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Full Length Research Paper

Evaluation of empirical formulae for the determination of hydraulic conductivity based on grain-size analysis

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Several empirical formulae were used to determine the hydraulic conductivity of aquifer materials in the Jimeta-Yola area. The results indicate that the best estimation of hydraulic conductivity is based on Terzaghi equation, followed by Kozeny-Carman, Hazen, Breyer and Slitcher equations, respectively. The mean values from these equations were 1508, 287.1, 213.3, 186.9 and 102.3 m/day. The estimated hydraulic conductivities from the different methods indicate the hydraulic conductivity of clean sand to gravelly materials. USBR method underestimated the hydraulic conductivity of the aquifer materials in the area. The method, indicate the hydraulic conductivity of fine sand.

Key words: Hydraulic conductivity, aquifer, empirical formulae, Bima Sandstone, sieve analysis.

INTRODUCTION

Hydraulic conductivity is a parameter describing the ease with which flow takes place through a porous medium (Schwartz and Zhang, 2003). The same author also stated that experiments have shown that hydraulic conductivity depends on both properties of the porous medium and the fluid (for example density and viscosity). Knowledge of hydraulic conductivity values and their distribution is an essential step towards conducting accurate and reliable analyses of hydraulic systems (Award and Al-bassam, 2001). Hydrogeologists always look for reliable techniques to determine hydraulic conductivity of aquifers with which they are concerned for better groundwater development, management and conservation (Odong, 2007). Many techniques for the determination of hydraulic conductivity under laboratory or field conditions have been described in Freeze and Cherry (1979); Todd (1980); Todd and May (2005). According to Uma et al. (1989), accurate estimation of hydraulic conductivity in the field environment is limited by the lack of precise knowledge of aquifer geometry and hydraulic boundaries. Economic consideration associated with field operations and well construction may also be a limiting factor. Alternatively, methods of estimating hydraulic conductivity from empirical formulae based on grain-size distribution characteristics have been developed and used to overcome these problems (Odong, 2007). Compared to aquifer tests, statistical grain-size methods are less expensive and less dependent on the geometry of porous media and hydraulic boundaries of the aquifer but reflects almost all the transmitting properties of the media (Alyamani and Sen, 1993; Award and Al-Bassam, 2001).

Researches from numerous investigators such as Hazen (1893), Krumbein and Monk (1942), Harleman et al. (1963), Terzaghi and Peck (1964), Masch and Denny (1966), Wiebega et al. (1970), Shepherd (1989), Uma et al. (1989) and Alyamani and Sen (1993) were considered in this study. The objective of this work is to evaluate the hydraulic conductivity of the aquifers in Jimeta-Yola area, using statistical grain-size methods. The findings from this work will aid to better groundwater resources development and its subsequent management.

Description of the study area

The study area is situated between latitudes 9°11'N to 9°20'N and longitudes 12°23'E to 12°33'E covering an

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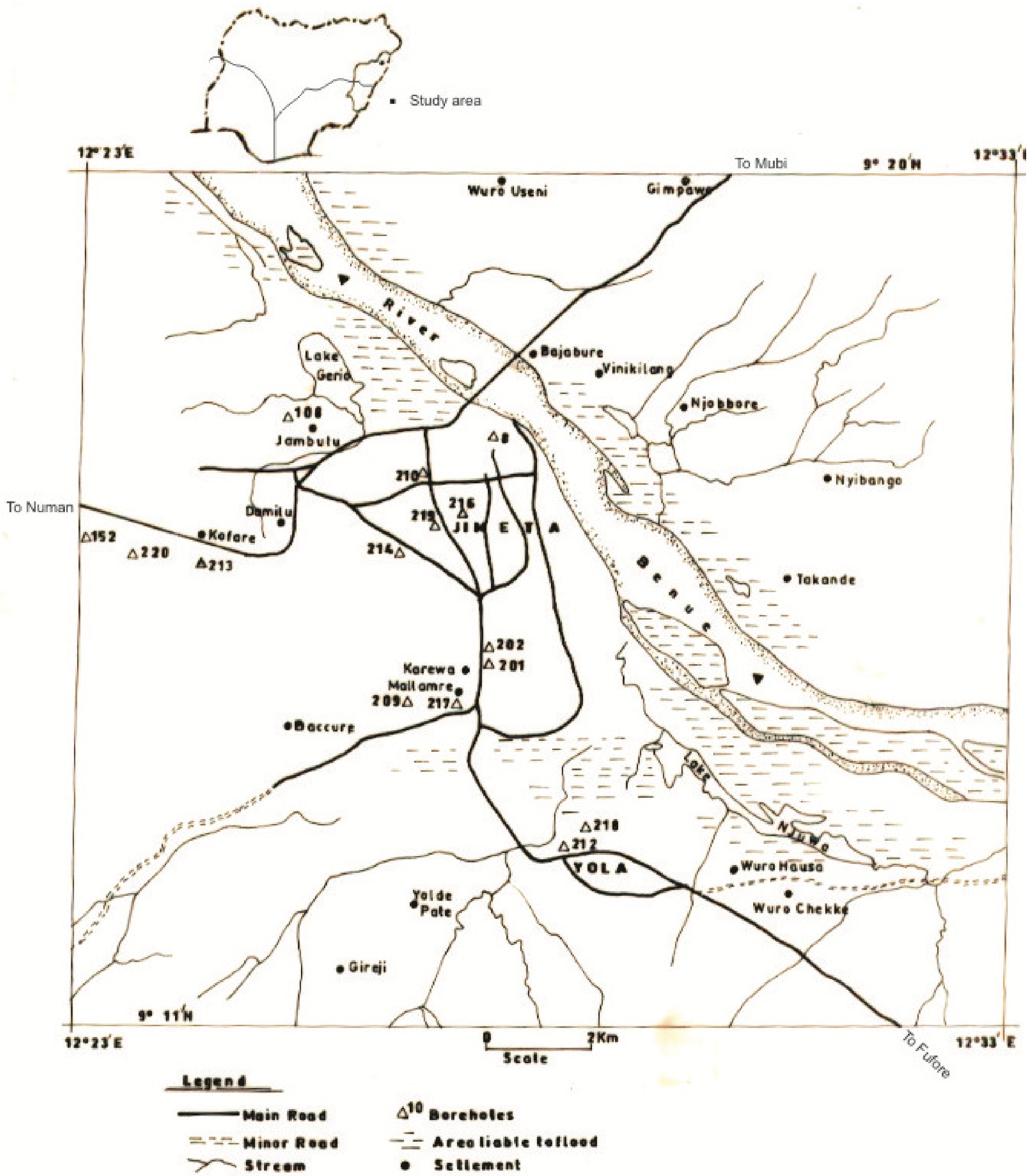

Figure 1. Map of the study area showing sample location.

estimated area of 305 km^2 (Figure 1). The area has a mean annual rainfall of 918.9 mm, and means monthly minimum temperature of 19°C and maximum temperature of 37.9°C. The mean monthly temperature is 28.5°C (Ishaku, 2007). The mean monthly relative humidity in Yola varied from 26% in February to 76% in August with mean relative humidity at 52.8% (Ishaku, 1995). The area is characterized by broadly flat to gentle undulations (Ishaku, 1995). The area is largely drained by the River Benue, which is characterized by extensive flood plains along which occur lakes Geriyo and Njuwa (Adekeye and Ishaku, 2004). Jimeta area is bordered by River Benue and lake Geriyo and is dissected by a number of small streams (Ntekim and Bello, 2001), while Yola is bordered by lake Njuwa in the east. The major occupation of the people is agriculture while industries such as Nimafoam, Faro bottling Company and some other small-scale industries occur in the area. The population of the area is about 325,925 based on 2006 population census.

The study area is underlain by the Albian-Aptian Bima Sandstone and recent river alluvium (Figure 2). The Bima

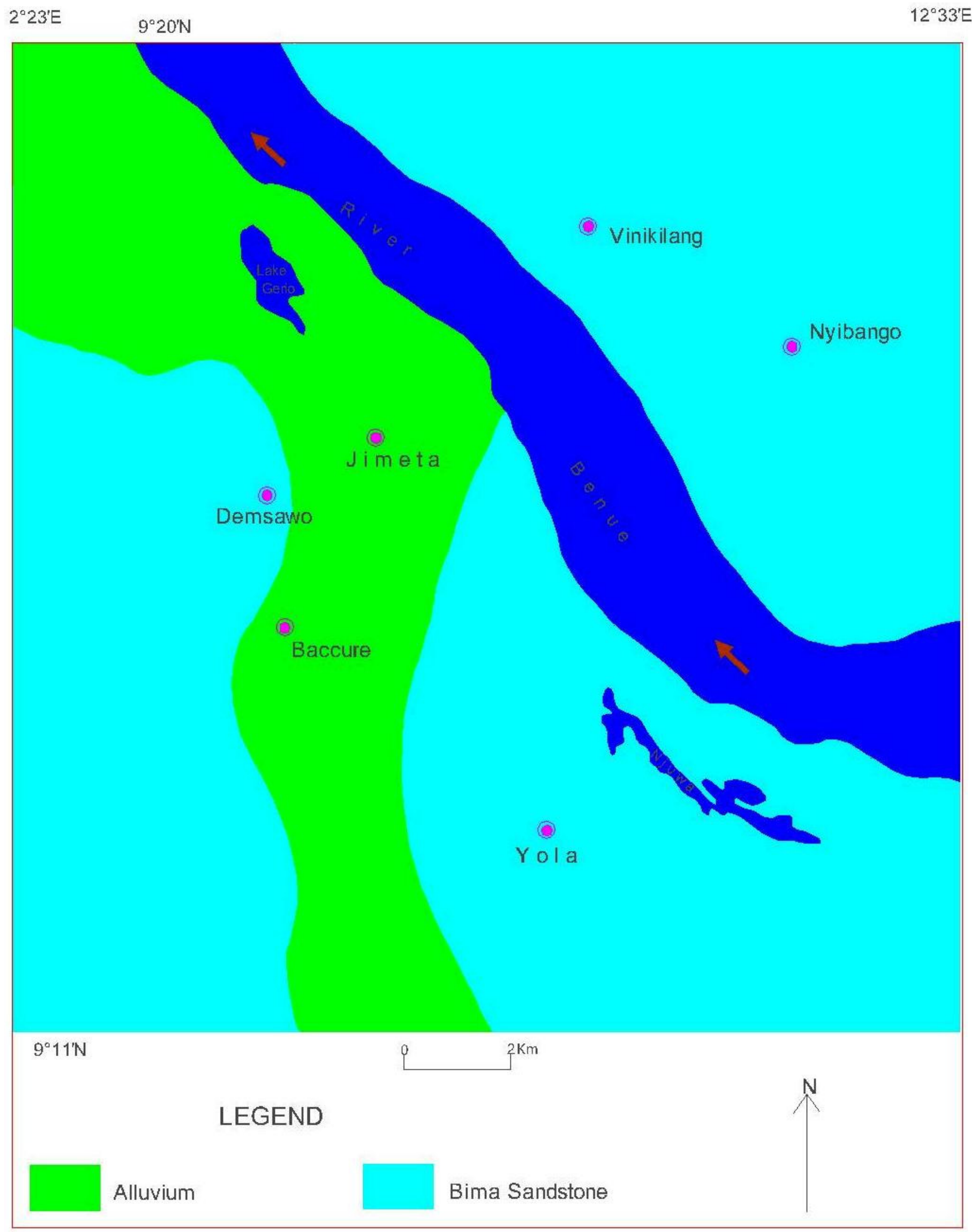

Figure 2. Geologic map of the study area.

Sandstone is the oldest Formation in the Upper Benue Trough and overlies the Basement Complex uncomformably. The detailed description of the Bima Sandstone were provided by Carter et al. (1963), Allix (1983), Popoff et al. (1986), Popoff (1988), and Guiraud (1990a, 1991a) into B1, B2 and B3 known as the Bima group. The outcrops of the Bima group belong to the Bima 2 and 3 in the Yola arm (Braide, 1992). The Bima Sandstone (B2) varies from fine to coarse grained (Allix, 1983), and the deposits were regarded as of proximal braided river origin (Guirand, 1990a, 1990b, 1991a In Zaborski, 1998). The Bima Sandstone (B2) is widely distributed, and is characterized by trough and tabular cross-bedding. The sandstone ranges from 100 to 500 m thick. The upper Bima Sandstone (B3) is fairly homogenous, relatively mature, and fine to coarse-grained sandstone, characterized by tabular cross-bedding, convolute bedding and overturned cross-bedding (Zaborski et al., 1997). The thickness ranged from 500 to 1500 m. Lithologically, the Bima Sandstone consists of feldspathic sandstone, grits, pebble beds and clay intercalations in some places (Eduvie, 2000). Borehole litholgic logs in the area reveal the presence of lateritic soils, sandstones, clays, mudstone, siltstones and ironstones (Ishaku and Ezeigbo, 2000).

The Bima Sandstone occurs in the southwestern, southeastern and northeastern parts of the study area (Figure 2). The river alluvium (recent) belongs to the quaternary age and is found along the main course of the Benue River, and extends towards the northeast and southern parts of the study area (Figure 2). The river alluvium consists of poorly sorted sands, clays, siltstones and pebbly sand (Ishaku and Ezeigbo, 2000; Yenika et al., 2003). Depths to water in the hand-dug wells range from 0.8 to 12.4 m in the dry season, and it is 0.05 to 11.9 m in the rainy season. Depths to water in boreholes range from 1.8 to 40.5 m in the dry season, and ranges from 1.1 to 38.8 m in the rainy season (Ishaku and Ezeigbo, 2008). The average hydraulic conductivity (K) for the aquifers is 1.63×10^{-6} m/s and average transmissivity (T) is 1.24×10^{-2} m^2/s (Ishaku, 1995).

MATERIALS AND METHODS

The field work for this study was conducted in several locations, covering the entire area of study (Figure 1). Fifteen representative samples were collected during borehole drilling operations in 2003 and 2004. The samples were collected and described at intervals of 3 m. The samples were subjected to mechanical sieve analysis, in order to construct the grain-size distribution curves as shown in Figure 3. The grain-size diameters d10, d20, d30, d50 and d60 were read off from the grain-size distribution curves. The statistical grain-size methods were then employed to determine the hydraulic conductivity values as presented in Table 1.

Grain-size analysis

Empirical methods are used to determine the hydraulic conductivity of porous medium materials from the grain-size analysis (Ayer et al., 1998). Vukovic and Soro (1992) summarized several empirical methods from former studies and presented a general formula:

$$K= \frac{g}{\nu}.C.f(n).de2 \quad (1)$$

Where K= hydraulic conductivity; g=acceleration due to gravity; v= kinematic viscosity; C= sorting coefficient; f(n)= porosity function, and de=effective grain diameter. The values of C, f(n) and de are dependent on the different methods used in the grain-size analysis. Porosity can be derived from the empirical relationship between porosity and the coefficient of grain uniformity (U) according to Vukovic and Soro (1992) as follows:

$$n= 0.255(1+ 0.83U) \quad (2)$$

where U is the coefficient of grain uniformity and is given by:

$$U= \frac{d60}{d10} \quad (3)$$

Here, d60 and d10 are the grain diameter in (mm) for which 60 and 10% of the sample respectively are finer than (Odong, 2007). The empirical formula which were formed on the same basis as represented in Equation (1) vary with C, f(n) and de. The different empirical formulas employed in this study are presented below:

$$\text{Hazen: } K= \frac{g}{\nu} \times 6 \times 10^{-4}\{1+ 10(n-0.26)\} d_{10}^2 \quad (4)$$

Hazen formula was originally developed for determination of hydraulic conductivity of uniformly graded sand but is also useful for fine sand to gravel range, provided the sediment has a uniformity coefficient less than 5 and effective grain size between 0.1 and 3 mm.

$$\text{Kozeny-Carman: } K= \frac{g}{\nu} \times 8.3 \times 10^{-2}\left[\frac{n^3}{(1-n)^2}\right] \quad (5)$$

The equation is one of the most widely accepted and used derivations of permeability as a function of the characteristics of the soil medium (Odong, 2007). The equation however is not appropriate for soil with effective size above 3 mm or clayey soils (Carrier, 2003).

$$\text{Breyer: } K= \frac{g}{\nu} \times 6 \times 10^{-4} \log \frac{500}{U} d_{10}^2 \quad (6)$$

The formula is often considered most useful for materials with heterogenous distributions and poorly sorted grains with uniformity coefficient between 1 and 20, and effective grain size between 0.06 and 0.6 mm.

$$\text{Slitcher: } K= \frac{g}{\nu} \times 1 \times 10^{-2}\, n^{3.287} d_{10}^2 \quad (7)$$

The formula is most applicable for grain size between 0.01 and 5 mm.

$$\text{Terzaghi: } K= \frac{g}{\nu} . C_T . \left[\frac{n-0.13}{\sqrt[3]{1-n}}\right]2 \quad (8)$$

Where the Ct= sorting coefficient and 61x10-3 < Ct<107x10-3. An average value of 8.4x10-3 is used in this study.

$$\text{USBS: } K= \frac{g}{\nu} \times 4.8 \times 10^{-4} d_{20}^{0.3} \times d_{20}^2 \quad (9)$$

The formula is most suitable for medium-grain sand with uniformity coefficient less than 5 (Cheng and Chen, 2007).

The $\frac{g}{\nu}$ from the above equations is taken as 9.77×10^6 for water at 20°C (Schwartz and Zhang, 2003: 52).

RESULTS AND DISCUSSION

The hydraulic conductivity values computed from the different statistical grain size methods are presented in

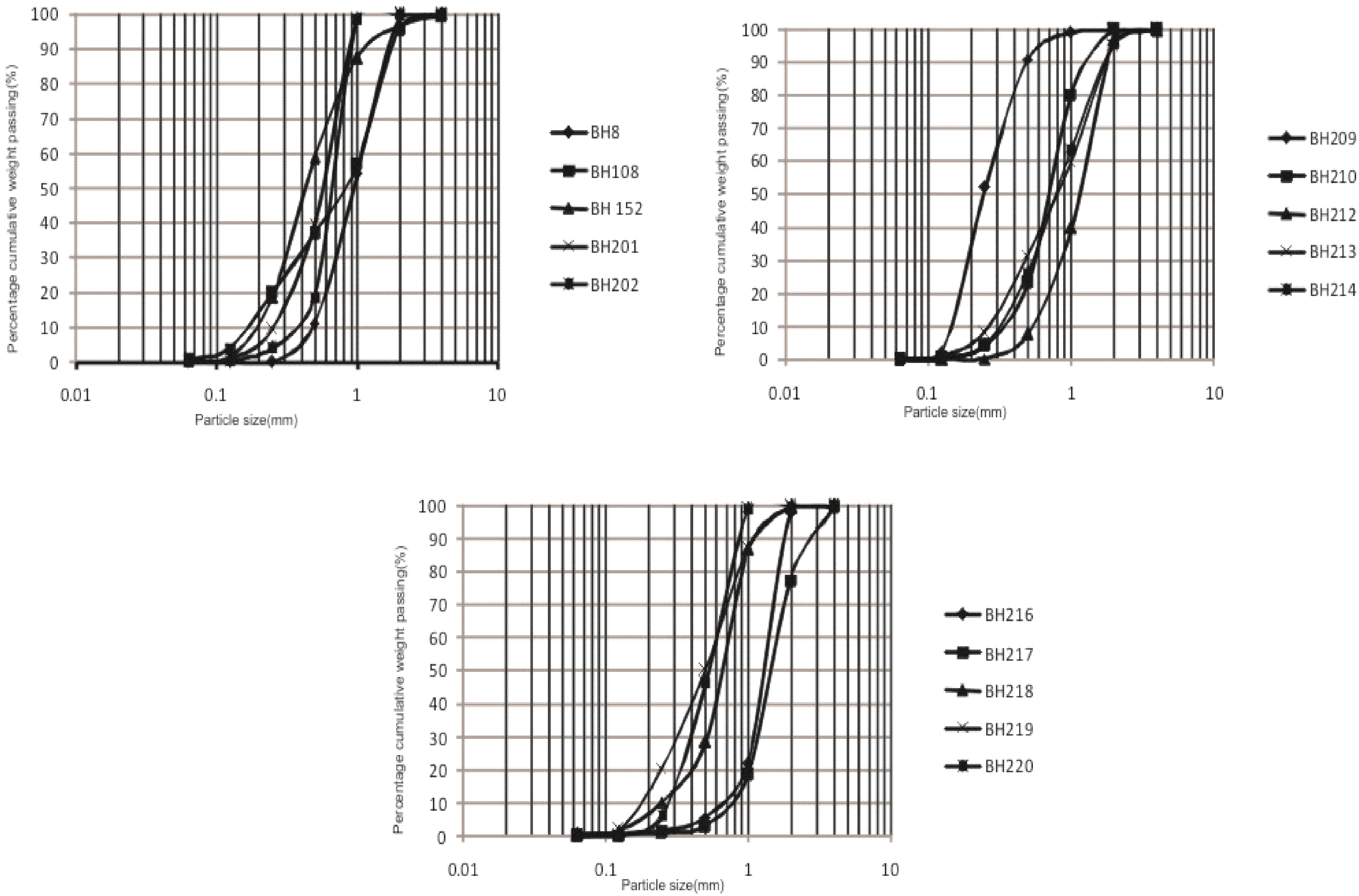

Figure 3. Grain size distribution curves of representative aquifer materials.

Table 1. Soil particle size distribution and hydraulic conductivity values computed from the statistical grain size method.

Project No (BH)	Lithology	d_{10} (mm)	d_{20} (mm)	d_{30} (mm)	d_{50} (mm)	d_{60} (mm)	(U)	(n)	(C_c)	Hazen (m/day)	K-C (m/day)	Breyer (m/day)	Slitcher (m/day)	Terzaghi (m/day)	USBR
8	Fine to medium sandstone	0.50	0.60	0.70	0.95	1.20	2.4	0.42	0.82	222.8	385.0	293.6	121.9	114.9	15.8
108	Coarse sandstone	0.18	0.25	0.37	0.80	1.20	6.67	0.33	0.63	27.9	18.2	30.8	7.2	2127.2	2.1
52	Fine to medium sandstone	0.20	0.25	0.32	0.44	0.50	2.5	0.67	1.02	103.3	756.7	46.6	90.5	1739.1	2.1
201	Fine to coarse sandstone	0.25	0.35	0.44	0.57	0.65	2.6	0.41	1.19	79.1	86.7	72.3	281.5	492.4	4.6
202	Fine to medium sandstone	0.40	0.50	0.56	0.66	0.71	1.78	0.44	1.10	226.9	304.5	81.0	90.9	1621.4	10.4
209	Fine sandstone	0.15	0.17	0.19	0.25	0.28	1.87	0.43	0.86	30.8	38.6	27.7	11.9	208.4	0.9
210	Fine to medium sandstone	0.36	0.48	0.55	0.80	0.93	2.58	0.41	0.90	164.6	180.3	150.6	58.6	1024.2	9.4
212	Fine to coarse sandstone	0.55	0.70	0.85	1.25	1.40	2.55	0.41	0.94	383.0	180.3	351.2	136.3	2383.3	22.5
213	Fine to coarse sandstone	0.27	0.36	0.47	0.80	1.00	3.7	0.38	0.82	81.2	72.9	78.7	25.6	447.2	4.9
214	Fine to coarse sandstone	0.33	0.43	0.55	0.80	0.95	2.88	0.40	0.96	132.5	135.8	123.6	45.3	798.5	7.3
216	Fine to coarse sandstone	0.70	1.00	1.20	1.40	1.50	2.14	0.43	1.37	670.1	840.1	587.8	258.1	4539.1	0.3
217	Fine to medium sandstone	0.80	1.00	1.30	1.50	1.70	2.13	0.43	1.24	875.2	1097.3	768.4	337.1	5928.6	0.3
218	Fine to coarse sandstone	0.25	0.42	0.52	0.66	1.50	6.0	0.34	0.72	57.0	39.5	60.8	15.2	258.2	6.9

Table 1. Contd.

219	Fine to medium sandstone	0.18	0.25	0.33	0.52	0.60	3.33	0.39	1.00	37.7	36.2	35.7	12.4	215.0	2.1
220	Fine to medium sandstone	0.28	0.34	0.39	0.53	0.60	2.14	0.43	0.91	107.2	134.4	94.1	41.3	726.3	4.3

Table 2. Summary of hydraulic conductivity values from the different statistical grain-size methods.

	Minimum	Maximum	Mean	Std. deviation
Hazen	27.90	875.20	213.2867	248.78465
Kozen	18.20	1097.30	287.1000	338.69747
Breyer	27.70	768.40	186.8600	222.86970
Slitcher	7.20	337.10	102.2533	107.22933
Terzaghi	114.90	5928.60	1508.2533	1696.92749
USBR	.30	22.50	6.2600	6.22997

Table 1 while the summary of the results are presented in Table 2. Table 2 indicate that Hazen method reveal hydraulic conductivity values ranging from 27.9 to 875.2 m/day with an average of 213.3 m/day. Kozey-Carman gave values between 18.2 to 1097.3 m/day and average of 287.1 m/day. Breyer and Slitcher gave values from 27.7 to 768.4 m/day with mean values of 186.9 and 102.3 m/day, respectively. Terzaghi and USBR reveal values from 114.9 to 5928.6 m/day and 0.3 to 22.5 m/day and averages of 1502.3 and 6.3 m/day, respectively.

The overall results showed that, the hydraulic conductivities calculated using the USBR and Slitcher methods are in all cases lower than for other methods which is consistent with the findings of Vukovic and Soro (1992) and Cheng and Chen (2007). These methods are always considered inaccurate (Odong, 2007). Terzaghi method gave the highest mean value which may be attributed to the use of an average value ($8.4x10^{-3}$) of sorting coefficient. Average conductivity values by Hazen, Kozeny-Carman and Breyer gave similar values. The overall mean hydraulic conductivity values estimated by the different statistical grain size methods were in the order of Terzahgi>Kozeny-Carman>Hazen>Breyer>Slitcher>USBR. The mean conductivity values reveal by the different methods indicate the hydraulic conductivity of clean sand to gravelly materials based on Todd (1980) classification. The mean hydraulic conductivity estimated by USBR method however indicated the hydraulic conductivity of fine sand. Based on the conditions stated under each method, the different statistical grain size methods are suitable for the determination of hydraulic conductivity of aquifer materials in the study area. USBR method may be unsuitable for the determination of hydraulic conductivity of aquifer materials in the study area. The method may have underestimated the hydraulic conductivities of the aquifer materials. In the use of Breyer formula which is suitable for effective grain size ranging from 0.06 to 0.6 mm, Table 1 indicated that BH216 and BH217 indicate d_{10}^2 greater than 0.6 mm. Also, Terzaghi method which is useful for larger grain size, Table 1 indicate the aquifer materials from seven samples out of 15 samples collected are characterized by fine to coarse grain and therefore can allow for the use of the method in the study area.

Conclusion

Based on the analysis and results from this study, the following conclusions can be drawn: The best overall estimation of hydraulic conductivity is reached based on Terzaghi's formula followed by Kozeny-Carman formula, Hazen, Breyer and Slitcher equations. USBR equation underestimated the hydraulic conductivities of the aquifer materials in the area. The hydraulic conductivities estimated from the different equations indicate hydraulic conductivities of

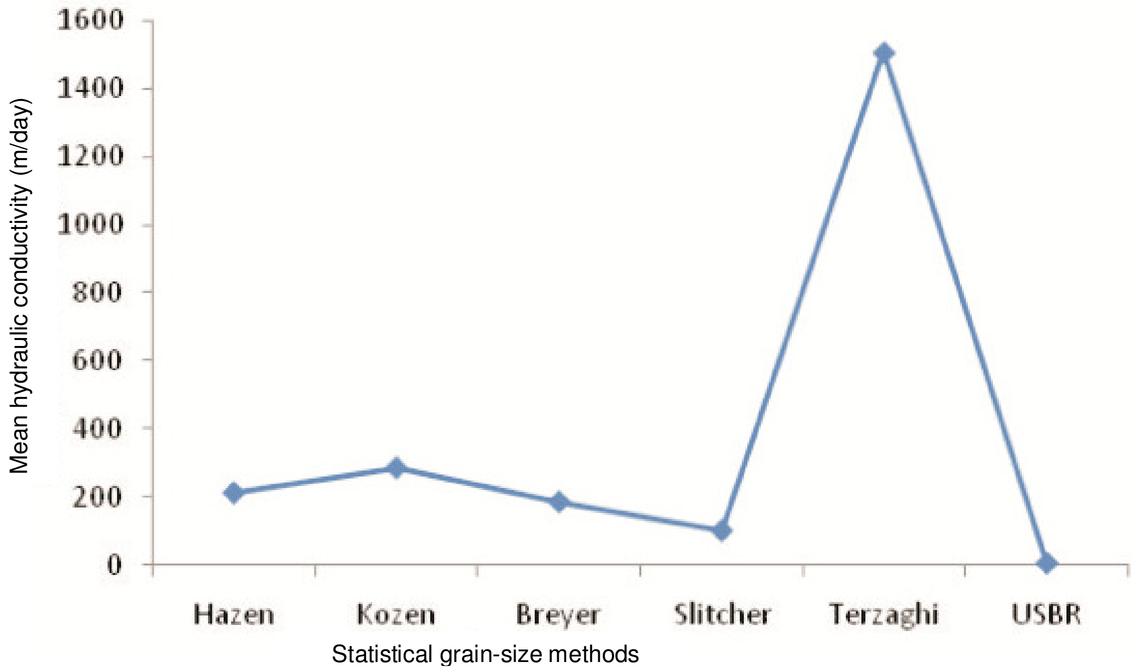

Figure 4. Plots of hydraulic conductivity versus grain-size methods.

clean sand to gravelly materials. USBR equation indicates moderate hydraulic conductivity and corresponds to hydraulic conductivity of fine sand. Therefore, the most suitable formulae for the estimation of hydraulic conductivities in this study were as follows:

Terzaghi formula= 1508 m/day
Kozeny-Carman formula= 287.1 m/day
Hazen formula= 213.3 m/day
Breyer formula= 186.9 m/day
Slitcher formula= 102.3 m/day

It can also be observed from (Figure 4) that after plotting the mean hydraulic conductivity against the different statistical grain size methods Terzaghi had the highest while USBR the lowest.

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