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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. The final modeling results demonstrated that an average recharge of 42 mm year/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 m³day⁻¹ 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.

Keywords:- Hydrogeology, continuity, geophysical methods, simplification, reduced levels, industrialization.

1.0 INTRODUCTION

Groundwater is defined by Freeze & Cherry (1979) 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 (Morris et al., 2003). Recent figures from the United States Geological Survey (USGS) (2013) 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 (MacDonald, 2005; Tindimugaya, 2008). 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 (Tindimugaya 2005), 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 12Km 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 (WSP/NWSC, 2008). 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 (DWRM permits data base, 2015).

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.

2.0 Study Area Setting

Kampala Industrial and Business Park-Namanve is located about 12km 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 15sqkm 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.

2.1.0 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. (Ministry of Local Government, Districts Information Handbook, 2007–2008). 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 (DWRM, 2014). 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 (Mukono District Plan, 2009).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-trondhjemitegranodiorite/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.

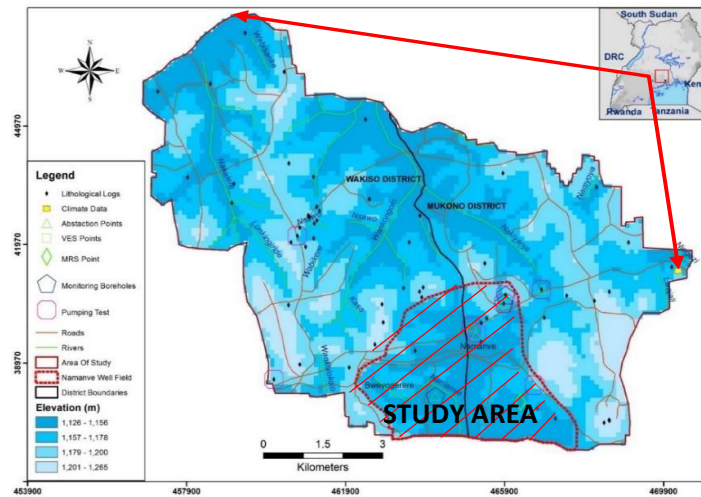


Figure 1: Map of the study area

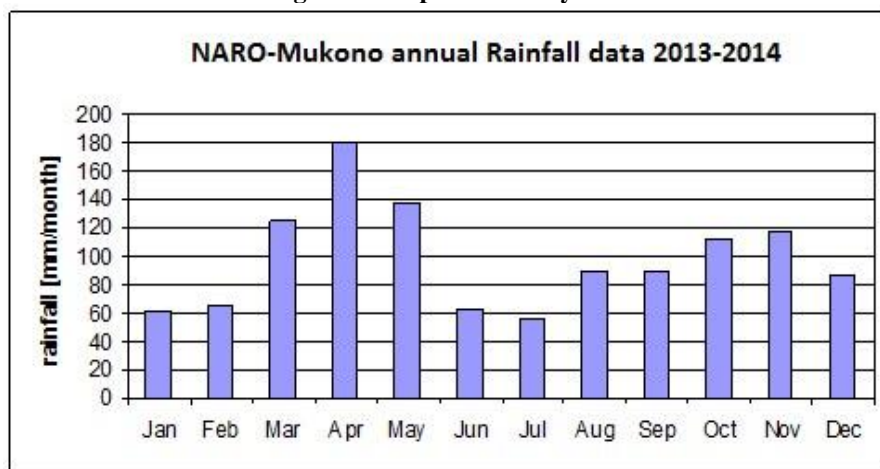


Figure 2: Mean Monthly distribution of rainfall in 2013-2014 (DWRM 2014)

b) 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 (Biryabarema, 2001).

3.0 Materials and Methods

3.1.0 Materials

Groundwater occurs in the crystalline rock aquifers in various continents of the world that include Africa, Asia and South America (Morris et al., 2003). Crystalline basement rocks are known to form the oldest rocks of igneous origin such as granotoids and gneisses. The age of these rocks ranges between 2.75-2.55Ga and have little or no primary porosity (Davis and DeWiest, 1966). Groundwater in these rocks is normally present in the fractures or the overlying weathered overburden.

3.1.1 Studies in the crystalline basement rock aquifers in Uganda

Geohydrological 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 (Howard and Karundu, 1992). 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.

3.1.2 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 (Howard, 1994). Aquifers occur in the fractured bedrock and at the

base of unconsolidated overburden where coarser bedrock fragments predominate. The occurrences of groundwater in these aquifers depend on the thickness of the weathered zone normally 10-90m (Tindimugaya, 2008) and this zone is anisotropic characterized by permeability and porosity that vary with depth (Chilton and Foster, 1995). Porosity and permeability of the bed rock depend mainly on the nature of the formation and the extent of fracturing (Tindimugaya, 2008).

3.1.3 Hydrogeological conceptual model

The equivalent porous medium (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 (Nyende et al., 2013).

3.1.4 Aquifer system to increased groundwater abstraction

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 (Harvey & Bencala, 2004).

3.2.0 Methods

Horizontal profiling in resistivity were detected while 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.

3.2.1 Analysis and interpretation of Geophysics Data-Vertical Electric Sounding (VES)

For the present study, geophysical survey results (Vertical Electric Sounding-VES) data obtained using Schlumberger configuration AB/2 distances (usually 200-300m). 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 (Figures 6, 7 and 8) Magnetic Resonance Sounding (MRS) 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 (Lubczynski and Roy, 2003). The resulting MRS geophysical parameters are the initial amplitude which is linked to the water content (Θ_{MRS}) and the decay time ($T2^*$) which is linked to the mean size of the pores that contain water and the main aquifer storage properties estimated by MRS is the aquifer specific yield S_y obtained from MRS free water content (Vouillamoz et al., 2012).

3.2.2 Aquifer hydraulic Parameters

Aquifer tests results particularly pumping test data have been used by many authors to estimate the aquifer hydraulic parameters in crystalline rock environments (Owor et al., 2009; Tindimugaya 2008). Cooper-Jacob (1946) 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 (Sandow et al., 2013). Computer software AQTESOLV has also been used.

3.2.3 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 (Chilton and Foster, 1995). 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.

3.2.4 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. 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). 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.

3.2.5 Hydrogeological Conceptual model of the study area

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. The nature of the conceptual model determines the dimensions and design of the grid involved in numerical modeling.

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. The commonly exposed lithological units within the study area was mainly lateritic soils and the Kampala Suite granites that consist of variably deformed granitoids and orthogenesis (Westerhof et al., 2014).

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 could be described as follows:

- i. Weathered overburden is expected to range between 12 to 40 meters.
- ii. Fractured bedrock formation of an estimated thickness between 9 to 30 meters.
- iii. The massive and hard granitic rock formation of an estimated depth of 55-70meters.

d) Hydraulic properties of the stratigraphic units

Hydraulic conductivity and transmissivity are key components of the groundwater conceptual model. The average mean hydraulic conductivity and transmissivity of the deeper fractured rock aquifers was estimated to be 0.1756m day^{-1} and $3.275\text{m}^3\text{day}^{-1}$ respectively. The specific storage of the aquifer demined using MRS soundings together with pumping test results is 4×10^{-3} .

e) Recharge

The recharge in the area occur mainly from rainfall/seasonal floods generated from the topographic elevated ridges surrounding the area. Owor et. al (2009) concluded that the magnitude of observed recharge events is better related to the sum of heavy rainfalls exceeding a threshold of 10 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 (Tindimugaya, 2000).

f) Groundwater discharge

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 (Gebregziabher, 2003).

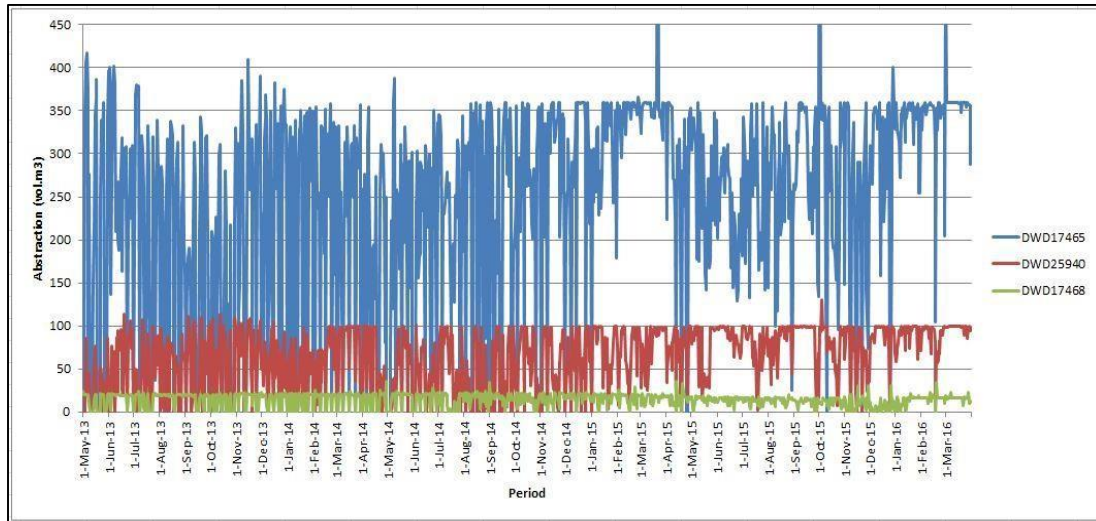


Figure 3. Variation of abstractions ($\text{m}^3/\text{day}^{-1}$) at 3 boreholes for a period of 3 years

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 (Tindimugaya, 2008). The mean annual rainfall fed groundwater recharge in the entire Uganda was estimated to be 120 mm/year. Basing on this information and the 3 year (2013-2016) daily rainfall record of the study area (Figure 3), the mean annual rainfall recharge of the study area was estimated to be 112mm/year

h) Graphical Representation of the conceptual model in the real world

Anderson & Woessner (1992) 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. 48 m of average aquifer thickness was considered.

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. 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

MODFLOW was 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 15Km) off. The governing partial differential equation 1 in which MODFLOW is based on, is given below (Harbaugh, et al., and 2000).

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

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.

6.2 Model geometry and Model thickness

The horizontal extent of the model domain was 5km by 4km 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.

6.3 Model design

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

i. 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.

ii. 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.

iii. 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 Later all aquifer parameters were adjusted during the modelling process in order to match the observed water levels in the area.

iv. 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.

v. 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). 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.

vi. Recharge

Rainfall data was used to generate recharge for a period 2013-2015. A daily rainfall threshold of 10mm 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. Therefore, this study used 10% recharge from rainfall amounts greater than 10mm in the years 2013-2016 (Owor et al., 2009; Taylor & Howard 1996).

6.4 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.

i. 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.

ii. Sensitivity analysis

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).

iii. 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.

4.0 Results and Discussions

4.1.0 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 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. 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). 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 (Figure 5, 6 and 7).

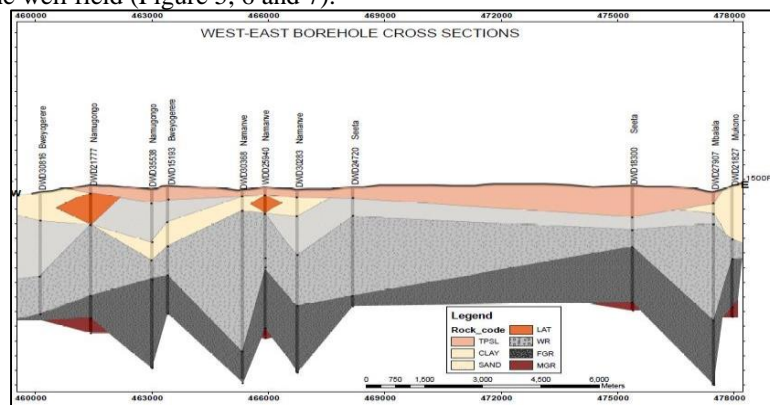


Figure 4. A 2D display of the stratigraphy of the study area using borehole drilling logs.

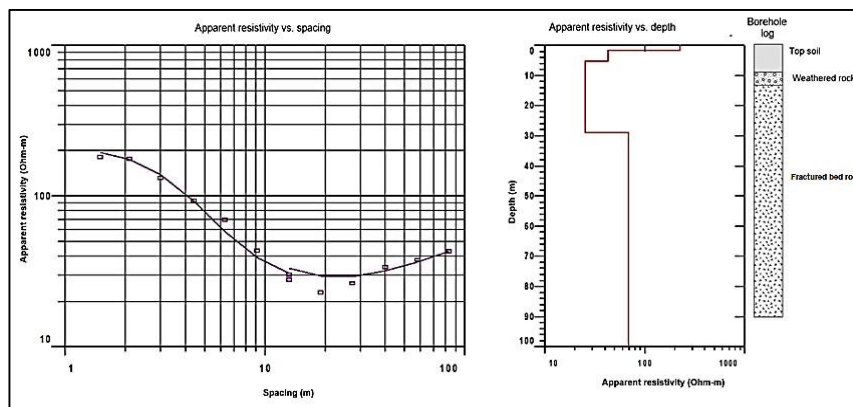


Figure 5. Correlation of apparent electrical resistivities with drill logs of borehole DWD 30368-Namanve.

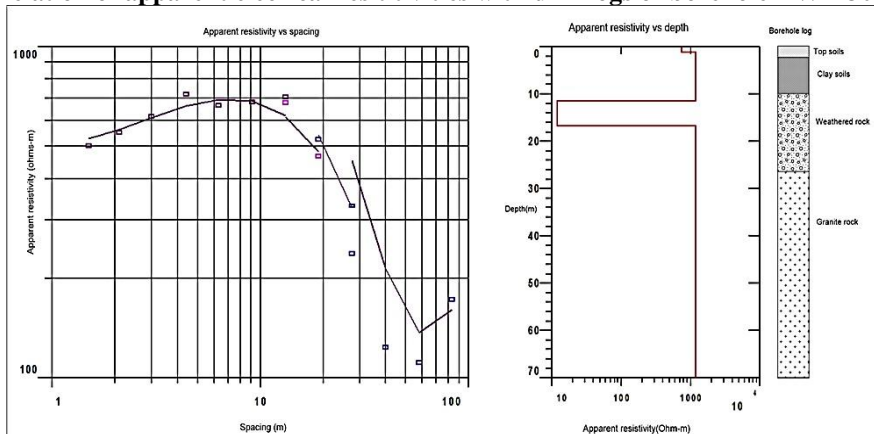


Figure 6. Correlation of apparent electrical resistivities with drill logs of borehole DWD 30283-Namanve.

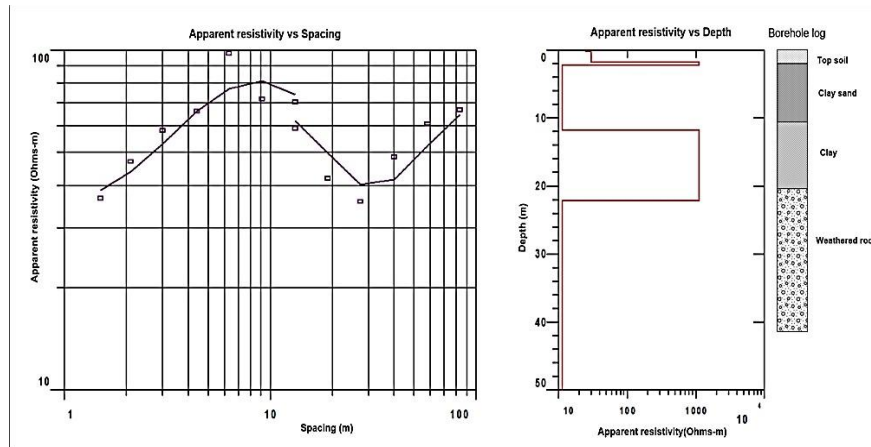


Figure 7: Correlation of apparent electrical resistivities with drill logs of borehole DWD 29736-Namanve.

4.2.0 Hydraulic properties of aquifers 4.2.1 Pumping tests data analysis

Pumping test data was analyzed using AQUISOLVE 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 (Fig 8 and 9). This effect caused the draw down response curves deviate from the perfect confined aquifer drawdown type curves as presented by (Theis, 1935) 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 (Kruseman & de Ridder, 2000) were assumed.

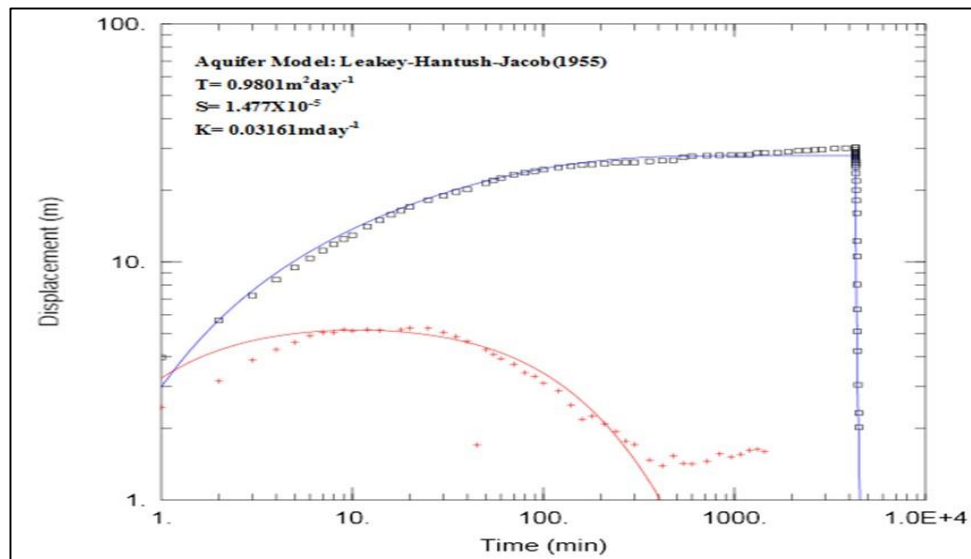


Figure 8. Roofing Rolling Mills Borehole 2, Leakey aquifer solution- Huntush Jacob.

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.

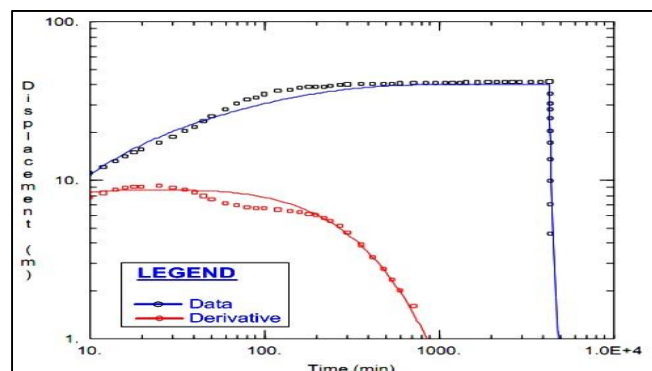


Figure 9. Rwenzori 1 : Leakey Aquifer solution - Neuman-Witherspon.

The current mean transmissivity value of the study area was estimated to be about $3.275 \text{ m}^2\text{day}^{-1}$ while the mean hydraulic conductivity was estimated to be $0.0574 \text{ m}^2\text{day}^{-1}$. The Average Storativity or storage coefficient generated from the AQUISOLVE 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.

4.3.0 Aquifer storage parameters using MRS.

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).

Table 4. Summary of the estimated MRS parameters at Roofing Rolling Mills site.

Estimated MRS			
Parameters			
$\Delta Z(\text{m})$	$\theta\%$	$T_2^*(\text{ms})$	$(T_2^*)^2(\text{ms})$
24.1	6.1	70	4900

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

4.3.1 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.

Table 5. Summary of pumping test data interpretation at Roofing Rolling Mills.

Aquifer property	Aquifer solution		Average
	Leakey	Unconfined	
Transmissivity (m^2s^{-1})	1×10^{-5}	8.425×10^{-6}	9.125×10^{-6}
Storativity	1.477×10^{-5}	1.786×10^{-5}	1.631×10^{-5}
Specific yield (%)	-	0.04093	0.04093

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

Estimated MRS Parameters				Estimated pumping test Parameters.		
$\Delta Z(\text{m})$	$\theta\%$	$T_2^*(\text{ms})$	$(T_2^*)^2(\text{ms})$	$T (\text{m}^2\text{s}^{-1})$	S	S_y
31	6.1	70	4900	9.125×10^{-6}	1.631×10^{-5}	0.04093

4.3.4 Comparison of MRS and pumping test results.

The estimated T_{MRS} and S_{yMRS} compares closely with the transmissivity and the specific yield estimated from pumping test Table 7.

Table 7. Comparison of MRS and pumping test results.

Method	Aquifer parameters	
	Transmissivity (m^2s^{-1})	Specific yield
MRS	9.116×10^{-6}	0.04093
Pumping test	9.125×10^{-6}	0.04093
Relative difference	0.01 %	0%

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.

4.3.5 Calculating the estimated MRS aquifer storage

$$MRS_{Storage} = S_y * \Delta Z;$$

$$S_y = \theta_{MRS} * K = 0.04093 = 0.061 * K = 0.670$$

$$MRS_{Storage} = K * \theta_{MRS} * \Delta Z = 0.671 * 0.061 * 24.1 = 0.98644$$

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

4.4.0 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. 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. 4.5.0 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.

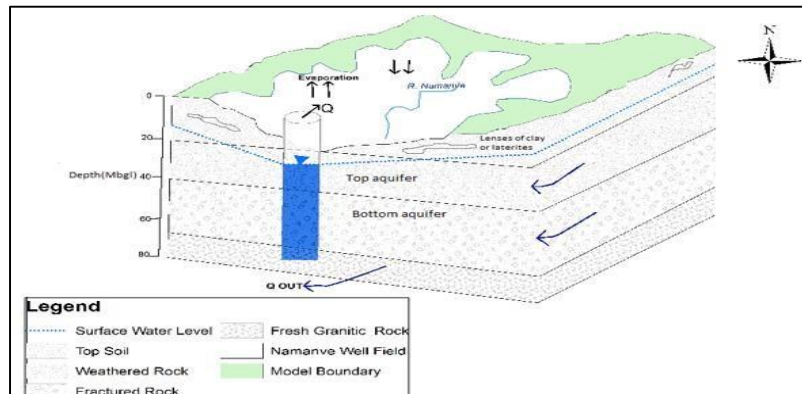


Figure 10. Conceptual model of the area.

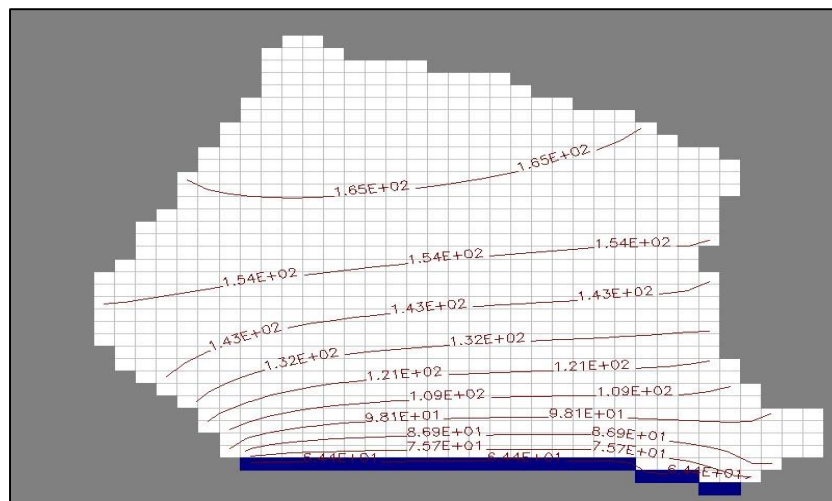


Figure 11. Distribution of hydraulic heads with non-pumping scenario.

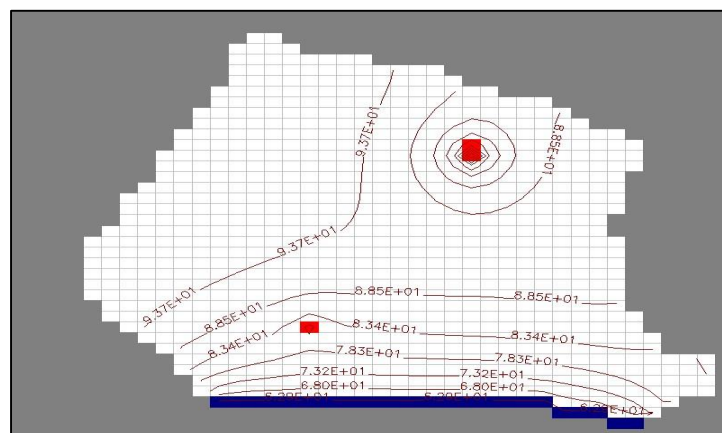


Figure 12. Distribution of hydraulic heads with pumping scenario.

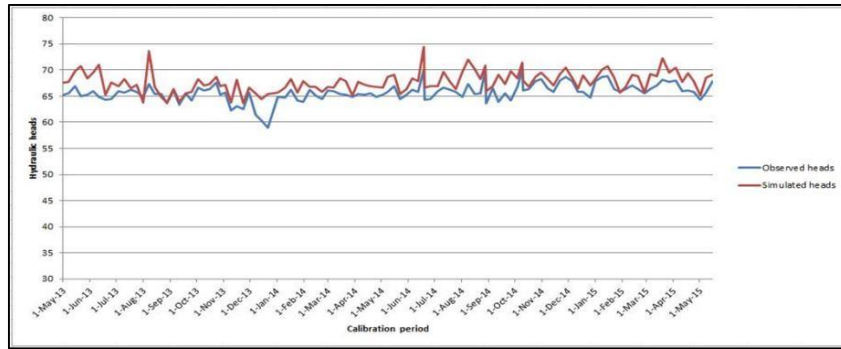


Figure 13. Correlation of the observed and simulated heads in the pumping scenario DWD 25940.

The results are also graphically presented as comparisons of the observed and simulated hydraulic heads in both cases of non-pumping and pumping scenarios (Figure 13 and Figure 14). The modelling results shows that most of the simulated heads were within the preestablished calibration target and the overall results of the model are comparable.

4.5.1. 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).

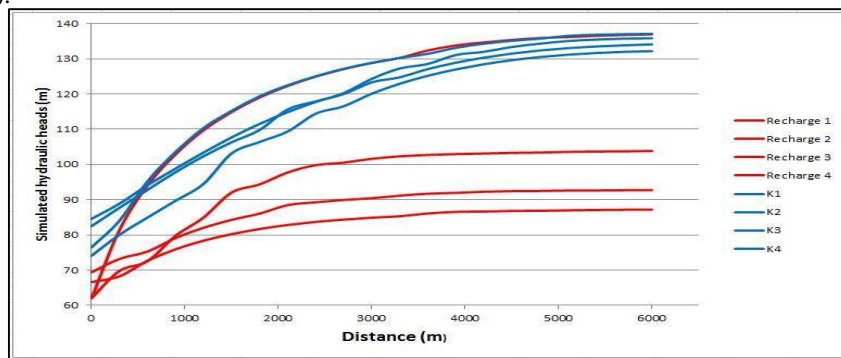


Figure 14: Sensitivity model with respect to recharge and hydraulic conductivity variations.

4.5.2. Groundwater budget

The input term to the groundwater 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.

Table 9: Simulated groundwater budget for non- pumping scenario

FLOW TERM	IN (m ³ /day)	OUT (m ³ /day)	IN-OUT (m ³ /day)
Head dependent flow through the southern boundary	0	15039	-15039
Wells	0	0	0
Recharge	15039	0	15039
Total	15039	15039	0

Table 10. Simulated groundwater budget for pumping scenario.

FLOW TERM	IN (m ³ /day)	OUT (m ³ /day)	IN-OUT (m ³ /day)
Head dependent flow through the southern boundary	0	14514	-14514
Wells	0	525	-525
Recharge	15039	0.0000	15039
Total	15039	15039	0

4.6.0. 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%.

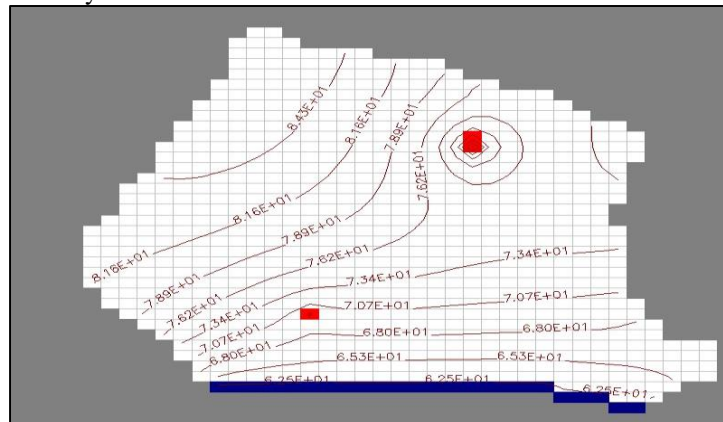


Figure 15. Distribution of hydraulic heads at 500% increase in the abstraction rate at the wells.

4.6.2. Limitations of the model

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. The area was conceptualized as a single layer assuming impermeable basement rock at the base.

5.0 Conclusions

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. A numerical groundwater flow model was developed using 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⁻¹. The accuracy of the model recharge is dependent on annual recharge value. A steady-state groundwater flow model demonstrated that an average recharge of 42 mm year⁻¹ maintains the natural equilibrium. On the other hand, the model results with pumping scenario show that the current estimated groundwater abstraction of 2175 m³ day⁻¹ 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.

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