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Well-Field Optimization Modelling at a Riverbank Filtration Site

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ملخص البحث

إن الأنهار من مصادر المياه الرئيسية ومن ثم يمكن الاعتماد عليها في تغذية المياه الجوفية والتي يمكن الاستفادة منها من خلال تنقية الترشيح الطبيعي لمياه الأنهار وذلك عن طريق حقل الابار التي تنفذ على ضفاف الأنهار. ويمكن الوصول للاستفادة القصوى من خلال دراسة التوزيع الأمثل لهذه الآبار من خلال النمذجة المثلى للآبار على برنامج (MOD FLOW) ومعرفة أفضل مسافة بين الآبار وكذلك أفضل معدل تدفق للمياه يمكن استخراجه من كل بئر على حده للوصول لمعدل التدفق الكلي المطلوب وفي الدراسة الحالية تم الوصول لأسلوب يمكن من خلاله تحديد أفضل توزيع ومعدل تشغيل للآبار للوصول إلى أقل تكلفة للتشغيل وفي المشروع قيد الدراسة تم الحصول على معدل تدفق يساوي 40,000 م^3/يوم بإجمالي عدد آبار 38 بئر منهم 32 أساسي و6 احتياطي على أن يتراوح معدل التدفق للبئر الواحد بين 500 م^3/يوم و2000 م^3/يوم طبقا لنفاذية الطبقات وسمكها. ويمكن تطبيق نفس الأسلوب على المشاريع المماثلة لوضع التصميم الأمثل لحقل الآبار.

Abstract

The rivers are one of the main water sources and thus can be relied upon to feed the groundwater, which can be used by purifying riverbank filtration (RBF) through well-field that is implemented on the riverbank. The maximum benefit can be reached by studying the optimum distribution of these wells through the optimal modeling of wells on the MOD FLOW program and knowing the best distance between wells as well as the best water flow rate that can be extracted from each well separately to reach the required total flow rate. In the current study, a method has been reached that can Through determining the best distribution and operating rate of the wells to reach the lowest operating cost and in the study area, a flow rate equal to 40,000 m^3/day was obtained with a total number of 38 wells of which 32 are operating and 6 standby. The flow rate for one well ranges between 500 m^3/day and 2000 m^3/day according to the permeability and thickness of the layers. This method can be applied to similar projects to develop an optimal design and placement for well-field.

Keywords: Groundwater modeling, Riverbank filtration, well field optimization

Introduction

Demand of high quality of potable water is increasing due to the world's growing population including Egypt. Therefore, water utilities have developed new technologies for treating waters of degraded quality, such as membrane filtration, soil-aquifer treatment, and advanced oxidation. In spite of that, an old method called riverbank filtration "RBF" is increasingly being used because it is a relatively inexpensive and sustainable means to improve the quality of surface waters (Abdel-Lah, 2013)

Surface and ground water are valuable sources for drinking water. Certain industrial, mining, and agricultural practices pollute these critical resources. River-bank filtration (RBF) is a cost-effective in situ water treatment process, which removes suspended solids and organic and inorganic pollutants. The RBF process is defined as a natural filter of soils and aquifer sediments at the river site. In RBF, river water moves through the pores of the natural soils of the riverbed and riverbank. RBF improves several physical, chemical, and biological properties of the river water. Several treatment actions including, filtration, sorption, and biological degradation occur during this process. Under specific conditions, RBF could be used as a treatment or pretreatment process to remove or decrease pollutants in surface water. The effectiveness of RBF in improving the river water quality is presented. Factors that affect the performance of the RBF process will be discussed. (Ahmed & Marhaba, 2017)

Several newly developed water treatment methods are being used to obtain higher quality water. However, the use of a simple, ancient, and natural method called river bank filtration (RBF) can easily be applied, due to its relatively low cost and sustainable means in improving the quality of surface waters (Thakur et al., 2012).
RBF is a water purification process, in which river water is naturally filtered to an aquifer through the riverbed or riverbanks. A series of biological, chemical, and physical actions take place during the underground passage that leads to the improvement of water quality (Sprenger et al., 2011).
Under certain circumstances, conventional surface water treatments could be replaced with the RBF process to remove or decrease pollutants in surface water. RBF is a simple and natural process because it utilizes the natural soil as a filtration media.
permeable aquifer connected to a river, water begin pumping steadily, and the drawdown cone is created around the pumping well. The drawdown enforces a segment of the river water to penetrate the aquifer on the way to the pumping well. The pumping well can be a vertical or horizontal collector as shown in Fig. 1 (Ray, 2011).

Water quality of RBF process

During the RBF process, surface water is lead through the aquifer media, decreasing or eliminating turbidity, chemicals, pesticides, industrial contaminants, organic matter, and other pollutants.

Factors affecting RBF efficiency

The complex geochemical, biological, and hydrologic factors, that influence the effectiveness of the RBF process, are complicated and connected. Only recently, researchers have begun to understand these factors (Ahmed & Marhaba, 2017)

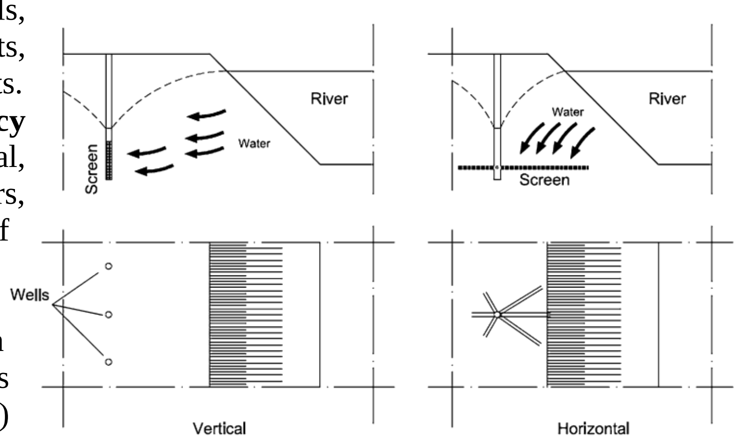

FIGURE 1 **HORIZONTAL AND VERTICAL WELLS IN BF SYSTEMS**

Vertical collector wells are the typical water extracting structures used widely around the world including India. Low cost, easy for construction and maintenance, more water withdrawal are the major advantages of these wells. The diameter and depth depend upon the aquifer conditions and surface water hydrology. These wells are preferred in comparatively high permeable aquifers.(Jeyakumar et al., 2017)

The distance of the RBF well is decided by considering the expected hydraulic gradient between the river and the well, as well as hydraulic conductivity. If the groundwater from the riverbank takes more than 50 days to reach the production wells the microbial content will be reduced tremendously which will save the cost of post treatment. In order to maximize the production several wells can be located at optimum distance parallel to the river course as practiced in Ahmedabad and Delhi.

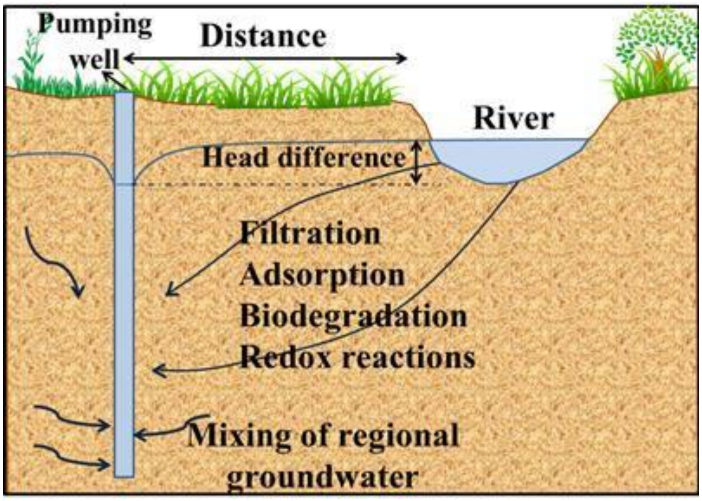

Figure 2 (Jeyakumar et al., 2017)

The well location and pumping rate were determined based on the discharge ratio value of the river water in the well and whether the aquifer is fully penetrated by the stream(Ekkehard Holzbecher, 2013) By pumping wells located in an alluvial plain hydraulically connected to a river it is possible to generate a hydraulic gradient so that surface water is forced to flow through the bed and the banks of the river. (Jaramillo, 2012) In many developing countries, disinfection (very often chlorination) is the only treatment applied to public water supply. In this context, there is a need for a robust water treatment technology which is effective, low- cost and could be operated and maintained relatively easily in developing countries. (Sharma & Amy, 2009)

RBF wells induce a large amount of river water to infiltrate the river base and travel towards the wells, giving the opportunity for mixing of infiltrated surface water and groundwater. (Shankar et al., 2009) At many locations in all parts of the world water supply is, at least partially, based on bank filtration systems. In the vicinity of a freshwater body, a river or a lake, water is pumped by a single well or a well gallery and fed into the water supply network.(E Holzbecher et al., 2008)

This research includes a developing of sustainable bulk water source for the Capital of Kigali City and Bugesera under a Public Private Partnership arrangement represented by the Government of Rwanda. The productivity of the designed system is expected to be 40000 m^3/day of extracted water from groundwater on the North bank of the Akagera River.

Study area

The Study area is located in Bugesera District, Ntarama Sector, Kanzenze Cell. The area of interest is located in a swamp with flat topographical characteristics whereby the altitudes vary between 1345 m and 1350 m (AMSL), the swamp area bounded from the north side by Nyabarongo River as shown in figure [4], and from the south surrounded by gentle sloped hill with an approximated top elevation of 1475 m (AMSL).

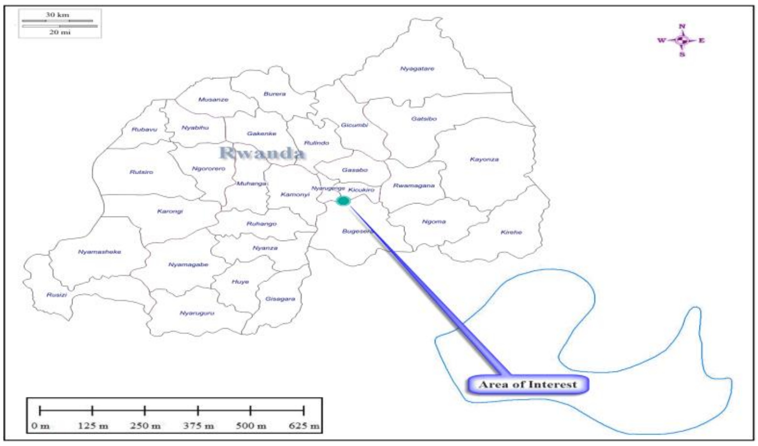

FIGURE 3: THE LOCALIZATION MAP OF THE STUDY AREA

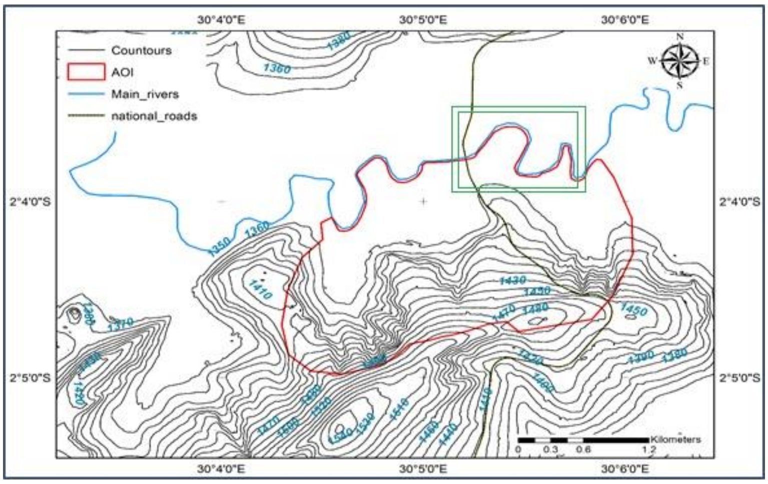

FIGURE 4 TOPOGRAPHICAL MAP SOURCE: MINISTRY OF NATURAL RESOURCES

1-Hydrogeological study

The hydrogeological study focused on assessment of groundwater resources at well field location. Most of the available water localized in the surficial sandy layer which is in a direct contact with Nyabarongo River. The hydrogeological study reported in three volumes, volume I and II contain detailed analysis of collected data and previous studies including hydrologic data and geologic information and pumping test analysis of some existing wells in well filed, in addition to hydrologic model to estimate groundwater recharge. The volume in hand summarizes the important field data which used to build the numerical model. The hydrogeological investigations were purposely carried to assess local bedrock and surficial geology for 30 m depth, including stratigraphy, depth, thickness, composition, texture, known relevant weathering /alteration/structural features (i.e. joints, fractures, faults), water bearing potential, and lateral continuity.

Rwanda has a dense hydrographical network divided in two unequal watersheds which are situated on either side of the Congo-Nile ridge: the Congo basin and the Nile basin. The Nyabarongo river basin is within the Rwandan Nile catchment that occupies 67% of Rwanda and drains most of the country's waters into the Nile through Akagera River. The Nyabarongo River is the major river of Rwanda and has its headwaters in Nyungwe Forest in the south-west. It follows a course up to the north-western part of the country, where Mukungwa and several other tributaries join the river. From Ngaru it goes down through the centre of the country, where the Akanyaru River joins from the south. From there the river officially form the Akagera River that eventually flows into Lake Victoria. Its upstream part is officially limited at the confluence of Akagera and Rusumo River. The area of interest is located in the Akagera upstream catchment which is a catchment that commences at the confluence of the Lower Nyabarongo and the Akanyaru Rivers. The map in (figure 5) is localizing the hydrological stations around the area of interest.

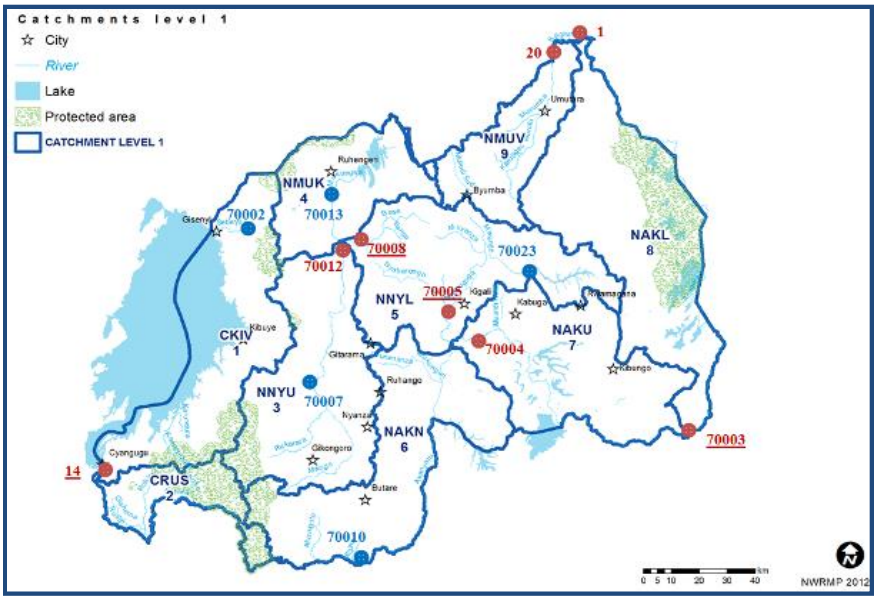

FIGURE 5 MAP OF THE HYDROLOGICAL STATIONS

The study area is near the hydrological stations of Kanzenze 70004, Ruliba 70005 and Ngaru 70008 shown in (figure 5) .Hydrological data for those three stations will allow a better understanding of surface and groundwater variation

The study area is also included in the NAKU catchment according to the delineation from the recent concluded Master Plan for Water Resources of RNRA (Rwanda Natural Resources Authority) and MINIRENA (Ministry of Natural Resources). The station 70004 collects the runoff from the Nyabarongo and the Akanyaru and its rating curve is shown in figures 6 and 7. That rating curve helps to convert the water level data to discharge

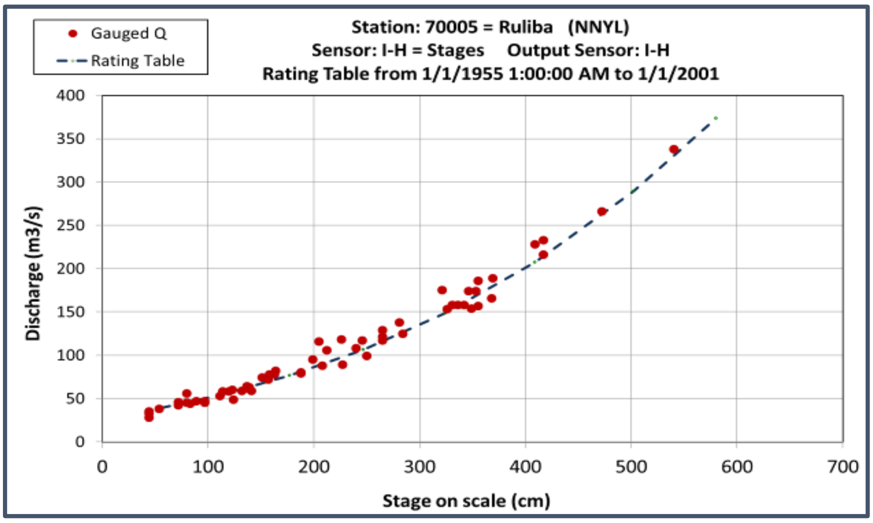

FIGURE 6 THE RATING CURVE OF NYABARONGO RIVER AT RULIBA STATION

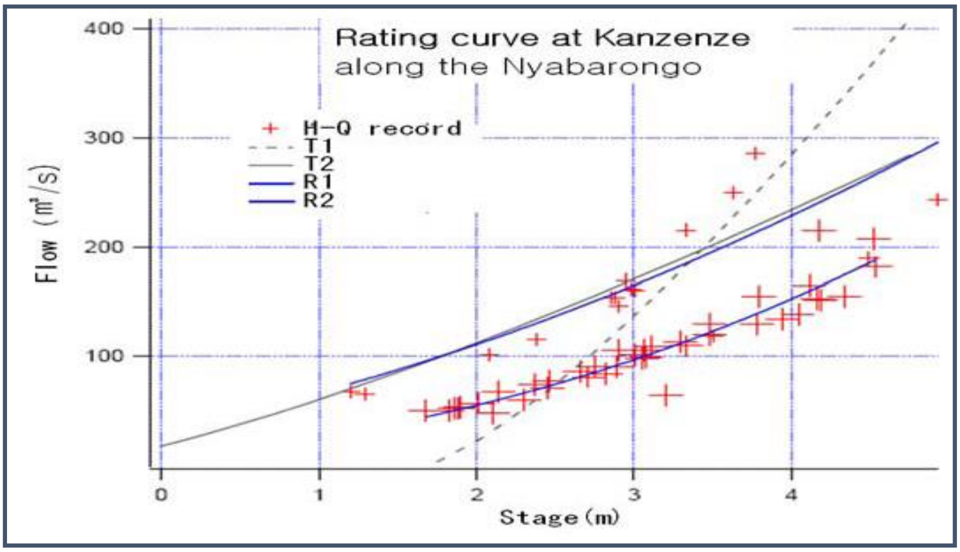

FIGURE 7 THE RATING CURVE OF NYABARONGO AT KANZENZE STATION

The hydrometric station named Kanzenze station located near the Bugesera Bridge represent all the upstream runoff contribution coming from the Nyabarongo Upstream, Nyabarongo downstream and Mukungwa catchments. From the available time series of the Kanzenze station, a daily average flow was estimated in order to understand the upstream area contribution in the area of interest. The runoff coming from upstream catchments flows through the area of interest which a very flat wetland around the Bugesera Bridge and therefore contributing to flooding the wetland and replenishing the groundwater in the area of interest. It is clear from figure 8 that the peak flows are mostly located in the end of the month of May with flow rates of around 400 cubic m per second. Low flows are located in the end of August with flow rates of around 100 cubic meter per second. The trend indicates that the river is always having a lot of water available, this indicate that the wetland is majority flooded over the whole year.

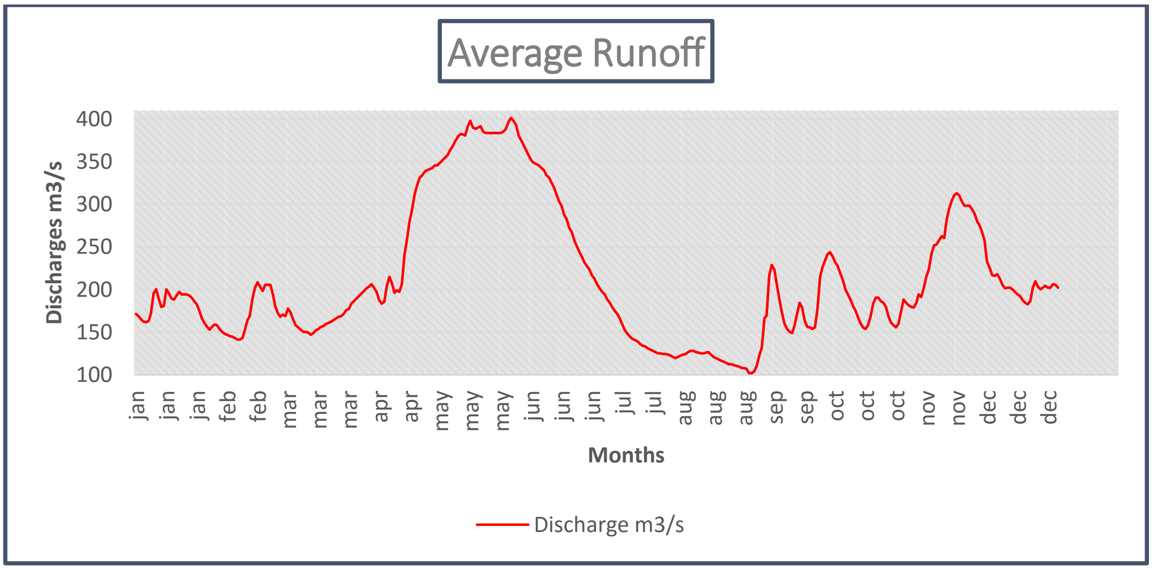

FIGURE 8 AVERAGE RUNOFF AT KANZENZE

2- Field Investigation – A) water level monitoring

About 12 monitoring wells shown in figure(9) were executed at riverbank to study the water level in river and the ground water table relation,.

FIGURE 9 MAP OF PUMPING TEST WELLS

Well No.	Coordi-nates UTM:X	Coordi-nates UTM:Y
1	175954	9771681
2	175975	9771702
3	175990	9771729
4	176001	9771756
5	176014	9771783
6	176033	9771806
7	176050	9771830
8	176069	9771853
9	176084	9771879
10	176097	9771906
11	176152	9771916
12	176180	9771928

TABLE 1 PUMPING TEST WELLS

The following Figure 10 is the simple diagram showing in summary the water balance in the area considering the whole catchment in which the area of interest is located.

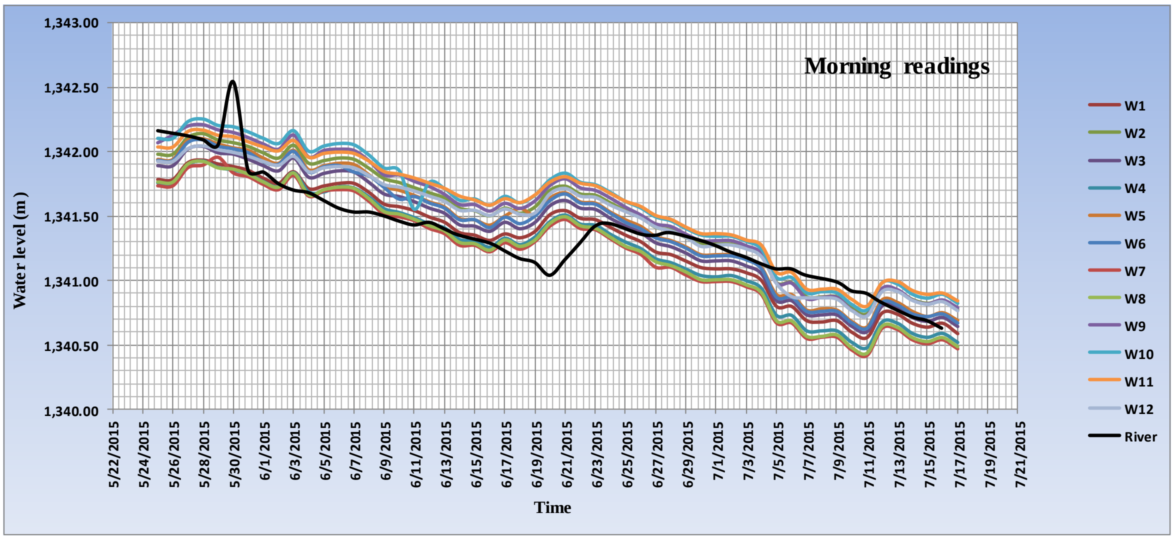

FIGURE 10 CHANGE IN GROUNDWATER LEVELS FOR 12 OBSERVATION WELLS (AT MORNING)

B) Geophysical investigation

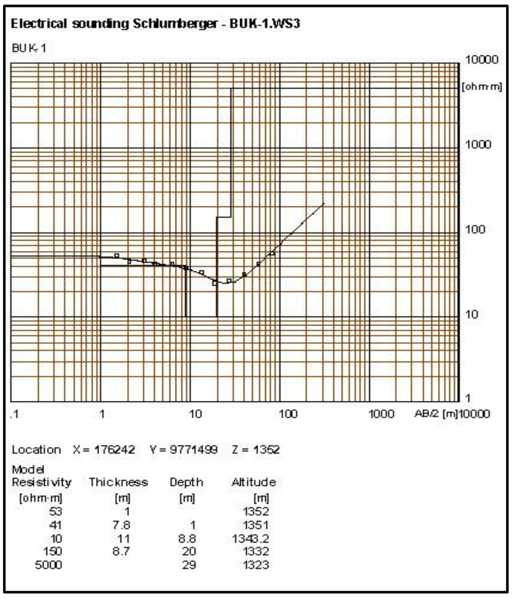

FIGURE 11 ELECTRICAL SOUNDING SCHLUMBERGER- BUK-1

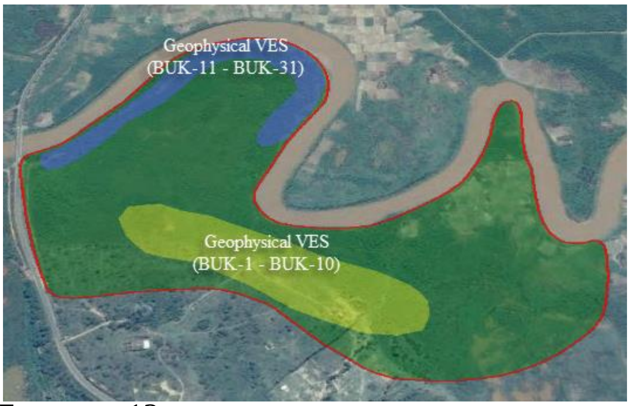

FIGURE 12 GEOPHYSICAL INVESTIGATION DISTRIBUTIONS IN THE AREA OF STUDY

The electrical borehole investigations carried out to confirm the geological data. During the drilling investigations, Mechanical boreholes have been drilled.

These Boreholes are effective for obtaining: Information on geological soil conditions, Data of subsoil profile and alluvial formations properties, Water level from the full length of each borehole up to 25 meters maximum, Lithological logs of boreholes and main features, The survey shows a continuous aquifer on 500m distance along the river despite the change of thickness, Water level in boreholes is approximately 0.80m from the surface (piezometer data), Most of the water comes from the recharge of the river, Water level in boreholes with the water level of Nyabarongo river, The aquifer in vertical position: It was found a top and a base of sand layers at a different depth, The thickness of sand layers is also different, The aquifer found in boreholes means that they are interconnected, The transition layers such as clayey sands or silty sands are excluded from the aquifer, Taking all boreholes into account, the average deepness is 4.04m (+/- 1.51m). The standard deviation is about 37%. This shows a very big variability, The average thickness for boreholes recorded is about 7.4 m (+/- 2.5 m), The average depth for boreholes where the aquifer is the deepest is estimated to 9m (+/-2.7m), The standard deviation represents 30%.

The combination of electrical boreholes and mechanical boreholes helps to know information on geological soil conditions, data of subsoil profile and alluvial formations properties, water level from the full length of each borehole up to 25 meters maximum, Lithological logs of boreholes and main features, Using these data, a 3D-simulation has been developed to describe the stratigraphy of the different layers in the area.

As it is indicated in the table blow, from the top to bottom, it is distinguished the following lithological succession: 1- Silty material (top soil, fine grained silt, clayey silt and silty clay), 2- Sands (fine to medium grained size, occasionally coarse), 3- Silty clays (not very stick), 4- Sticky clays

Sample	Identification	Grading	Compactness
Sample 1	Sand	Poorly to well graded rounded & subangular grain shape	Loose to medium
Sample 2	Silty sand	Fine to medium graded, rounded & subangular grain shape	Loose to medium
Sample 3	Clay	Very fine graded	Soft, sticky
Sample 4	Silt, Silty clay	Very fine graded	Soft, sticky

TABLE 2 IDENTIFICATION OF SOIL TAKEN FROM BOREHOLES

Methodology

Alignment of wells for limited area

Required system give us best alignment of wells, where: $S \alpha q_{well}$

$S_1, S_2, S_3, \ldots S_n \rightarrow L$

$L = S \times N_{wells} - 1$ $\quad Q_{station} = \Sigma q_{well}$

$q_{well} \alpha K$ $\quad q_{well} \alpha Dd$

Where:

S = spacing between wells

L= length of bank

N= Number of wells

q_{well} = flow of one well

Qstation = flow of station

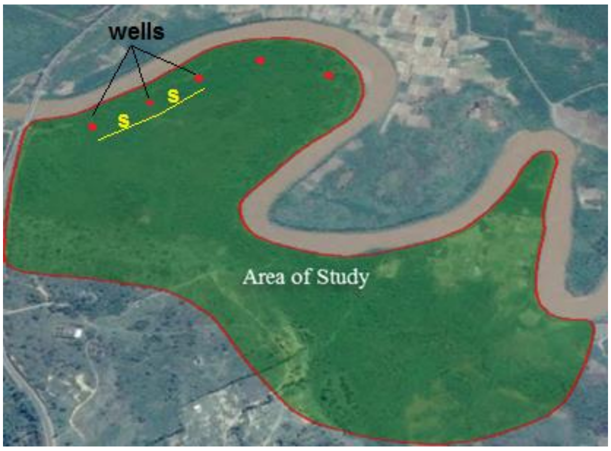

FIGURE 13 STUDY AREA SHOWING SPACING BETWEEN WELLS

Theoretical Approach

The equation for Darcy's Law is based on the observations that the flow rate through a porous medium (such as an aquifer) is proportional to the cross-sectional area perpendicular to flow and is also proportional to the head loss per unit length in the direction of flow. Putting these two proportionalities together gives the following equation: $Q = KA(hL/L)$,

where

Q = flow rate of liquid through

A = cross-sectional area perpendicular to flow

hL = head loss over a horizontal length, L, in the direction of flow

The Figure number ( ) shows an experimental apparatus illustrating the Darcy's Law equation and its parameters.Darcy's Law is valid only for laminar flow, which occurs for Reynold's number less than 1.

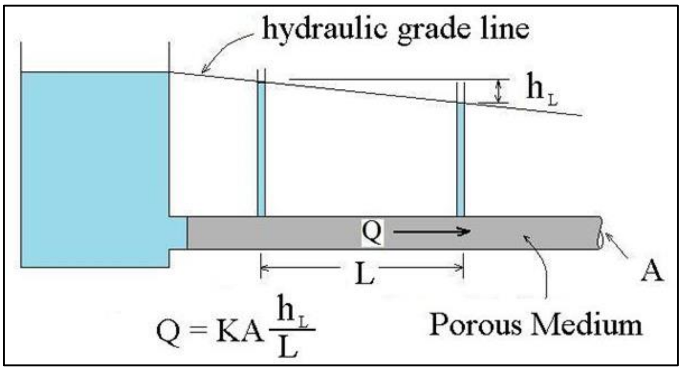

FIGURE14 DARCY'S LAW APPARATUS

Modelling

To develop the numerical simulation for the study area, the Mod flow program to simulate three-dimensional steady state groundwater flows. The model consists of multi-layers aquifer system. The first layer represents the permeable layer (sand layer) The second layer represents the semi-confining layer (clay layer), which overlies the third layer (weathered rock). It is modeled as an aquifer in which vertical and horizontal flows simulated. A finite difference grid is generated for the modeled area. The grid consists of 619 rows, 801 columns and 3 layers, for a total of around 275000 active cells. All of the cells have relative dimensions due refinement around wells equal 1:1.1 starting by 0.5m and the total area is 382186m^2; the cell size is small enough to reflect both the density of input data and the desired output detail, and large enough for the model to be manageable.

The results of the topographical studies as well as the results of the hydrological studies were used to create a model on the MOD FLOW program and run more than one scenario and match the different scenarios with nature and found that it is sometimes possible to rely on the upper layer only (sand) to withdraw the required quantity from the well and sometimes we need to reach the bottom layer (Weathered stone) to complete the required amount of water from the well due to the small thickness of the sand layer.

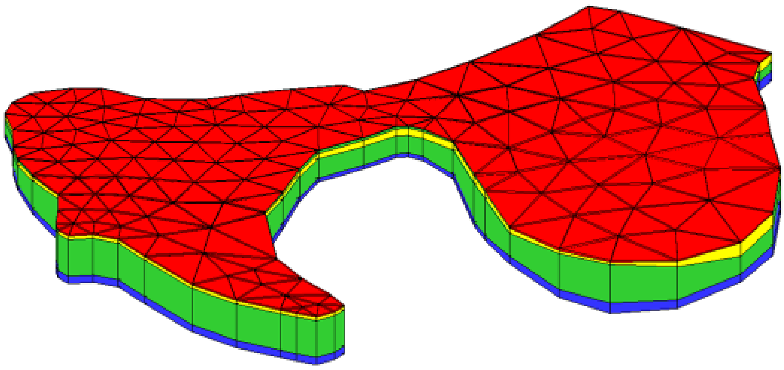

FIGURE 15 MODELING OF STUDY AREA SHOWING DIFFERENT LAYERS

FIGURE 16 MODEL BOUNDARY CONDITION

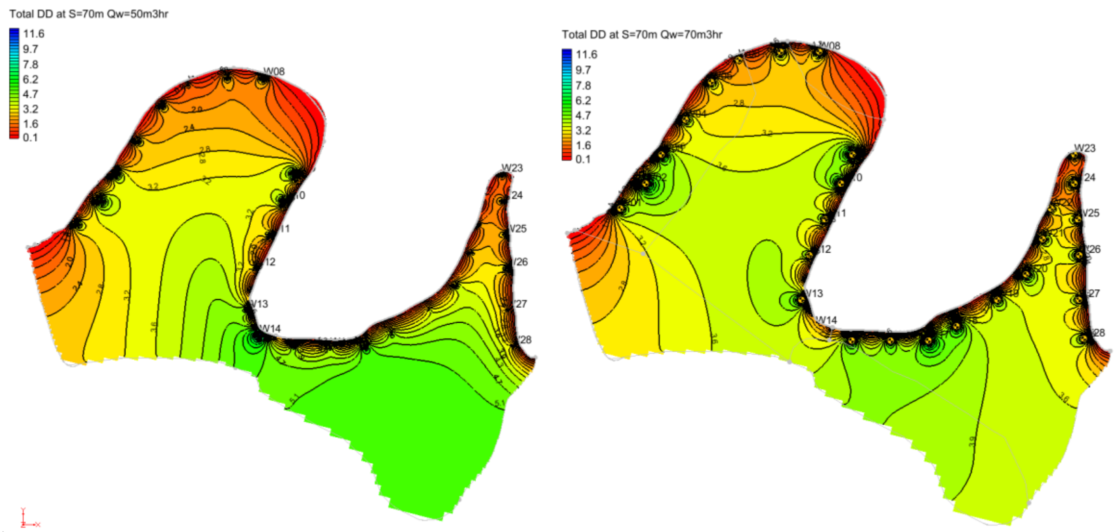

FIGURE17 DIFFERENT SCENARIOS FOR MODELING

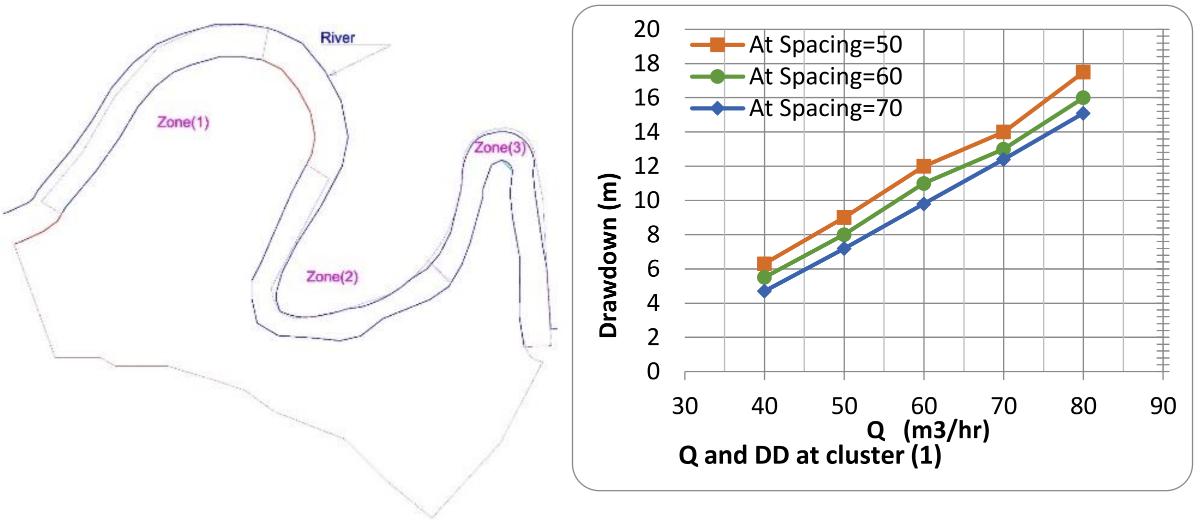

FIGURE18 ZONES OF MODEL

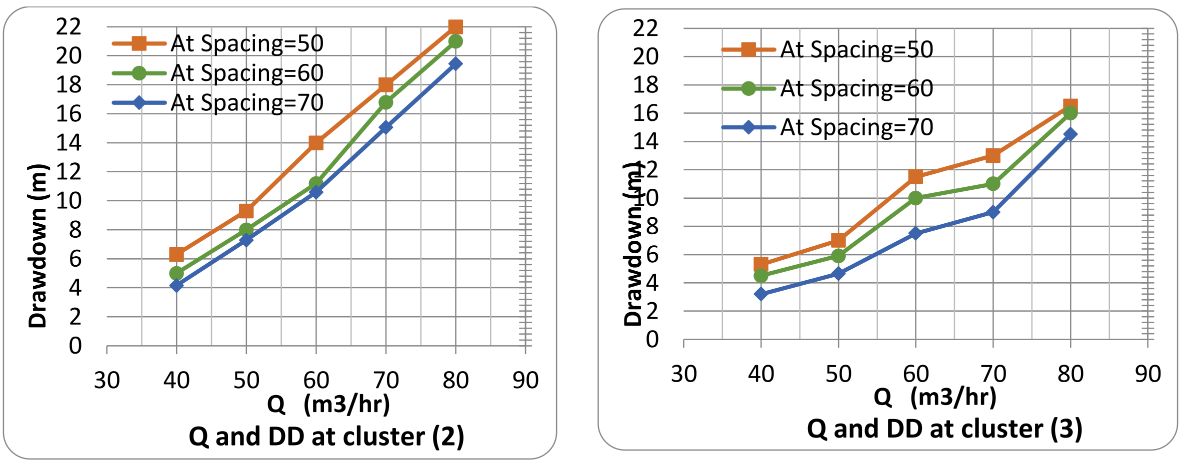

FIGURE19 RELATIONS BETWEEN Q AND DRAWDOWN AT EACH CLUSTER

Results and Analysis

The riverbank was divided into three regions according to the permeability and thickness of the permeable layer. The model was designed on the MOD FLOW program and implemented several trials with multiple distances between wells ranging from 40 meters to 70 meters between each well and the next, in order to find out the optimal operating rate for each region and then find out the optimal solution for the study Area as a whole. The results are as follows: It was found that the best scenario was when the distance between the wells ranged between 50 meters at area 1 and 40 meters at area 2, and in area 3 the best distance between the wells was 65 meters.

This research show a three dimensional steady state groundwater model which has been used in design of required supply wells to afford 40000 m3/d.

A total number of thirty-two supply wells have been proposed to supply the water treatment plant with the required flow. The average operating flow rate ranges from 40 to 80 m3/h (24 hours operation). This variance in operating flow resulted from the small thickness of the sandy layer in some modeled areas. Another six wells have been proposed to be standby wells, however during dry season these wells will be in service. Through dry season the expected low water level in Nyabarongo River was recorded in 2014 as 1388.9 masl. The flow rate during dry season will be reduced to control the drawdown in each well; operation of standby wells will maintain the required capacity.

The optimum length of wells can be calculated by simulating the maximum drawdown can be occurred and outer diameter will be 0.6m and 0.4 m for casing. The proposed depth will penetrate the weathered rock aquifer which supposed to be productive layer. Most of abstraction rate will be withdrawn from the sandy layer, however during well construction it's proposed to extend the penetration into the weathered rock layer to complete shortage of flow in areas withs thin sandy layers.

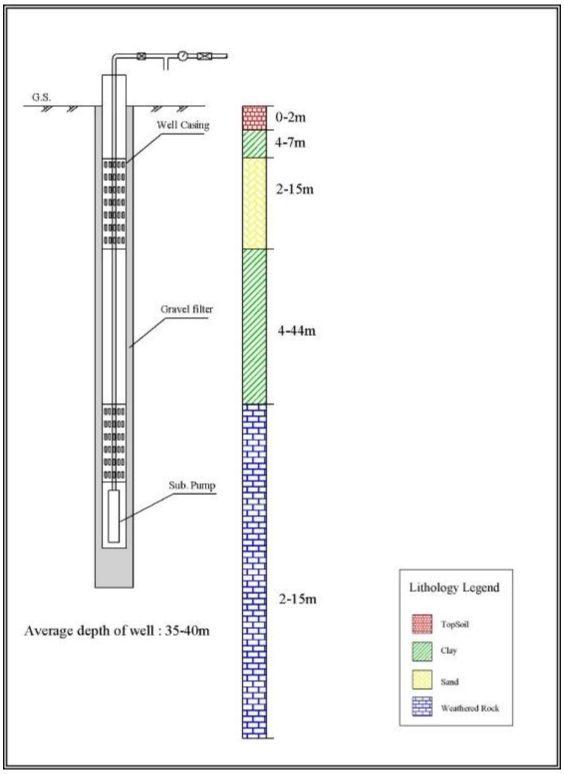

FIGURE20 SECTION FOR WELL

Conclusions

- The work in this research presented a novel approach for the optimization of well field design at riverbank.
- This optimization includes wells numbers, distributions and flow rate. Which can be applied to similar projects to enhance the capital and operating cost.
- The approach has been applied to case study at Kigali (Rwanda) for well field design to supply a water treatment plant within average daily flow rate of 40,000 m^3 obtained with a total number of 38 wells of which 32 are operating and 6 standby.
- This optimization method can be relied upon to obtain the best position for well field, as well as the amount of water required from the total wells.

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