ESTIMATION OF HYDRAULIC PROPERTIES FROM PUMPING TESTS DATA OF NAIROBI AREA, KENYA

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Abstract

The aim of this study was to determine the hydraulic properties of Nairobi area in order to highlight the groundwater potential and to identify the distribution of hydraulic characteristics of aquifers in the area as well as to highlight vulnerability of the aquifer to heavy abstraction. Documented pumping tests data of boreholes located in Nairobi County were analyzed. Pumping test data from eighty four (84) single-well boreholes were analyzed in AQTESOLV software to determine transmissivity and storativity using Cooper-Jacob's, Theis's, Papadopolus-Cooper's and Theis's recovery methods. Hydraulic conductivity was calculated based on the relationship between hydraulic conductivity and transmissivity. The values of transmissivity for all wells ranged between 1.11 and 360.58 m²/d by using Theis -and Cooper-Jacob methods, 1.10 and 360.58 m²/d by Papadopulos-Cooper method and between 1.289 and 677.81 m²/d by Theis recovery method. The city of Nairobi faces increasing ground-water demand due to ever rising population which is mainly driven by rural-urban migration and industrial growth. Surface water has not only been over-stretched but also heavily polluted and unreliable thus groundwater is the only reliable alternative source of water in the area. Lava and pyroclastic formed during Cenozoic age make up the geology. Under these lavas and pyroclastic rocks lie schists of Precambrian age and gneisses of Mozambique belt of the same age. These results indicate that the aquifer is heterogeneous and that the groundwater supply for local water supply (small communities and plants) is reliable but withdrawal for great regional supply is limited.

Keywords: *Hydraulic Properties, Groundwater Management, Igneous Rocks, Pumping Test, Nairobi*

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1. INTRODUCTION

The ever growing population of Nairobi puts a lot of pressure on the groundwater water resources because surface water has not only been over-stretched but also heavily polluted thus unreliable leaving groundwater as the only reliable alternative in terms of quantities that meet the demand of the residents as well as suitable and acceptable quality (Coetsiers et al., 2008). The choice of original location of Nairobi city is one of the factors that contribute immensely to its perennial water shortage. The original planning of the city only took into account was a smaller population, however; today large population occupies the city due to its metropolis nature. Nairobi city is not only principal urban center of population but also the social, economic and communication hub of the whole country. Like any other city of the world it is faced with the problem of ever growing population, in 2010 Kenya National Bureau of Statistics (KNBS) reported the population of the city to be 3,138,369. The high population has strained the water resources in this city.

Since the 20th Century, development of groundwater has been carried out in Nairobi and its environs even though the understanding of the quantity and quality of the groundwater in the area remain very scanty. The assumption of unlimited resource has dominated this development (Coetsiers et al., 2008). The already poor health conditions in the slums continue to deteriorate as a result of urbanization which pushes poor city residents to the slums which face acute water shortage and poor dilapidated sanitation infrastructure. The city of Nairobi is supplied with both surface and groundwater, with most of the water utilized in Nairobi obtained from Tana River Catchment (Foster and Tuinhof, 2005). Surface water originally considered as freshwater from three main rivers: Nairobi, Mathare and Ngong and their tributaries that flow through Nairobi are currently highly polluted. Unfortunately, these polluted rivers continue to be heavily utilized by the poor residents in the slums and suburbs as their leading source of water. Dams such as Ndakaini and sasumua are also a major of the water supply in the city.

The city suffered severe drought in 2009 due to delayed 2008 October-December rains. The drought led to falling of water level in major dams like sasumua which is a major source of water supply of the city. In order to alleviate the water shortage, the Government of Kenya through the Ministry of Water and Irrigation drilled approximately fifty (50) boreholes in Nairobi. Borehole drilling in Nairobi area is increasing rapidly also due to increase in the demand of water supply for rapidly growing population, industrialization, agriculture and alternative to contaminated surface water thereby posing a threat to groundwater exploitation. Ministry of Nairobi Metropolitan Development (2008) projected that the domestic water demand will be about 900 million m³ by 2030. According to World Bank report number 28398-KE (2004), Kenya is classified as chronically water - scarce in absolute and relative terms. It is estimated that the country's renewable fresh water endowment stands at 518m^3 per capita per year, against the UN recommended threshold of 1000m^3 (Kenya State of Environment, 2011). By 2025, Kenya is projected to have renewable freshwater supply of 235 m³ per capita per year (Ministry of Water and Irrigation, 2007). Analysis of pumping test has proved to be one of the most effective methods for understanding hydraulic characteristics of aquifers (Kruseman and de Ridder, 1990; Delleur, 1999). Many groundwater studies have emphasized on qualitative investigation (Coetsiers et al., 2008; Nair et al., 1984); however, for holistic understanding of groundwater resources, quantitative assessment is paramount. Hydraulic parameters of an aquifer indicate its significance (importance) through portraying its water storage and transmission ability.

The aim of this study was to determine the hydraulic properties of Nairobi area in order to highlight the groundwater potential and to identify the distribution of hydraulic characteristics of aquifers in the area as well as to highlight vulnerability of the aquifer to heavy abstraction to ensure best practices in utilization of the current available water resources taking in to account the needs and interests of future generation.

2. MATERIALS AND METHODS

2.1 Study area

The city of Nairobi is bounded by latitudes 1° 9'S, 1° 28'S and latitudes 36° 4'E, 37° 10'E (Figure 1). The total area of the city is approximately 696 km² (CBS, 2001). According to Mitullah (2003) the altitude of the city range from 1,600 to 1,850 m above the sea level with the high western side having altitude ranging from 1,700 to 1,800 m above sea level while the low eastern side is approximately 1600 m and sometimes flat as observed by Saggerson (1991). The close proximity of Nairobi to the Rift Valley makes the city to experience tremors and minor earthquakes (Onyancha *et al.*, 2011).

Nairobi has a temperate tropical climate. Data record for 50 years from Kenya Meteorological Department (2001), show that Nairobi is characterized by mean minimum temperatures of 11.5° to 14.4 °C; and mean maximum temperatures ranging from 22.3° to 28 °C. Low temperatures are registered during the cool, dry and rather cloudy months of June to mid – October; with mean maximum temperatures of 22.3° to 25.3 °C. High temperatures are recorded in the months of mid - December to mid - March, with mean maximum temperatures in the range of 26.8° to 28 °C. The weather could be generally described as warm to hot, and dry with sunny days during this latter period of the year.

The coldest month is July with an average monthly temperature of 16.9 °C; while the hottest month is March with an average monthly temperature of 20.9 °C. The mean monthly range across the year is from 9.2 °C in November to 14.6 °C in February.

2.2 Data Collection

The available borehole completion reports in the Ministry of Water and Irrigation were collected for this study. To supplement the collected data, fieldwork was carried out from 19th-22nd June 2012. A total of twelve (12) boreholes were sampled. Their positions were obtained using GPS. Information gathered throughout the course of this study was stored in ArcGIS 10, a Geographical Information System (GIS) for use as graphical database and ease of data presentation and analysis. Well logs were compiled and stored using GeODin software.

Data for boreholes used in this study were drilled and test pumping performed between 2007 and 2012. In principal, pumping tests were performed as follows:

Boreholes were drilled, cased and developed. After completion of the boreholes, submersible pumps and dipping pipes were installed and pumping test was done. The pumps were installed at positions which were determined by specific casing design of each borehole during drilling. The submersible pumps were powered by diesel generators. Before the pump was switched on, static water levels in all the boreholes was measured and recorded. The rate of water flow was regulated with a control valve. The pumped water was conveyed by discharge pipe to a point where it could not recharge the well under investigations. The steps involved in performing the pumping test were: measurements of water level changes in the borehole with time as pumping progressed; and recovery measurements which consisted of measuring the rebound of water level towards the pre-existing conditions immediately following pumping.

Data measurements taken during the pumping test were: water levels, time, and flow rates. Depth to water level in each borehole was measured with water-level meter which was either electric sounding and/or lighting dipper. A PVC dipper tube was installed alongside the test pump rising main and tied securely to it. Each borehole was pumped at a constant rate for 24 hours and water-level measurements were taken at regular time intervals and recorded. The constant pumping rate for each borehole was based on the yield which was estimated during drilling period. Water that was pumped from the boreholes were discharged to waste at a distance and in a manner that it did not pond or flow back towards the borehole under test. All time measurements were done by means of a stopwatch.

20 liters calibrated container was used to measure the flow rate (discharge) of the boreholes. The container was placed under the discharging pipe and time taken to fill it recorded and used to calculate the discharge.

After the pumps were shut off, recovery measurements were taken for additional 1-3 hours depending on the recovery rate of individual boreholes. The secondary data (available data) was found collected from borehole completion reports in hard copy. The data was first typed in Microsoft Excel 2010 and saved as .txt files which were then imported AQTESOLV software.

2.3 DATA ANALYSIS

Aquifer tests were evaluated by fitting analytical solutions for pumping tests to measured data (Kruseman & de Ridder 1990) using AQTESOLV for Windows V4.5 (Duffield, 2008). AQTESOLV applies the principle of superposition in time to simulate variable-rate pumping tests including recovery, which treats the variable rate as a sequence of steps in which the discharge rate is constant in each step. AQTESOLV provides a flexible, user-friendly environment with automatic type curve fitting to a data set. Where an automatic curve fit does not yield satisfactory results, data was manually fitted to the type curve using parameter controls based on our knowledge of the geologic and hydrogeologic setting.

Theis's, Cooper-Jacob's, Papadopolus-Cooper's and Theis's recovery methods described by (Kruseman & de Ridder 1990) were used to calculate the aquifer hydraulic properties. Cooper-Jacob's, Theis's and Theis's recovery methods were used because they are the commonly applied methods for pumping test analysis. A Papadopolus-Cooper method was used because it is the recommended method for analysis of single-well analysis. The method also takes into account well-bore storage. Transmissivity was obtained from software results directly while hydraulic conductivity was calculated based on the relationship between hydraulic conductivity and transmissivity.

A statistical analysis was performed to determine the variation of aquifer transmisivity obtained from different methods using one-way analysis of variance (ANOVA) with $p < 0.05$. According to Verbovšek (2008), hydraulic parameters belong to lognormal distribution, therefore the data was therefore log transformed and analyzed using PAST software (Hammer et al., 2001).

3. RESULTS

The transmissivity values ranged between 1.11 and 360.58 m^2/d by Theis method and Cooper-Jacob method, 1.10 and 360.58 m^2/d by Papadopulos-Cooper method and 1.289 to 677.81 m^2/d by Theis recovery method. The lowest transmissivity value was recorded at Kangemi chief's camp borehole while the highest transmissivity was recorded at Pilli management consultant Limited for Theis, Cooper-Jacob and Papadopulos- Cooper methods and Camilla Elizabeth Held for Theis recovery method. Detailed results of the aquifer tests for each well are presented in Figure 2. The statistical summary of transmissivity values from all the four methods are compiled in Table 1 whereas Table 2 gives a statistical summary of the log transformed transmissivities. The values of hydraulic conductivity recorded range between 0.011 and 3.84 m/day (Figure 3). Kangemi chief's camp borehole recorded the lowest hydraulic conductivity while highest hydraulic conductivity was recorded at Pili management consultant limited. Specific capacity ranged between 1.24 and 248.73 m^2/day and is presented in Figure 4.

The eastern side of the city is characterized by higher hydraulic properties than the western side as shown in Figures 2, 3 and 4.

After analysis using ANOVA, the confidence level (p) was found to be 0.87 implying that the mean obtained from set of results using different methods of transmissivity evaluation are not significantly different.

4. DISCUSSION

Transmissivity in the Nairobi phonolite is higher than that obtained from the trachytes. This difference could be as a result of lacustrine deposits intercalated with the lavas (Gevaerts, 1964) which improve transmissivity. Hydraulic properties of the aquifer is also influenced by faults as observed in boreholes Waithaka D.O's camp borehole which is located in Karura trachyte but has relatively high transmissivity as compared to other wells in the same geology. The same observation is made on Camila Elizabeth Held borehole which is located is Kerichwa valley sediments.

Using Krásný (1993) standards for transmissivity, the aquifer generally has low to high transmissivity capacity that provides withdrawals for local water supply (private consumption) to withdrawal of lesser regional importance. Areas of intermediate transmissivity can be used for local water supply i.e. small communities and plants.

Based on Krásný (1993) classification of transmissivity variation, the aquifer can be classified as moderate (fairly heterogeneous). This classification was done after determining standard deviation of index of transmissivity (Y) by determining logarithm of transmissivity (Krásný, 1993). Based on both standards for transmissivity and transmissivity variation, the aquifer can be classified into three classes: IIC (high transmissivity with moderate variation), IIIC (intermediate transmissivity with moderate variation) and IVC (low transmissivity with moderate variation). The aquifer has moderate prospects of striking groundwater; however, areas of high and moderate transmissivity are the best for future prospects.

Some of the obtained storativity are not reliable because there were no observation wells during test pumping.

Specific Capacity and Transmissivity

Based on the Dupit-Thiem equation, Fetter (2001) and Verbovšek (2008) established an empirical relationship between the transmissivity (T) and the specific capacity (q) of the form:

$$T = C * q^a \qquad (1)$$

where C and a are constants that are empirically determined from available data sets of T and q

If such a non-linear empirical relationship can be established it may be used as a rough estimate of T when full aquifer test analysis for a well is not available (Fetter, 2001).

From this study, a relationship between T and q was established from 86 data points as follows:

$$T = 1.36 * q^{0.9316} \tag{2}$$

if T is given in m²/d and q in m³/day/m.

Possible errors during the pumping tests may involve discharge measurement. Discharge measurement involved two people, one reading stop watch while the other checking if the measurement container is full. This might have been erroneous due to improper coordination of the involved parties. This could be common for the initial readings because they are taken after a short interval of time. Other error includes not maintaining a constant pumping rate as the pumping rate decreases as drawdown increases. However, when these data are plotted serious mistakes can be identified as they will not fall well along the curves.

During data analysis, potential error is attributed to the researcher's judgment in curve fitting. The curve fitting was done manually in AQTESOLV and errors on the part of data interpreter were inherent. The accuracy of a curve or line fitted by visual inspection cannot be determined.

There is no way to properly estimate the storativity value from empirical data because no observation wells were available.

5. CONCLUSION

Aquifer sustainability is threatened by increasing water abstraction which is to disadvantage of the future generations. Hydraulic parameters derived from aquifer test data are a good indicator of the quantity of the water that can be abstracted from the aquifer.

The evaluation of hydraulic properties of the aquifer in Nairobi area reveals that the area has moderately good groundwater potential. The aquifer can be classified as moderately heterogeneous with moderate transmissivity variation based on the guidelines by Krásný (1993).

High variation of the aquifer hydraulic properties at different parts can be attributed to structural geological differences in the aquifer for example fracturing and contact between different geological units.

From the results, an empirical relationship between transmissivity and specific capacity has been established. The relationship is significant in that it can be used to derive approximate values of transmissivity in cases where full aquifer test is lacking.

It is recommended that future borehole drilling should be done on the eastern, northern and south eastern sections of Nairobi because they have high transmissivity hence higher maximum sustainable yields. The sections towards western and south western of the city recorded relatively low transmissivity hence lower maximum sustainable yields and should therefore be avoided be for future drilling.

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Figures

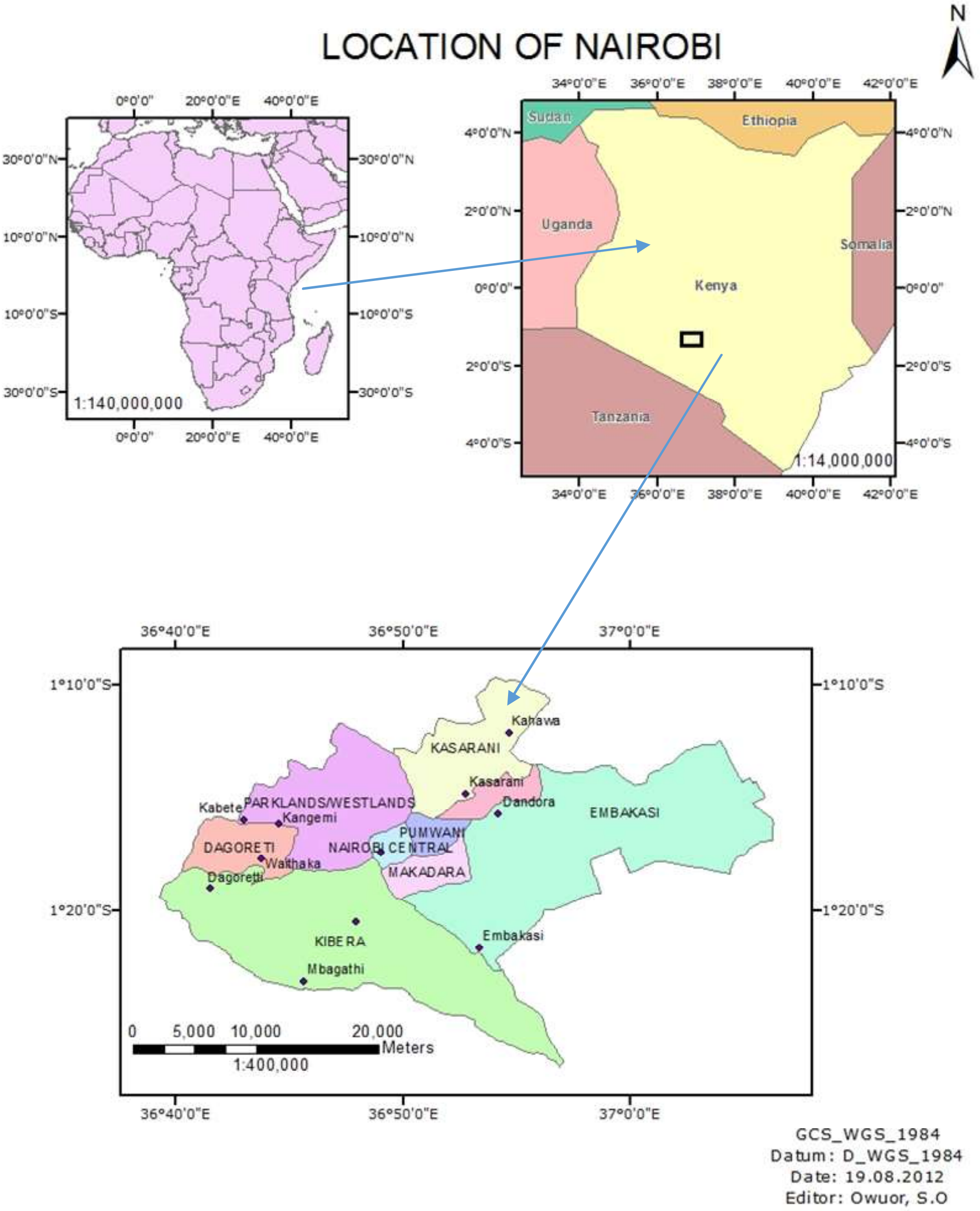

Figure 1: Position of Nairobi City (Modified from ESRI, 2010 and CCN, 2007).

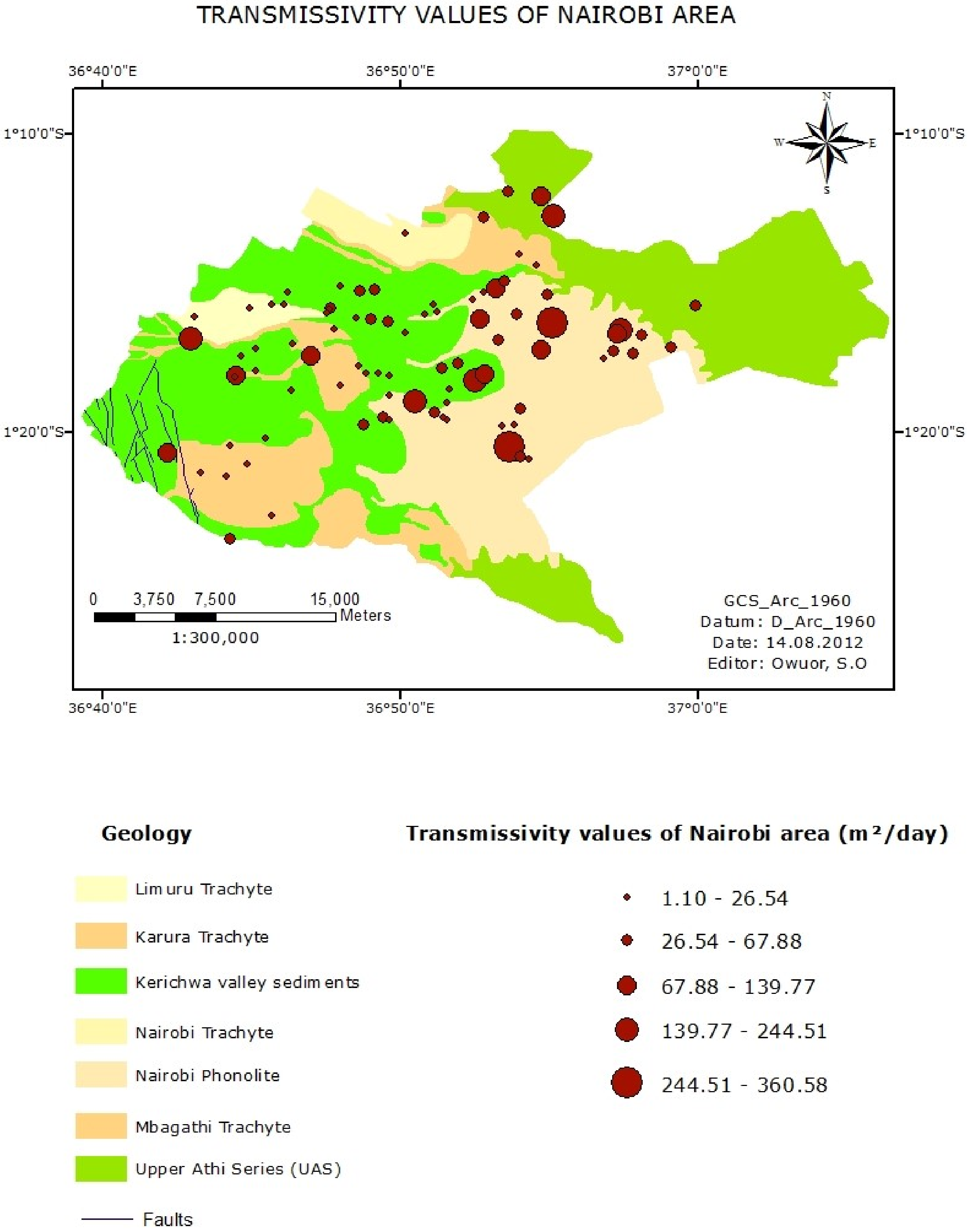

Figure 2: Map of transmissivity values of Nairobi area (m²/day).

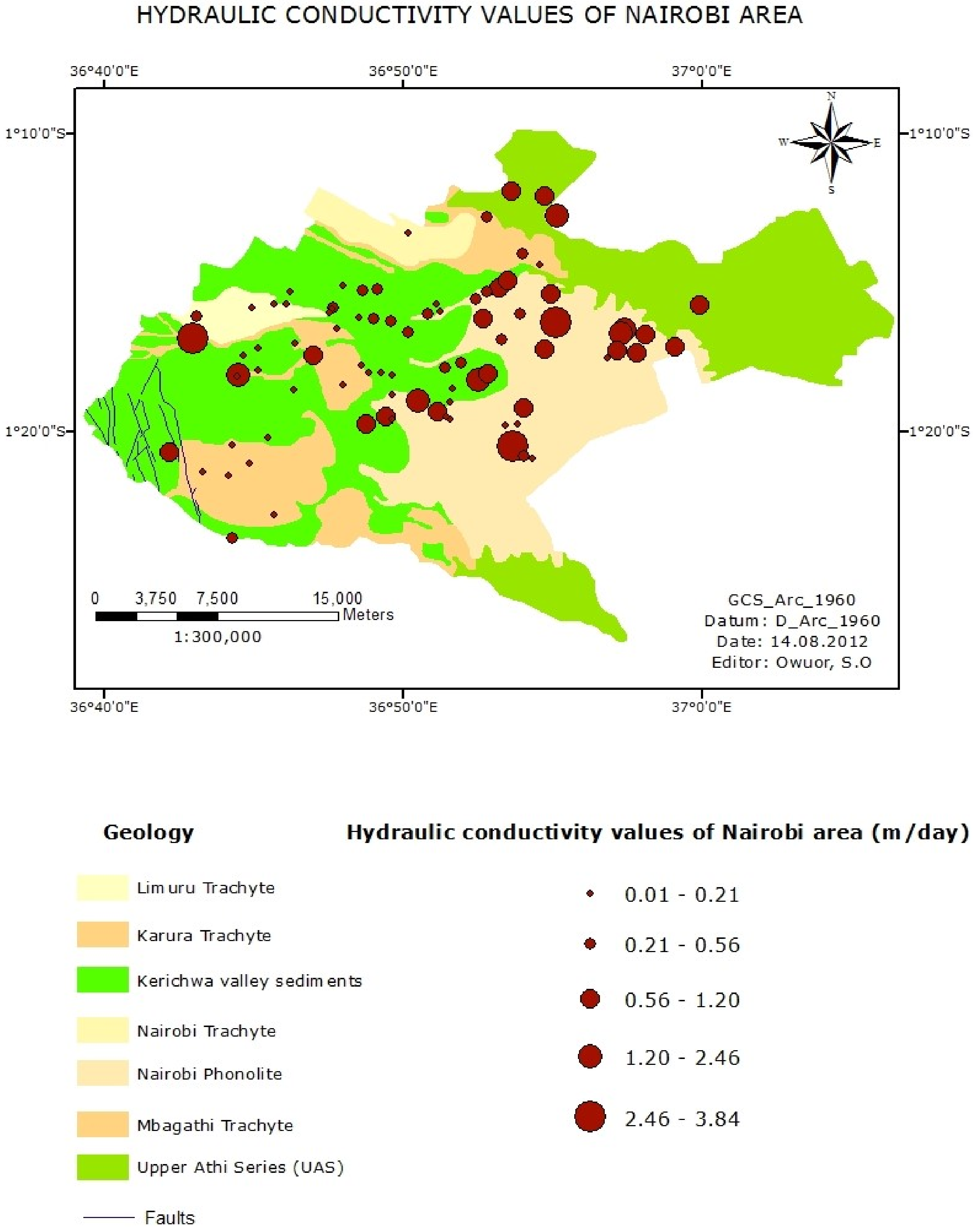

Figure 3: Map of hydraulic conductivity values of Nairobi area (m/day).

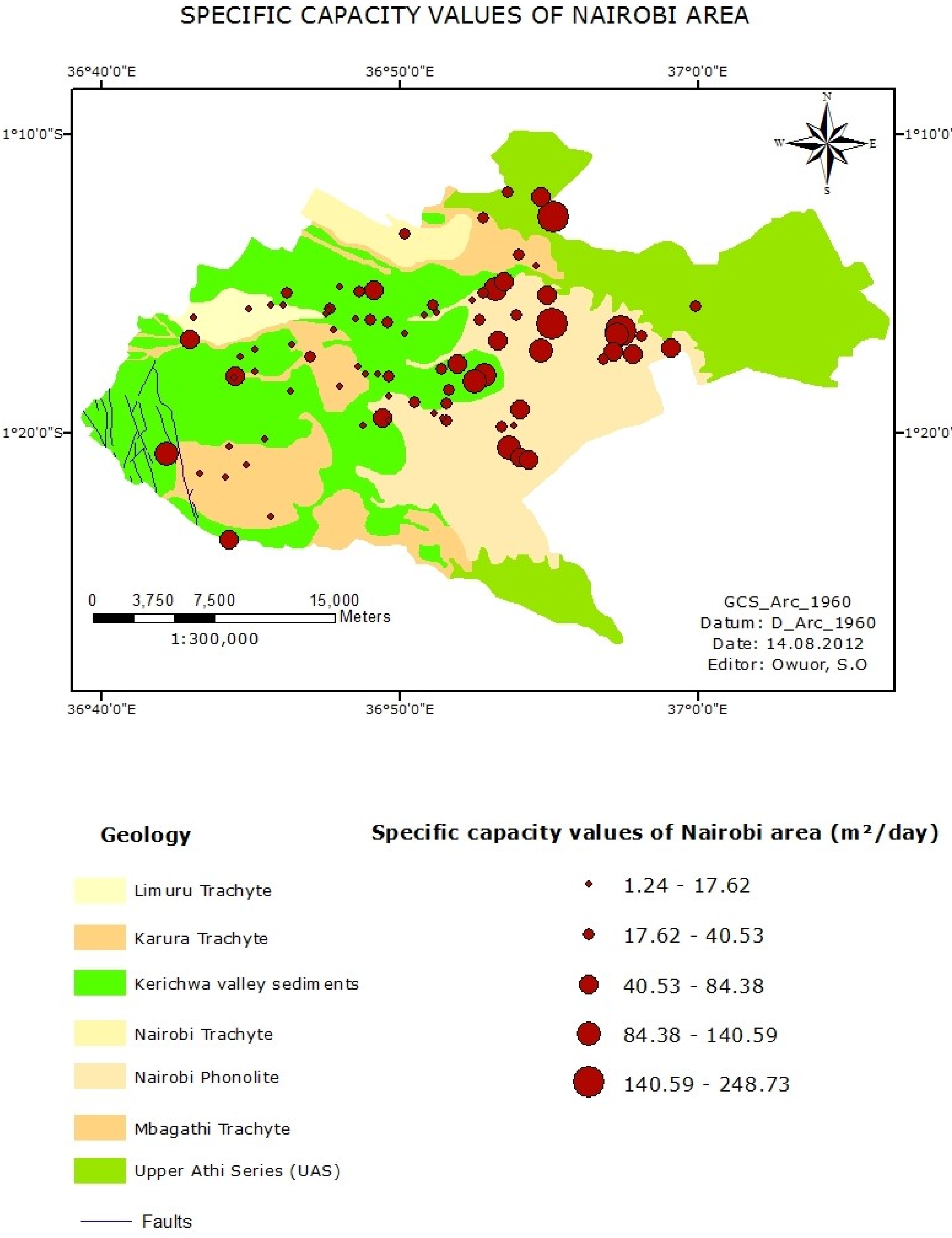

Figure 4: Map of specific capacity values of Nairobi area (m^2/day).

Tables

Table 1: Statistical summary of transmissivity estimates from different methods for Nairobi area

	Theis (m²/day)	Cooper- Jacob (m²/day)	Papadopulos-Cooper (m²/day)	Theis recovery (m²/day)
N	84	84	84	84
Min	1.11	1.11	1.10	1.29
Max	360.58	360.58	360.58	677.81
Mean	48.90	49.23	50.63	58.50
Std. error	7.65	7.44	7.53	11.13
Variance	4911.51	4644.24	4758.95	10408.74
Stand. dev	70.08	68.15	68.99	102.02
Median	22.25	24.077	24.36	22.42
25 prcntil	9.53	9.53	11.69	7.79
75 prcntil	49.54	50.22	56.35	60.33
Skewness	2.68	2.62	2.66	3.77
Kurtosis	7.53	7.57	7.86	17.51
Geom. mean	23.23	23.73	25.25	21.36

Table 2: Statistical summary of log transformed transmissivity values from different methods for Nairobi area

	Theis (m²/day)	Cooper-Jacob (m²/day)	Papadopulos-Cooper (m²/day)	Theis recovery (m²/day)
N	84	84	84	84
Min	0.045	0.045	0.041	0.11
Max	2.56	2.56	2.56	2.83
Mean	1.37	1.38	1.41	1.33
Std. error	0.059	0.059	0.058	0.07
Variance	0.29	0.30	0.28	0.42
Stand. dev	0.54	0.54	0.53	0.65
Median	1.35	1.38	1.39	1.35
25 prcntil	0.98	0.98	1.07	0.89
75 prcntil	1.70	1.70	1.75	1.78
Kurtosis	-0.26	-0.33	-0.26	-0.53
Geom. mean	1.22	1.23	1.26	1.1