes over a given period of time considering that hydraulic head changes due to other discharge and recharge process in the area are negligible.

Three years (2013-2015) weekly monitoring data for groundwater levels belonging to boreholes within the well field were used in this study (DWD 17468, DWD 17465 and DWD 25940).

**Model code selection:** The selected model code was MODFLOW which is a modular three-dimensional finite-difference groundwater flow model and is based on the flow equation of Darcy and mass continuity equation. MODFLOW numerically uses block-centered finite differences to solve the flow equations in three dimensions. The modules are grouped into packages and each package deal with a specific hydrogeological feature to be simulated. MODFLOW was selected because it is one of the most widely used groundwater flow code in hydrogeological studies, is extensively tested in various environments under different conditions and the theory behind it is well documented and relatively easy to understand. MODFLOW was as well considered for this study based on its relationship with the GMS software that has been used to model ground flow in Kawempe III parish, nearest to my study area (about 15 Km) off. The governing partial differential equation 1 in which MODFLOW is based on, is given below [50].

$$\frac{\partial}{\partial x} \left( k_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_{zz} \frac{\partial h}{\partial z} \right) - w = S_s \frac{\partial h}{\partial t} \quad (1)$$

Where;

$k_{xx}$ ,  $k_{yy}$ ,  $k_{zz}$  represents hydraulic conductivity along  $x$ ,  $y$  and  $z$  coordinate axes ( $LT^{-1}$ ), which are assumed to be parallel to the major axes of hydraulic conductivity,  $h$  represents the potentiometric head (L),  $w$  is flux per unit volume representing sources and/or sinks of water ( $T^{-1}$ )  $S_s$  represents the specific storage of the porous material ( $L^{-1}$ ) and  $t$  is time. For consideration of the present study, a two-dimensional model was adopted hence the third component of the equation goes to zero.

### Model geometry and model thickness

The horizontal extent of the model domain was 5 Km by 4 Km length. It's bounded by UTM coordinates: 464659E/52102N, 458044E/46561N, 469057E/33436N and 478269E/40466N (Figure 1) in the introduction. The model covers an estimated area of about 20 square kilometers with a constant layer of average thickness of 48 meters considered.

### Model design

By simplifications and assumptions of the actual field condition, the model area was discretized to one layers with a regular grid of (250 m by 250 m, 32 rows by 82 columns) consisting of 1492 active cells.

**Model boundaries:** The expression applied for the head dependent flow in the general head flow boundary in equation 2 is:

$$Q_b = C_b * (h_b - h) \quad (2)$$

Where;

$C_b$  = Hydraulic conductance of the boundary ( $L^2T^{-1}$ )

$h_b$  = Hydraulic head at or beyond the boundary (L)

$h$  = Hydraulic head in the aquifer (L)

The Northern, Western and Eastern boundaries of the model area are generally high relief features/ridges that are assumed to hinder local groundwater inflow into and out the well field and were assigned to be no flow boundaries. Namanve stream cuts through the well field

and flows north wards of the model area. There was lack of discharge data for this stream that hindered determining the river-groundwater interaction for various stress periods. For the purpose of modelling, it was assumed that all other indirect discharge and recharge sources e.g. drains reservoirs are integrated in the areal estimated rainfall recharge and borehole abstraction respectively.

**Initial conditions:** For this case, the static water level records of the wells are averaged within the model to obtain the initial hydraulic heads for the entire model.

**Representation of aquifer parameters:** The vertical and horizontal hydraulic conductivity of the model area was assumed to be uniform at  $0.1756 \text{ m day}^{-1}$  and transmissivity at  $3.275 \text{ m}^3\text{day}^{-1}$ . Storativity or Storage coefficient was estimated to be 0.004 while specific yield was calculated to be 10% of the Specific storage.

All these parameters were assigned based on pumping test and MRS analysis results of this study in relation to previous studies done in similar environments near or far from the study area [6,51]. Later all aquifer parameters were adjusted during the modelling process in order to match the observed water levels in the area.

**Observation wells:** It was hardly possible to obtain a continuous time series monitoring groundwater level data for an independent observational well within in the study area. The three observation boreholes that provided groundwater level monitoring data were as well pumping wells. This implies that the groundwater level data might have been affected by the transient effect of the pumping at the time of water level measurements. Details of the above three wells are highlighted in Table 2. The data of these wells were fed in the model software creating a BOR and OBS file types as described in PMWIN 5.6 manual.

**Borehole abstraction:** Three-year daily abstraction monitoring data was available from three boreholes (DWD 17468; DWD 17465 and DWD 25940). But the total number of regulated abstraction boreholes in the area is 18 boreholes (DWRM permits data base 2014 and Table 2). Each of these boreholes has its own permitted daily maximum volume of abstraction. Considering the permitted maximum volume at each borehole in comparison with the three-year daily abstraction records at the above named three boreholes, the average maximum daily abstraction from all the 18 regulated boreholes in the well field was estimated to be  $2571 \text{ m}^3 \text{ day}^{-1}$ . The three boreholes that have abstraction data were defined in the MODFLOW well package and were used to represent all other the pumping wells. Abstraction of groundwater was assigned to the model as negative and it was assumed that the wells were fully penetrating.

**Recharge:** Rainfall data was used to generate recharge for a period 2013-2015. A daily rainfall threshold of 10 mm and above was considered because it was assumed to be the minimum amount required to overcome evaporation and interception for recharge to occur and also spark runoff. This method was in accordance with the previous work done in Uganda where it was established that rainfall events greater than 10 mm are considered to influence recharge [12,29]. Therefore, this study used 10% recharge from rainfall amounts greater than 10 mm in the years 2013-2016.

### Model calibration

In this case, the field measurements were the observed water levels at the three abstraction/observation boreholes and the target was to match water levels calculated by the model with those measured at the boreholes. However, the field measured heads were definitely associated

S/N	Xcord	Y cord	ID NO	Operator	Permit No	Daily vol (m3d-1)
1	468208	40526	DWD15844	Ridar Hotel Ltd	MN0100717/2GW1DW 2009	30
2	466400	38195	DWD 38183	Roofing Rolling Mills LTD	MNO200940/3WDIDW 2012	56
3	466348	382%	DWD 35578	Roofings Rolling Mills Ltd	MPGI0C077/2GWDDW 2000	6
4	466317	38137	DWD 38184	Roofings Rolling Mills Ltd	MNO200940/2GWIDW 2011	56
5	466509	38256	DWD 35578	Roofings Rolling Mills Ltd-DWD 35578	MNO201110/26W1DW 2013	64
6	466502	4.00E+05	DWD 38183	Roofings Rolling Mills Ltd - DWD 38183	MNO201111/2GWIDW 2013	32
7	466581	38213	DWD 38184	Roofings Rolling Mills Ltd - DWD 38184	MNO201109/2GWIDW 2013	48
8	466369	38042	DWD 39095	Roofings Rolling Mills Ltd - DWD 39095	MNO201116/2GWIDW 2013	
9	466218	38213	DWD39097	Roofings Rolling Mills Ltd - DWD 39097	MNO201129/2GWIDW 2013	48
10	466400	38195	DWD 17468	Rvienzori Bottling Co. Ltd	MN0100664/2GWIDW 2011	1001
11	466348	382%	DWD 17465	Rwenzod Bottling Co. Ltd	MN0100810/2GWIDW 2010	
12	466317	38137	DWD 34040	Rvienzori Bottling Co. Ltd	KLA102109/2GWIDW 2011	208
13	458747	37259	DWD25940	Rbsenzori Bottling Co. Ltd - Namanve	MNO200339/2GWIDW 2004	3601
14	458747	37259	DWD25941	Rvienzori Bottling Co. Ltd- Namanve	MN01339/2GWIDW 2011	360
15	466099	40185	DWD 33678	Rvienzori Bottling Co. Ltd DWD 25940	MN0101664/2GWIDW 2013	100
16	465139	40031	DWD 30370	Century Bottling Ca Ltd	MN0100904/26W1DW 2011	403
17	465139	40031	DWO 30369	Century Bottling Co. Ltd	MN0100903/2GWIDW 2011	38
	466674	40319	DWD 24720	VERO Foods	MN0100904/2GW1DW 2012	130
18	466314	40273	DWD 24195	Irrayi Property Consultants Ltd	MN0100720/2GWDDW 2009	418
Total Volume						2,571

**Table 2:** Details of regulated groundwater abstraction in Namanve well field.

with some major errors to note:

- The static water level measurements used to calculate the heads are normally taken just after well completion without stabilization.
- There were no independent monitoring wells, the water level observations data used came from pumping wells.
- Measurement errors related to measuring instrument accuracy and operator errors.

The combined effect of these errors was assumed to result in a maximum of 15.0m difference between the observed and calculated water levels. The modeling was carried out for the scenarios of non-pumping and pumping.

**Correlation graphs:** A scatter plot of observed water levels against simulated water levels is one way of showing the model fit. The scatter plots are visually examined whether points in a plot deviated from the straight line in a random distribution. Deviation of points from the straight line should be randomly distributed.

**Sensitivity analysis:** The sensitivity analysis was performed by systematically changing one calibrated parameter at a time while noting the observed changes in hydraulic heads. A number of sensitivity analyses were conducted to test the effects on model results due to changes in input parameters or boundary conditions. The values of these input variables e.g. recharge and hydraulic conductivity were multiplied by factors of 0.5, 0.8, 1.1, 1.2 and 1.5. The resulting hydraulic heads for each scenario were graphically compared (Figure 14). The magnitude of change in water levels from the initial model results was the measure of the sensitivity of the model to that particular parameter.

**Model validation:** Unfortunately, it was impossible to validate a model because usually too short set of observed state data was available, which was already used for calibration. For this reason, model validation was not accomplished in this study.

**Simulation of groundwater abstraction in the area:** This was done by trial and error modelling where aquifer hydraulic parameters were varied while comparing the simulated heads to those initially observed in wells. During this process, the hydraulic conductivity, recharge and boundary conditions were modified manually, and trial runs were carried out until the model output (hydraulic heads) were within the range of a reasonable error.

The best fit results were achieved when the estimated recharge value was reduced by 4.5% while hydraulic conductivity values applied in this state was 0.25 m day<sup>-1</sup>. During the pumping scenario, three boreholes that belong to Rwenzori Bottling Company, one of the leading groundwater abstractors in the area were added to the model. The current average abstraction rates per day at each of these boreholes was considered as the initial pumping rate for the pumping scenario. Values for recharge and hydraulic conductivity obtained in the initial non-pumping scenario were maintained. In order to establish the effects of increased groundwater abstraction on the water levels in the area, abstraction at the above three boreholes was gradually increased up to 500% while monitoring the change in the output (simulated water levels). The expected response signal to sustainable groundwater abstraction was considered to be either stable or decreased of the simulated water levels. The maps of spatial distribution of the simulated hydraulic heads for

the non-pumping and pumping scenarios are shown in Figure 11 and Figure 12 respectively.

## Results

### Analysis of the borehole drilling logs and electrical resistivity data

Analysis of the archived drilling logs from 12 boreholes distributed across the study area using ARC GIS v10 generated a 2D cross-section of the stratigraphy of the study area (Figure 4). The cross section was interpreted to consist of two major zones of weathering that include the upper zone also called the saprolite and the lower zone also called the sap rock.

The saprolite has inconsistency occurrences of the following lithological units: top soils, sands, clays and laterites units while the sap rock consists mainly the weathered granitic rock. At the base of the above weathering profile, there is a fractured granitic rock and is present at most of the boreholes considered in the study. The bottom layer of the profile was interpreted to be a massive granitic rock and only a few boreholes were drilled up to the depth of this rock unit (DWD 21777; WDD 25940; DWD 18300 and DWD 21827).

The eastern part of the cross section area represented by boreholes in Seeta, Mukono and Mbalala shows fairly uniform and continuous distribution of lithological units (clays, weathered granitic and the fractured granitic rocks). The western part of the cross section area is represented by boreholes in Bweyogerere and Namanve areas that shows increased vertical and horizontal variation in the lithological units e.g. the laterites and sands in boreholes (WDD25940 and DWD 2177). Surface water levels (SWL) and borehole construction details obtained from the borehole logs information indicate that the weathered granitic rock and the fractured bedrock are the main saturated geologic units in the area.

Groundwater in these units (aquifers) occurs under confined and semi confined conditions mainly because of the presence of the semi impervious clay and laterite units and percolates from the upper weathered zone aquifer into the lower fractured zone aquifers. The main aquifer storage in the area appear to be confined in the fractured bedrock zone because all boreholes in the area have been drilled to a depth below the upper weathered zone/aquifer. The massive and impermeable granitic bedrock below the fractured zone acts as a barrier to vertical groundwater percolation in the area.

Correlation of borehole drilling logs and geo-electric resistivity (VES) data interpreted using 1x1D v3 software at three borehole sites (DWD 18300; DWD 30368 and DWD 30283) delineated three major stratigraphic units in the well field (Figures 5, 6 and 7). The top stratigraphic layer ranges from (~5 to ~10 mbgl) and most times consists of thin inter-beds/layers of top soils, clays, sands and laterites that display one to three micro-layering in the VES model.

This layer has an averagely low apparent resistivity ranging from 10 to ~80  $\Omega$ -m. The next stratigraphic layer ranges from (~12 to ~65 mbgl) with a slightly low apparent resistivity ranging from ~30 to ~150  $\Omega$ -m. This layer may be interpreted to consist of the saturated weathered and fractured bed rock units hence the low recorded apparent resistivities. Lastly is the bottom layer that has a very high apparent resistivity (above 1,000  $\Omega$ -m) and corresponds to the massive and impermeable bedrock of igneous origin that occurs at an average depth of ~60m but its thickness could not be specified by the VES layer model.

### Hydraulic properties of aquifers

**Pumping tests data analysis:** Pumping test data was analyzed using AQUISSOLVE software to generate aquifer hydraulic properties e.g. transmissivity and storage coefficients for the aquifers in the area. Pumping of most wells caused a greater influence on the draw down in the first few minutes of pumping but the influence generally reduced with increasing duration of pumping (Figures 8 and 9). This effect caused the draw down response curves deviate from the perfect confined aquifer drawdown type curves as presented by Theis [52] much as the studied hydro-stratigraphy of the area was indicative to confine or semi confined aquifer conditions. For this reason, effects of boundary conditions e.g. specific head boundaries such as adjacent surface water bodies and leakages within the penetrated formations [21,53] were assumed. Field observation from the study area confirmed the above assumption where the presence of minor streams e.g. River Namanve were noted in the area. Basing on this background knowledge, several AQUISSOLVE aquifer analytical solutions were fitted to test the suggested hypothesis but aquifer solutions that take into account well bore storage effects and leaky conditions were mostly adopted to represent the response of the aquifers in the area.

Table 3 presents the hydraulic parameters obtained from different model curve matching fits. Since there were several models that could try to fit the observed data within a given uncertainty range, the values for the best match fit for each pumping test data set has been presented.

The aquifers in the area presented generally low values of aquifer hydraulic properties that varied in a non-uniform manner. The current mean transmissivity values of the study area was estimated to be about 3.275  $\text{m}^2 \text{day}^{-1}$  while the mean hydraulic conductivity (calculated from the equation:  $K = \frac{T}{b}$  where:  $K$  = Hydraulic conductivity,  $T$  = Transmissivity and  $b$  = Aquifer thickness) was estimated to be 0.0574  $\text{m}^2 \text{day}^{-1}$ . The Average Storativity or storage coefficient generated from the AQUISSOLVE software was 0.004 but was further refined using of MRS method.

The low values of aquifer hydraulic properties and their non-uniform variation respectively suggest low primary porosity and geologic heterogeneity in crystalline rock aquifers as suggested by Chilton and Foster [22]. The obtained hydraulic parameters closely match with values estimated by Tindimugaya [6]. However, the same parameter values are quite higher than those suggested in other parts of Uganda with similar geological environments [5,54].

### Aquifer storage parameters using MRS

Aquifer storage of the upper weathered zone mainly rely on rainfall recharge while the fractured lower bedrock aquifers partly rely on the vertical leakage from the weathered overburden [6], but also from the horizontal flow through the interconnected fracture system. MRS raw data for one sounding site within the study area was used alongside pumping test data to estimate the aquifer storage in the area. The interpreted MRS results at this site were parametrized (Table 4) using pumping test data for a borehole adjacent to the sounding site hence aquifer storage was determined (Table 6).

**Interpreted pumping test data for a borehole adjacent to the MRS sounding site:** The pumping test data was for a period of 72 hours and was interpreted using AQTESOLTM/Pro V4.5 software and results are presented in Table 5 below.

### Calculation of un-parametrized MRS aquifer parameters:

$$\text{MRS Transmissivity is given by: } T_{\text{MRS}} = \theta(T_2^*)^2 \cdot \Delta Z$$
$$0.061 \times (0.7)^2 \times 31 = 0.9269 \text{ms}^2$$

Boreholes		Pumping test data records		Aquifer properties			Best matching Pumping test Solution	Aquifer zone
No.	Location	Rate (m <sup>3</sup> /h)	Duration (hours)	T (m <sup>2</sup> /day)	K (m/day)	S		
<b>Namanve</b>								
1	Rwenzori1	3.4	72	0.610	0.0145	0.00034	Neuman (1969)	RF
2	Rwenzori 2	5.5	72	1.320	0.0307	0.00091	Neuman (1969)	RF
3	Rwenzori 3	3	72	0.760	0.0107	0.00006	Papadopoulos	F
4	Roofings 1	3	72	10.34	0.5574	0.0011	Theis (1935)	RF
5	Roofings 2	3	72	0.728	0.0234	1.78 × 10 <sup>-5</sup>	Neuman (1979)	F
6	Sai Bev.	2	69	0.867	0.196	0.00069	Moench (1984)	F
7	Cent Bott 1	22.38	72	23.36	0.865	0.00042	Cooper-Jacob (1946)	RF
8	Cent Bott2	2.12	72	0.4917	0.00983	0.00981	Papadopoulos	F
9	Vero Bev	6.5	72	5.656	0.1824	1.21 × 10 <sup>-7</sup>	Moench (1984)	RF
<b>Mukono</b>								
10	Fore Front	2.05	18	1.514	0.0378	0.00426	Papadopoulos (1967)	F
11	Boss Bev	1.01	12	0.8097	0.026	0.00117	Papadopoulos (1967)	F

Key = RF- Regolith and fracture rock aquifers, F-Fractured rock aquifers

Table 3: Summary table of aquifer hydraulic properties in the study area.

Estimated MRS Parameters			
ΔZ (m)	θ%	T <sub>2</sub> * (ms)	(T <sub>2</sub> *) <sup>2</sup> (ms)
24.1	6.1	70	4900

Table 4: Summary of the estimated MRS parameters at roofing rolling mills site.

Aquifer property	Aquifer solution		Average
	Leaky	Unconfined	
Transmissivity (m <sup>2</sup> s <sup>-1</sup> )	1 × 10 <sup>-5</sup>	8.425 × 10 <sup>-6</sup>	9.125 × 10 <sup>-6</sup>
Storativity	1.477 × 10 <sup>-5</sup>	1.786 × 10 <sup>-5</sup>	1.631 × 10 <sup>-5</sup>
Specific yield (%)	-	0.04093	0.04093

Table 5: Summary of pumping test data interpretation at roofing rolling mills.

MRS Storage is given by:  $S_{MRS} = \theta \cdot \Delta Z$

$$0.061 \times 31 = 1.891$$

#### Parametrizing of the MRS results using pumping test results

$$T_{MRS} \cdot K = Tpt$$

where;  $T_{MRS}$  is MRS Transmissivity, K is Constant,  $Tpt$  is pumping test transmissivity.

$$K = \frac{Tpt}{T_{MRS}} = \frac{9.12 \times 10^{-6}}{0.9269} = 9.893 \times 10^{-6}$$

$$T = 9.893 \times 10^{-6} \cdot \theta_{MRS} \cdot (T_2^*)^2 \cdot \Delta Z$$

**Comparison of MRS and pumping test results:** The estimated  $T_{MRS}$ ,  $Sy_{MRS}$  and compares closely with the transmissivity and the specific yield estimated from pumping test (Table 7).

The major limitation of these results was the unfavorable MRS noisy conditions in the area that hindered carrying out more soundings at any other suitable location in the area hence a more accurate link between MRS measurements and pumping tests in the study area could not be achieved due to the limited number of MRS sounding sites.

#### Calculating the estimated MRS aquifer storage

$$MRS \text{ storage} = S_y \cdot \Delta Z$$

$$S_y = \theta_{MRS} \cdot K = 0.04093 = 0.061 \times K$$

Estimated MRS Parameters				Estimated pumping test Parameters		
ΔZ (m)	θ%	T <sub>2</sub> * (ms)	(T <sub>2</sub> *) <sup>2</sup> (ms)	T (m <sup>2</sup> s <sup>-1</sup> )	S	S <sub>y</sub>
31	6.1	70	4900	9.125 × 10 <sup>-6</sup>	1.631 × 10 <sup>-5</sup>	0.04093

ΔZ is the aquifer transmissivity,  $T_2^*$  is the water content in % volume,  $T_2^*$  is the decay time of the MRS signal.

Table 6: Summary of both MRS and pumping tests results at roofing.

Method	Aquifer parameters	
	Transmissivity (m <sup>2</sup> s <sup>-1</sup> )	Specific yield
MRS	9.116 × 10 <sup>-6</sup>	0.04093
Pumping test	9.125 × 10 <sup>-6</sup>	0.04093
Relative difference	0.01 %	0%

Table 7: Comparison of MRS and pumping test results.

$$MRS \text{ storage} = K \cdot \theta_{MRS} \cdot \Delta Z = 0.671 \times 0.061 \times 24.1 = 0.98644$$

$$= 0.670$$

$$MRS \text{ storage} = K \cdot \theta_{MRS} \cdot \Delta Z = 0.671 \times 0.061 \times 24.1 = 0.98644$$

$$\text{Hence, MRS Storage} = 986.44 \text{ mm}$$

**Comparison of MRS results in Uganda and Benin under same geological environment:** Vouillamoz [51] used numerous data sets from MRS and pumping test results in the basement rocks of western Africa (Benin) to estimate aquifer hydraulic properties and he has defined the relation between the two sets of data using equations (3) and (4)

$$Sy_{MRS} = 0.52 \cdot \theta_{MRS} + 0.0097 \quad (3)$$

$$T_{MRS} = 3.10^{-9} \cdot \theta_{MRS} \cdot T_2^{*2} \cdot \Delta Z \quad (4)$$

Using equation (1),  $Sy_{MRS}$  at Roofing Rolling Mills can be calculated as;

$$Sy_{MRS} = 0.52 \times 0.061 + 0.0097 = 0.0414$$

Using equation (1),  $Sy_{MRS}$  at Roofing Rolling Mills can be calculated as;

$$T_{MRS} = 3 \times 10^{-9} \times 0.061 \times 0.49 \times 24 = 2.1 \times 10^{-9}$$

Using equation (2)  $T_{MRS}$  at Roofing Rolling Mills can be calculated as:

$$T_{MRS} = 3 \times 10^{-9} \times 0.061 \times 0.49 \times 24 = 2.1 \times 10^{-9}$$

### Comparison of the MRS results in Uganda and Benin

In comparison of Uganda to the Benin scenario, the MRS results of this study presented a certain degree of linkage with pumping test results that can be improved by carrying out more MRS measurements in the study area in order to confirm the conclusion (Table 8) above.

### Model Conceptualization

Despite of the heterogeneous hydrogeological conditions in the area, a simplified conceptual hydrogeological model (Figure 10) of the area was developed on the basis of information from the geology, hydrogeology and hydrology. The model was however based on a number of assumptions in order to reduce the real hydrogeological system into a simplified version but acceptable in view of its validity to represent the important hydrogeological conditions and the objectives of the study.

### Demonstrating sustainability of groundwater abstraction in the area

This was undertaken by simple numerical modelling. The main output of the of the numerical modelling was simulated ground water levels under variable major input parameters conditions that include; rainfall recharge and pumping rates. The response signal for sustainable groundwater abstraction was either stable or decreased simulated groundwater levels. Stability of the simulated groundwater levels indicated sustainability of groundwater abstraction in the area while the decrease in the simulated groundwater levels indicated vise-versa. The maps of spatial distribution of the simulated water levels for the non-pumping and pumping scenarios in Namanve area are shown in (Figures 11 and 12) respectively. The results are also graphically presented as comparisons of the observed and simulated hydraulic heads in both cases of non-pumping and pumping scenarios (Figures 13 and 14).

The modelling results shows that most of the simulated heads were within the pre-established calibration target and the overall results of the groundwater model are comparable with the measured well data and in agreement with conceptual model.

**Model sensitivity graphs:** It was found out that slight changes in rainfall recharge rate affected the distribution of water levels in the model more as compared to the hydraulic conductivity hence the model is more sensitive to recharge fluxes than hydraulic conductivity changes (Figure 14).

**Groundwater budget:** The input term to the groundwater

Method	Aquifer parameters	
	Transmissivity ( $m^2s^{-1}$ )	Specific yield
MRS Uganda-calculated	$9.116 \times 10^{-6}$	0.04093
MRS-Benin equation	$2.1 \times 10^{-9}$	0.0414
Relative difference	9.76%	1.135%

Table 8: Figures of MRS results in Uganda and Benin.

considered for the present study is a direct recharge from rainfall. The output terms considered are well withdrawals and head dependent, groundwater flows out of the aquifer system through the southern boundary. The groundwater flow budgets calculated by the model for the non-pumping and pumping scenarios are indicated in Table 9 and Table 10 respectively.

### Model predictions

Scenario groundwater level simulations were undertaken by increasing the monthly abstraction rates at each well by 20%, 50%, 100%, 200% and 500% while maintaining all other parameters constant. Significant change (decrease) in the water levels was not realized until the pumping rate at the wells was increased up to 500% of the current monthly pumping rate. The resulting water levels generated from this simulation is indicated in Figure 15.

In this scenario, decrease in the hydraulic head was calculated to be 10%. The abstraction rate at which lowering of groundwater levels started indicates that there is still a high potential of groundwater abstraction in the area without causing any serious stressful conditions.

**Reliability of the model results:** There are several indicators that the overall result of the model developed are realistic.

- There is a minimal deviation of the simulated heads from the observed heads.
- The model calculated inflow and outflow terms are balancing.
- Groundwater flow direction simulated by the model is reasonable and in agreement with the flow direction defined in the conceptual model.

**Limitations of the model:** Nevertheless, there are a number of limitations and uncertainties because numerical models are basically limited in their representation of the physical groundwater flow system. The built model of this research can therefore be associated with uncertainties such as; the hydro geological heterogeneity that caused difficulties in the conceptual simplification of the field conditions due to lack of detailed description of the heterogeneity. Assumptions and simplifications were therefore made during the conceptualization of the system. Definitely there were uncertainties that were introduced in as the result of these assumptions and simplifications because various forms of heterogeneity in the porous media can have different fluid flow behavior in the individual zones [55]. There were generally few locations where hydrogeological observations were available and the geological structure of the aquifer was only partially known. Groundwater abstraction in the area is poorly documented and the little recorded data has quite a number of inconsistencies. The operating periods of the boreholes are also not well known; thus, it was difficult to get the accurate borehole abstraction rate from the area.

Lack of proper site characterization could also have resulted in a model that does not representative the actual field conditions. Other main constraints include; data gaps and poor quality of the available data.

The data which have a key role in defining the model geometry (screen length and aquifer thickness) are not well documented. The available records of the water level measurements were continuous for only 3 years and were highly associated with measurement errors.

There was no sufficient independent data for model calibration or validation. Defining the boundary conditions of the model domain also presented uncertainties because it was done based on physical features

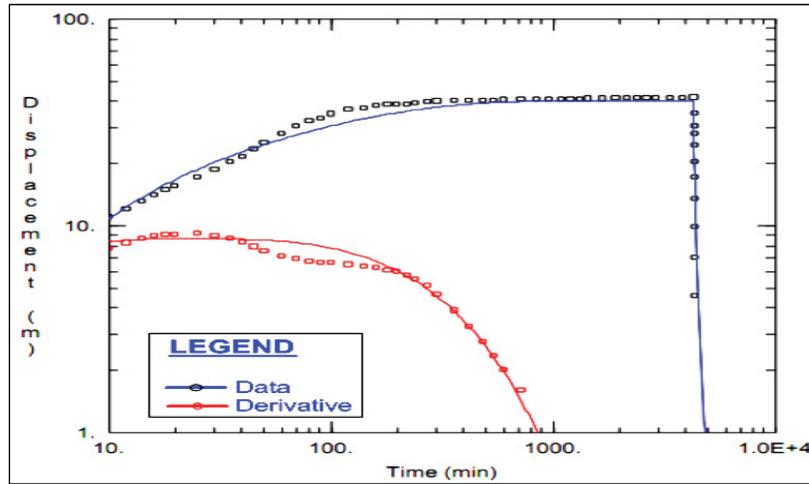


Figure 9: Rwenzori 1 : Leakey Aquifer solution - Neuman-Witherspon.

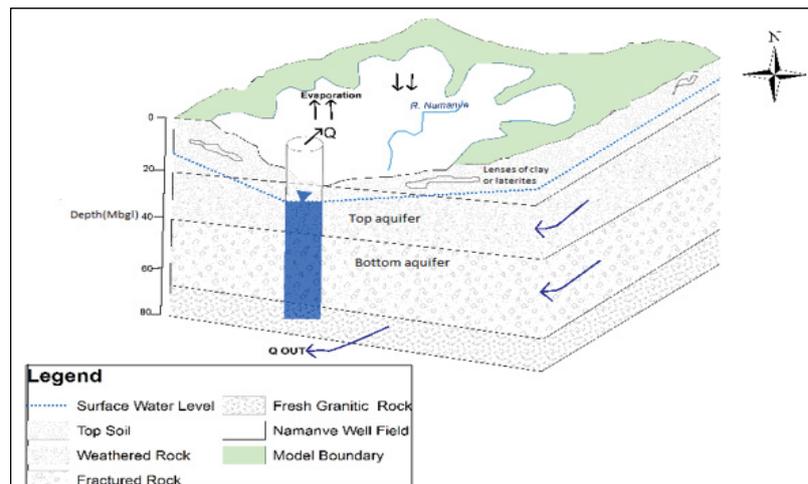


Figure 10: Conceptual model of the area.

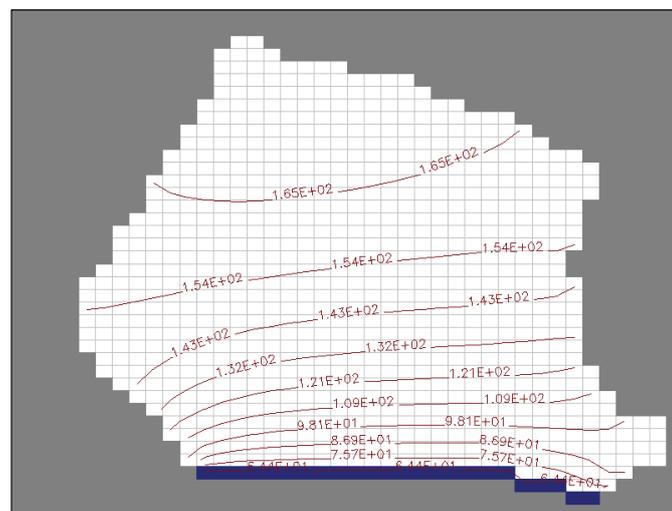


Figure 11: Distribution of hydraulic heads with non-pumping scenario.

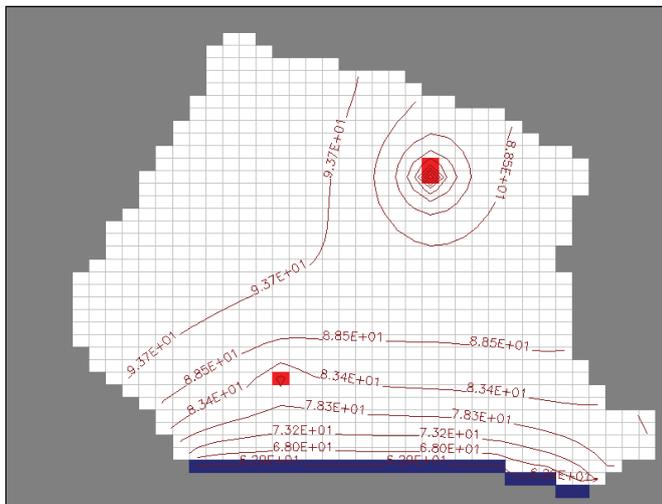


Figure 12: Distribution of hydraulic heads with pumping scenario.

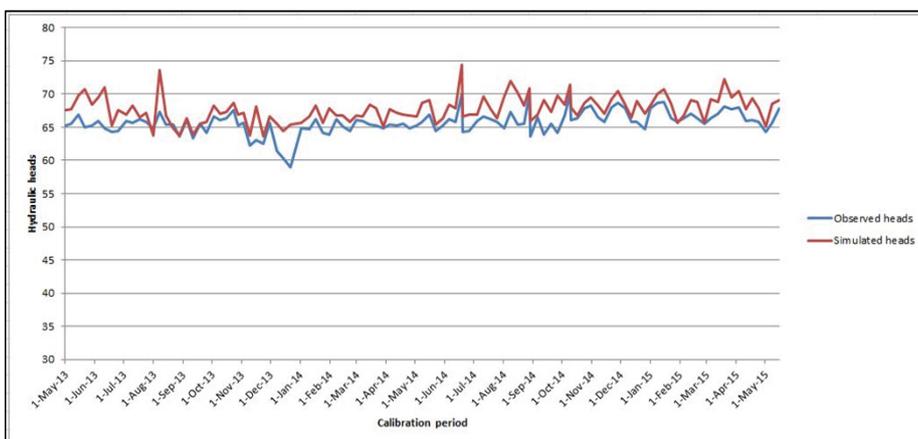


Figure 13: Correlation of the observed and simulated heads in the pumping scenario DWD 25940.

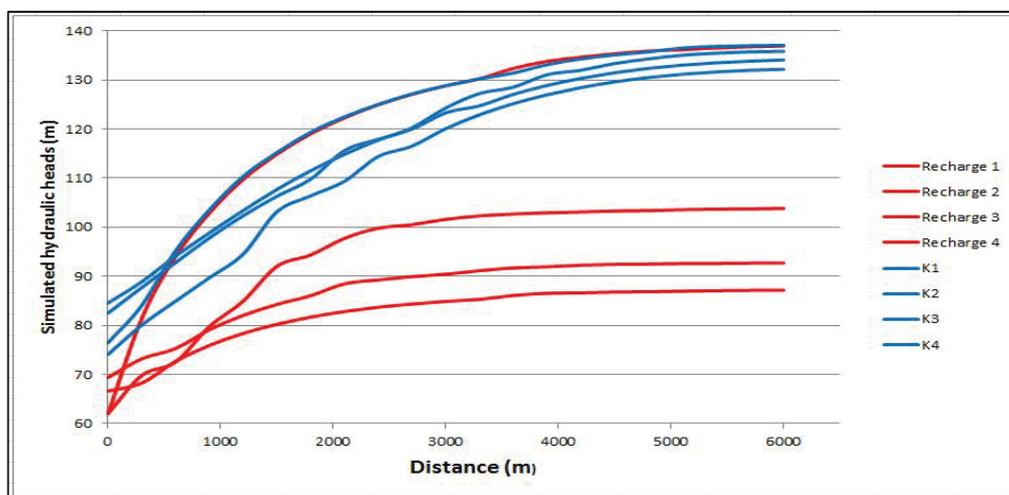


Figure 14: Sensitivity model with respect to recharge and hydraulic conductivity variations.

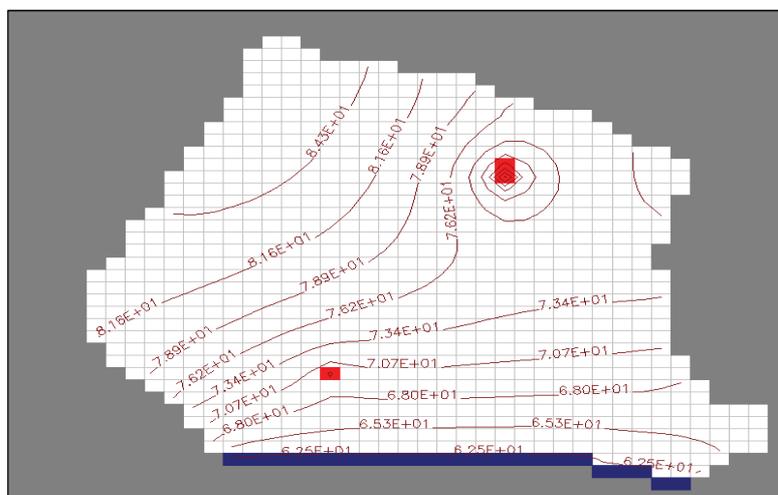


Figure 15: Distribution of hydraulic heads at 500% increase in the abstraction rate at the wells.

Flow Term	In (m <sup>3</sup> /day)	Out (m <sup>3</sup> /day)	In-Out (m <sup>3</sup> /day)
Head dependent flow through the southern boundary	0	15039	-15039
Wells	0	0	0
Recharge	15039	0	15039
Total	15039	15039	0

Table 9: Simulated groundwater budget for non- pumping scenario.

Flow Term	In (m <sup>3</sup> /day)	Out (m <sup>3</sup> /day)	In-Out (m <sup>3</sup> /day)
Head dependent flow through the southern boundary	0	14514	-14514
Wells	0	525	-525
Recharge	15039	0.0000	15039
Total	15039	15039	0

Table 10: Simulated groundwater budget for pumping scenario.

in the area, yet the extent of the well field/sub catchment may not coincide with the surface expressions of these features.

The lack of model input data e.g. the base flow through the aquifer, evapotranspiration and runoff may also contribute to a number of uncertainties. The area was conceptualized as a single layer assuming impermeable basement rock at the base of the layer. In reality, this may not be true because the bottom of the layer may be partially pervious due to localized fractures.

## Conclusion

Sustainability of groundwater abstraction in the area was investigated by use of combined methods of hydrogeological data analyses and numerical modelling. The study noted that stratigraphy of the area is highly heterogeneous in both lateral and vertical extent and is made up of permeable and less permeable geologic units that include, top soils, sands, clays, laterites and fractured/fresh granitic rocks. The area has two aquifers systems the top aquifer that occurs in the weathered overburden and the lower aquifer that occurs in the fractured bedrock. The latter aquifer is the main/ principal aquifer in the area as it was noted that all boreholes in the area were drilled up to its depth despite of the initial water strikes encountered in the top aquifer system. The occurrence of the impermeable and semi permiable layers in the stratigraphical sequency of the area presented both confined and semi

confined aquifer systems in the area. In response to the geological heterogeneity, broad ranges of aquifer parameters (transmissivity and hydraulic conductivity) are reported from the results of pumping test analysis. However, in a general sense, the area is characterised by low values of hydraulic parameters as a result of low porosity values in the crystalline basemet rocks. Despite of the heterogeneous hydrogeological condition in the area, a simplified conceptual hydrogeological model of groundwater system was constructed and was implemented in the numerical modelling within the same study. A numerical groundwater flow model was developed a non-pumping and pumping scenarios to assess the groundwater resource sustainability in the area.

The model simulated a mean annual recharge of 42 mm year<sup>-1</sup>. The accuracy of the model recharge is dependent on annual recharge values obtained by other authors in Uganda. A steady-state groundwater flow modeling has demonstrated that an average recharge of 42 mm year<sup>-1</sup> maintains the natural equilibrium. On the other hand, the model results with pumping scenario show that the current estimated groundwater abstraction of 2175 m<sup>3</sup> day<sup>-1</sup> in the area has resulted in a groundwater level decline of up to 38.3 meters in the well field and the decline will increase with increased abstraction.

## Further Study Areas

This preliminary research forms a good starting work for detailed groundwater water assessment in the study area. With additional data, further refinement of this

research is possible and can be expected to improve the accuracy of the results. Therefore, extensive field-based hydrological and hydrogeological data acquisition and observations using various geological and geophysical techniques are necessary in order to delineate a detailed hydrogeological framework for the study area. Furthermore, groundwater modelling in the area under study require detailed geological structural mapping in order to characterize the aquifer systems in the area and re-define the boundary conditions. In the present study, only the deeper aquifer system is modeled as there is no data for the shallow aquifer system, thus future studies should consider the upper aquifer system and study the relation between the two aquifer systems together with the regional groundwater flow in the area. The hydraulic conductivity and recharge to which the model is highly sensitive requires better future refinement and finally the cell size applied in the discretization of the model domain (250 m by 250 m) is not small enough to adequately represent the drawdown in the wells. Thus, the model can be further improved by integrating additional data and by applying finer grids in the pumping areas.

Finally, I do advise in considering the following actions in relation to groundwater resources development in the well field: Future actions on groundwater resource development plans in the well field should take into account the balance between the groundwater recharge and the intended abstraction rates to ensure the sustainability of the resource in the catchment; and In order to reduce the groundwater stress resulting from localized pumping, drilling of boreholes should be evenly be distributed within any area under study.

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### References

- Freeze RA, Cherry JA (1979) *Groundwater*; Prentice-Hall, Inc. Englewood Cliffs, New York, USA. pp: 604.
- Morris B, Lawrence ARL, Chilton PJC, Adams B, Calow RC, et al. (2003) *Groundwater and its susceptibility to degradation: A global assessment of the problem and options for management* 2: 1.
- USGS Professional Paper (2013) *Global groundwater availability* 1766: 225.
- MacDonald A, Davies J, Calow R, Chilton J (2005) *Developing groundwater: A guide for rural water supply*; ITDG Publishing pp: 301-358.
- Taylor RG, Howard KWF (1998) *Post-Palaeozoic evolution of weathered land surfaces in Uganda. by tectonically controlled deep weathering and stripping. Geomorphology* 25: 173-192.
- Tindimugaya C (2008) *Groundwater flow and storage in weathered crystalline rock aquifer systems of Uganda: Evidence from environmental tracers and aquifer responses to hydraulic stress*. Unpublished Ph.D. Thesis. University College London, London, UK. pp: 157.
- Tindimugaya C (2005) *Maximizing the benefits from water and environmental sanitation: Groundwater resources management in urban areas of Uganda; experiences and challenges*. Proceedings of 31st WEDC International Conference, Kampala, Uganda.
- WSP/NWSC (2008) *Identification of management options for improved water and sanitation services in informal settlements in Kampala, Situational Assessment Report for Water and Sanitation Programme*. National Water and Sewerage Corporation pp: 140.
- DWRM (2015) *Water and environment sector Performance Report 2015 Permits Data Base*.
- Batte A, Muwanga A, Sigrist P, Wowor M (2008) *Vertical electrical sounding as an exploration technique to improve on the certainty of groundwater yield in the fractured crystalline basement aquifers of eastern Uganda. Hydrogeology Journal* 16: 1683-1693.
- Batte A, Barifajjo E, Kiberu JM, Kawule W, Muwanga A, et al. (2010) *Correlation of geoelectric data with aquifer parameters to delineate the groundwater potential of hard rock terrain in central Uganda. Pure Appl. Geophys* 167: 1549-1559.
- Owor M, Taylor RG, Tindimugaya C, Mwisigwa D (2009) *Rainfall intensity and groundwater recharge: Empirical evidence from the Upper Nile Basin. Environ. Res Lett* 4: 035009.
- Brassington R (1998) *Field hydrogeology (Second edition)* Wiley & Sons, Chichester pp: 372.
- Jusseret S, Vu TT, Dassargues A (2009) *A groundwater flow modelling in the central zone of Hanoi, Vietnam. Hydrogeol J* 17: 915-934.
- Fetter CW (2001) *Applied hydrogeology, Visual Modflow, Flownet and Aqtesolv student version software on CD - ROM (4th edn)*. Upper Saddle River: Prentice Hall.
- Scanlon BR, Mace RE, Barrett ME, Smith B (2003) *Can we simulate regional groundwater flow in a karst system using equivalent porous media models? Case study, Barton Springs Edwards aquifer, USA. Hydrogeol J* 276: 137-158.
- Ministry of Local Government (2007–2008) *Uganda Districts Information Handbook, Expanded edition*.
- DWRM (2014) *Mapping of groundwater resources in Uganda: Mukono district groundwater report, Kampala. European Union Water Facility* pp: 67.
- Mukono District (2009). *Five-year District Investment Plan, 2009-2014*; Ministry of Local Government, Unpublished Report pp: 212.
- Biryabarema M (2001) *Groundwater contamination and the role of geologic strata in retaining pollutantants around waste disposal sites in greater Kampala*. PhD thesis, Makerere University, Kampala, Uganda.
- Davis NS, De-Wiest JMR (1966) *Hydrogeology*. John Wiley Sons, New York, USA. pp: 428.
- Chilton PJ, Foster SSD (1995) *Hydrogeological characterization and water supply potential of basement aquifers in tropical Africa. Hydrogeol J* pp: 36-49.
- Taylor RG, Barrett M (1999) *Urban groundwater development in sub-Saharan Africa*. IN: Pickford, J. (ed). *Integrated development for water supply and sanitation: Proceedings of the 25th WEDC International Conference*, Addis Ababa, Ethiopia pp: 203-207.
- Chilton PJ, Smith-Carrington AK (1984) *Characteristics of the weathered basement aquifer in Malawi in relation to rural water supplies. Presentation on Challenges in African Hydrology and Water Resources Symposium, IAH Series Publication* 144: 15-23.
- Houston FT, Lewis RT (1988) *The Victoria Province drought relief project II; Borehole yield relationships; Groundwater* 26: 418-426.
- Howard WFK, Arundu J (1992) *Constraints of the development of basement aquifers in East Africa- water balance implications and the role of the regolith. J Hydrol* 139: 183-196.
- Howard AD (1994) *Bad lands in Geomorphology of Desert Environments*, Edited by A. Abrahams and A. Parsons, Chapman and Hall, London pp: 213-242.
- Taylor RG, Howard WFK (1999) *Lithological evidence for the evolution of weathered mantles in Uganda by tectonically controlled cycles of deep weathering and stripping. Catena* 35: 65-94.
- Taylor RG, Howard WFK (1996) *Groundwater recharge in the Victoria Nile basin of East Africa: support for the soil-moisture balance method using stable isotope and flow modelling studies. Hydrogeol J* 180: 31-53.
- Tindimugaya C (2000) *Assessment of groundwater development potential for Wobulenzi town, Uganda*. Unpublished MSc, UNESCO- IHE, Delft, The Netherlands.
- Anderson MP, Woessner WW (1992) *Applied groundwater modelling: Simulation of flow and Adjective transport*. San Diego: Academic Press 15: 167-173.
- Yuri M, Christopher G, Henkar U (2004) *Development and Application of a MODFLOW preprocessor using percolation theory for fractured media. J Am Water Resour Assoc* 40: 229–239.
- Nyende J, Vermeulen VTG (2013) *Conceptual and numerical model development for groundwater resources management in a regolith-fractured-basement aquifer system. J Earth Sci Clim Change* 4: 156.
- Klismas A, Gregorauskas M (2002) *Groundwater abstraction and contamination in Lithuania as geoindicators of environmental change. Environ Geol* 42: 767-772.
- Harvey JW, Bencala KE (2004) *The effect of groundwater over abstraction in the mountainous catchments within the Basement aquifers of tropical Africa. Water Resour Res* 29: 89-98.
- Carrera-Hernandez JJ, Gaskin SJ (2006) *The groundwater modeling tool for GRASS (GMTG): Open source groundwater flow modeling. Computers & Geosciences* 32: 339-351.
- Legchenko A, Valla P (2002) *A review of the basic principles for proton magnetic resonance sounding measurements. J Appl Geophys* 50: 3-19.

38. Lubczynsky MW, Roy J (2003) Hydrogeological interpretation and potential of the new magnetic resonance sounding (MRS) method. *Hydrogeol J* 283: 19-40.
39. Schirov M, Legchenko A, Creer G (1991) A new direct non-invasive groundwater detection technology for Australia. *Explor Geophys* 22: 333-338.
40. Vouillamoz JM, Sokheng S, Bruyere O, Caron D, Arnout L (2012) Towards a better estimate of storage properties of aquifer with magnetic resonance sounding. *Hydrogeol J* 458: 51-58.
41. Lawson, FMA, Vouillamoz JM (2014) Application of the Magnetic Resonance Sounding (MRS) method to characterize aquifers in Uganda: Result of a fieldwork carried out in Uganda from the 5th of March to the 3rd of May 2014; unpublished report pp: 31.
42. Cooper H, Jacob C (1946) A generalized graphical method for evaluating formation constants and summarizing well-field history, *AGU*: 27: 256-354.
43. Sandow M, Obed FF, Larry PC, Daniel KA (2013) Hydrogeological conditions of a crystalline aquifer: Simulation of optimal abstraction rates under scenarios of reduced recharge. *Sci World J* pp: 1-8.
44. Yihdego Y (2005) Three dimensional ground water model of the aquifer around Lake Naivasha area, Kenya. Unpublished MSc Thesis, ITC, Enschede.
45. Westerhof AB, Paavo H, Isabirye E, Katto E, Koistinen T, et al. (2014) Geology and geodynamic development of Uganda with explanation of the 1: 1,000,000 -Scale Geological Map; Geological Survey of Finland Special Paper.
46. Owor M, Taylor RG, Mukwaya C, Tindimugaya C (2011) Groundwater - surface water interactions on deeply weathered surfaces of low relief: evidence from Lakes Victoria and Kyoga. *Hydrogeol J* 19: 1403-1420.
47. Gebregziabher B (2003) Integrated geophysical methods to investigate the geological structures and hydrostratigraphic unit of the Aynalem area, Southeast Mekelle. MSc thesis Addis Ababa University, Ethiopia.
48. Hussien K (2000) Hydrogeology of Aynalem Wellfield, Tigray, Northern Ethiopia. Unpublished Msc. thesis, Addis Ababa University, Ethiopia.
49. Harbaugh AW, Banta ER, Hill MC, McDonald MG (2000) MODFLOW-2000, the US Geological Survey Modular groundwater model: User guide to modularization concepts and groundwater flow processes: US Geological Survey, Reston, VA, USA.
50. Vouillamoz JM, Lawson FMA, Yalo N, Descloitres M (2014) The use of magnetic resonance sounding for quantifying specific yield and transmissivity in hard rock aquifers: The example of Benin. *J Appl Geophys* 107: 16 - 24.
51. Theis CV (1935) The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. *Am Geophys Union Trans* 16: 519-524.
52. Kruseman G, De-Ridder S (2000) Analysis and Evaluation of pumping test data. International Institute for land reclamation and Improvement (ILRI) Wageningen. pp: 377.
53. Howard K, Hughes M, Charlesworth D, Ngobi G (1992) Hydrogeologic evaluation of fracture permeability in crystalline basement aquifers of Uganda. *Applied Hydrogeology* 1: 55-65.
54. Vouillamoz JM, Sophoeun P, Bruyere O, Arnout L (2014) Estimating storage properties of aquifer with MRS: A field verification in Northern Cambodia of the gravitational water apartment cutoff time concept. *Near Surf Geophys* 12: 211-216.
55. Das DB, Lewis M (2007) Dynamics of fluid circulation in coupled free and heterogeneous porous domains. *Chem Eng Sci* 62: 3549-3573.