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Research paper

A new method for estimating hydraulic conductivity in un-screened concrete-lined large-diameter hand-dug wells

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ABSTRACT

The use of large-diameter hand-dug wells as main source of rural water supply for drinking, domestic and irrigation uses in many developing countries has offer an opportunity to developed Darcy-based methods for estimating hydraulic conductivity in screened-lined large-diameter hand-dug wells to determine the yield and discharge potential of the wells. However, in many rural areas of sub-Saharan African countries, the use of un-screened concrete lining is most common method of protecting large-diameter hand-dug wells against collapsing and pollution due to the affordability of the method. The use of un-screened concrete lining prevents horizontal water flow to the well and inflow of water in un-screened concrete well occur through well base, therefore, existing Darcy-based method not suitable to estimate hydraulic conductivity for this well design. This study proposed a new method for estimating aquifer hydraulic conductivity for un-screened concrete-lined large-diameter hand-dug wells. To demonstrate the viability of the new method, field recovery tests were conducted in twelve (12) un-screened concrete lined large-diameter hand-dug wells to estimate apparent hydraulic conductivity (Ka) of aquifer formation. The twelve (12) un-screened concrete wells were screened for the second round of recovery tests to estimate horizontal hydraulic conductivity K. The results showed that the estimated apparent hydraulic conductivity Ka values were lower than the horizontal hydraulic conductivity K values and this show effect of un-screened concrete-lining. A relationship between Ka and K was established to make a correction factor for estimation of K from Ka by a regression analysis which showed a linear regression of 0.78 with a significant strong relationship of 0.00 between Ka and K using a bivariate Pearson correlation coefficient. The new method will be useful to determine well yield most especially in the rural areas of developing countries where un-screened concrete-lined large-diameter hand-dug wells are being practiced.

1. Introduction

Accessibility to water supply in the rural areas has continued to be one of the most complex challenges facing developing African countries, particularly in sub-Saharan Africa. Today, this region accounts for about 40% of the water stress globally (United Nations, 2018). Groundwater serves as the most affordable means of meeting the ever-increasing demands of water resources in the rural areas for different purposes such as drinking, domestic and agricultural uses. Groundwater development has reduced poverty and promote sustainable livelihood in many rural communities, particularly in the sub-Saharan African countries (Calow et al., 2002). The most affordable way of accessing groundwater in the rural areas for drinking, domestic and irrigation uses is through large-diameter hand-dug wells.

Large-diameter hand-dug wells are suited to unconsolidated formations which make it easy to excavate by using manual methods and can be installed in any kind of formation where manual excavation is possible. Therefore, it is possible to say that in some good hydrogeological situations, large-diameter hand-dug wells can be cost-effective and cheaper to excavate and give good yield like borehole. Some good examples of these include alluvial aquifers where the water-bearing alluvial deposits are basically unconsolidated and can be excavated manually; these also goes for weathered basement aquifers. The depths of the large-diameter hand-dug wells are mostly varying,

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Fig. 1. Abstracting water from large-diameter hand-dug well in rural area of Nigeria.

Fig. 2. Showing un-screened concrete-lined large-diameter hand-dug well.

depending on the hydrogeological/geohydrological situations and water needs of the concerned area (Gomo et al., 2019). Though some developed countries have changed to modernised water system by constructing boreholes but large-diameter hand-dug wells are still used in rural areas of developing countries (Aina and Oshunrinade, 2016; Gipson and Singer, 1969; Gomo et al., 2019; 1999; Rushton and De Silva, 2016) as shown in Fig. 1.

Large-diameter hand-dug well construction includes the use of curb lining such as brick, rock and concrete to protect the well against collapsing. The lining is screened to allow horizontal water flow to the well and increase the well yield. For the screened hand-dug wells, standard recovery methods were developed based on Darcy's law (Darcy, 1856) to estimate aquifer hydraulic conductivity that used to determine aquifer yield and well discharge. These includes the work of Boulton and Streltsova (1976); Herbert and Kitching (1981); MacDonald et al., 2008; Papadopulos and Cooper (1967); Rupp et al., 2011; Rupp et al. (2011); Rushton & De Silva, 2016; Uribe et al. (2014)). The use of un-screened concrete-lining in protecting large-diameter hand-dug well (Fig. 2) has been a most common method of lining in many rural areas of developing sub-Saharan African countries due to the simplicity of the method and affordable materials involved.

The use of un-screened concrete-lining prevents horizontal water flow to the well and inflow of water occur through well base (Fig. 3a), this make Darcy-based method for screened-lined well (Fig. 3b) not suitable to be used for this well design. Based on reviewed of existing methods for estimating aquifer hydraulic conductivity in hand-dug wells, it is possible to argue that the estimation of aquifer hydraulic conductivity in un-screened concrete-lined large-diameter hand-dug wells have not been covered in previous research studies. This study proposed a new method for estimating hydraulic conductivity in un-screened concrete-lined large-diameter hand-dug wells. To estimate horizontal hydraulic conductivity K of aquifer formation in un-screened concrete-lined large-diameter hand-dug wells, the apparent hydraulic conductivity Ka was determined through which horizontal hydraulic conductivity (K) of aquifer formation was estimated.

2. Method development

Fig. 4 shows the flow in an unconfined aquifer for un-screened concrete-lined, large-diameter hand-dug well, with the basic components of the proposed equation for estimation of Ka of the aquifer formation in an unscreened concrete-lined, large-diameter hand-dug well.

The derivation of groundwater flow starts from Darcy's law (Darcy, 1856). The Darcy's law is a simple proportional relationship between the instantaneous inflow/outflow rate through a porous medium, the viscosity of the fluid and the pressure drop over a given distance. The flow into the well (Q) at a particular value of y can be determined.

From Darcy's law, we get:

$$Q = KiA \tag{1}$$

In un-screened concrete-lined large-diameter hand-dug well, the water flows to the well through the uncemented well base; therefore, the area providing water to the well is given as $A = \pi r^2$. From Fig. 4 above, r_c is the inside radius of the concrete-lined well (m), r_w is the distance from the well centre to the original aquifer or the inside radius plus the thickness of the concrete lining (m), y is the vertical distance between the water level in the well and equilibrium water table in the aquifer, y is (h_o–h) where h_o is the equilibrium water table in aquifer (m) and h is the water level in the well (m).

From Fig. 4:

$$Q = \pi r_c^2 K_a \frac{\partial h}{\partial r_w} \tag{2}$$

By re-arranging eq. (2):

$$\partial h = \frac{Q}{\pi r_c K_a} \frac{\partial r_w}{r_c} \tag{3}$$

Integrated eq. (3):

$$h = \frac{Q}{\pi r_w K_a} \ln(r_c) + c \tag{4}$$

$$h = h_0 \ at \ r_c = R_e \tag{5}$$

where R_e is the effective radius over which y is dissipated (L) and c is constant

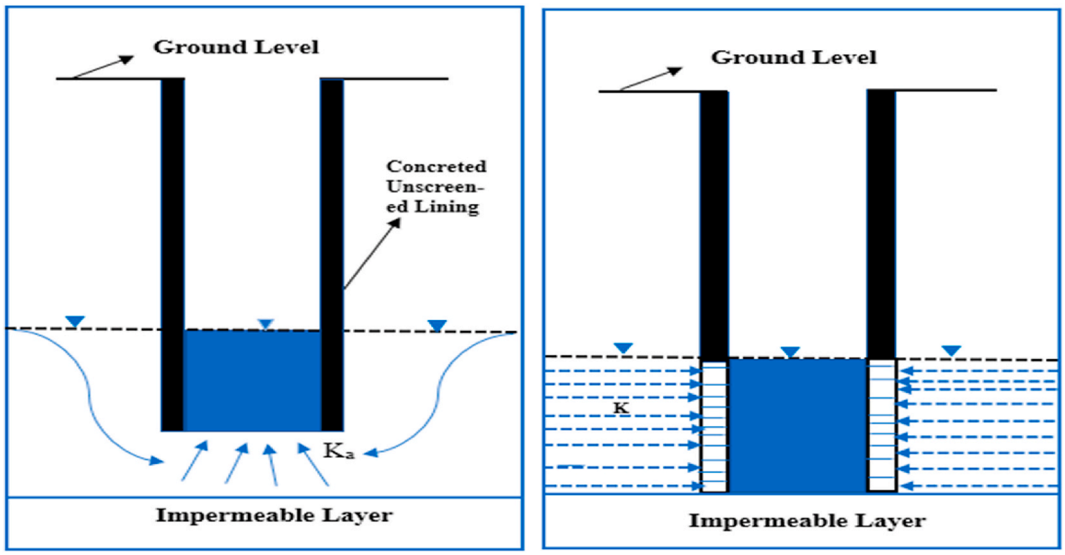

Fig. 3. a Showing water flow to the well through well base in un-screened well (K_a is apparent hydraulic conductivity) b Showing water flow to the well in a screened well (K is horizontal hydraulic conductivity).

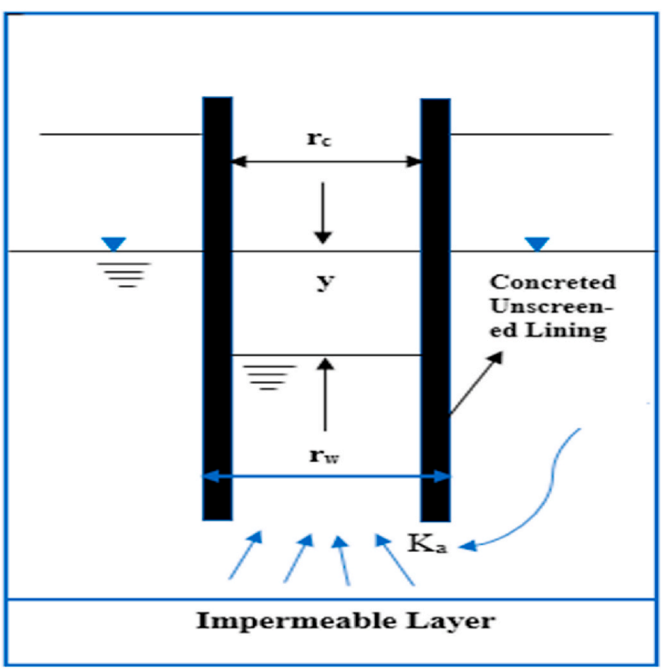

Fig. 4. Showing flow in un-screened concrete-lined large-diameter hand-dug well in unconfined aquifer.

$$h_0 = \frac{Q}{\pi r_w K_a}\ln(R_e) + c \tag{6}$$

Eliminating the constant (*c*):

$$h_0 - h\,(y) = \frac{Q}{\pi r_w K_a}\ln\left(\frac{R_e}{r_w}\right) \text{ (from integration of equation 3 above)} \tag{7}$$

where:

- h_o is the equilibrium water table in aquifer (m)
- h is the water level in the well (m)
- y is the vertical distance between the water level in the well and equilibrium water table in the aquifer (m)

From above:

$$y = \frac{Q}{\pi r_w K_a}\ln\left(\frac{R_e}{r_w}\right) \tag{8}$$

The inflow of water to the well (Q) at a particular value of *y* for unscreened concrete-lined large-diameter hand-dug well can be calculated as:

$$Q = \pi r_w K_a \frac{y}{ln\left(\frac{R_e}{r_w}\right)} \tag{9}$$

where:

- Q is the inflow of water to the well (length^3/time)
- K_a is the apparent hydraulic conductivity of the aquifer (length/time)
- y is the vertical distance between the water level in the well and the equilibrium water table in the aquifer (L)
- R_e is the effective radius over which y is dissipated (L)
- r_W is distance from well centre to the original aquifer (L)

The terms y, R_e, and r_W are expressed in units of length. In a large-diameter hand-dug well, when the water level in the well is lowered, the recovery or rate of rise (d_y/d_t) of the water level back to the initial or pretest level is related to the inflow Q (Herbert and Kitching, 1981; Rushton and Holt, 1981) given as:

$$\frac{dy}{dt} = \frac{Q}{\pi r_c^2} \tag{10}$$

where:

- Q is the inflow of water to the well (L)
- y is the head change (L)
- t is the time (t)
- r_c is the inner radius of the well (L)

From eq. (9) above, where $= \pi r_w K_a \frac{y}{\ln\left(\frac{R_e}{r_w}\right)}$.

By inserting equation (9) into equation (10) and integrate, a working equation will be derived to determine apparent hydraulic conductivity (K_a) for an un-screened concrete-lined large-diameter hand-dug well as follows:

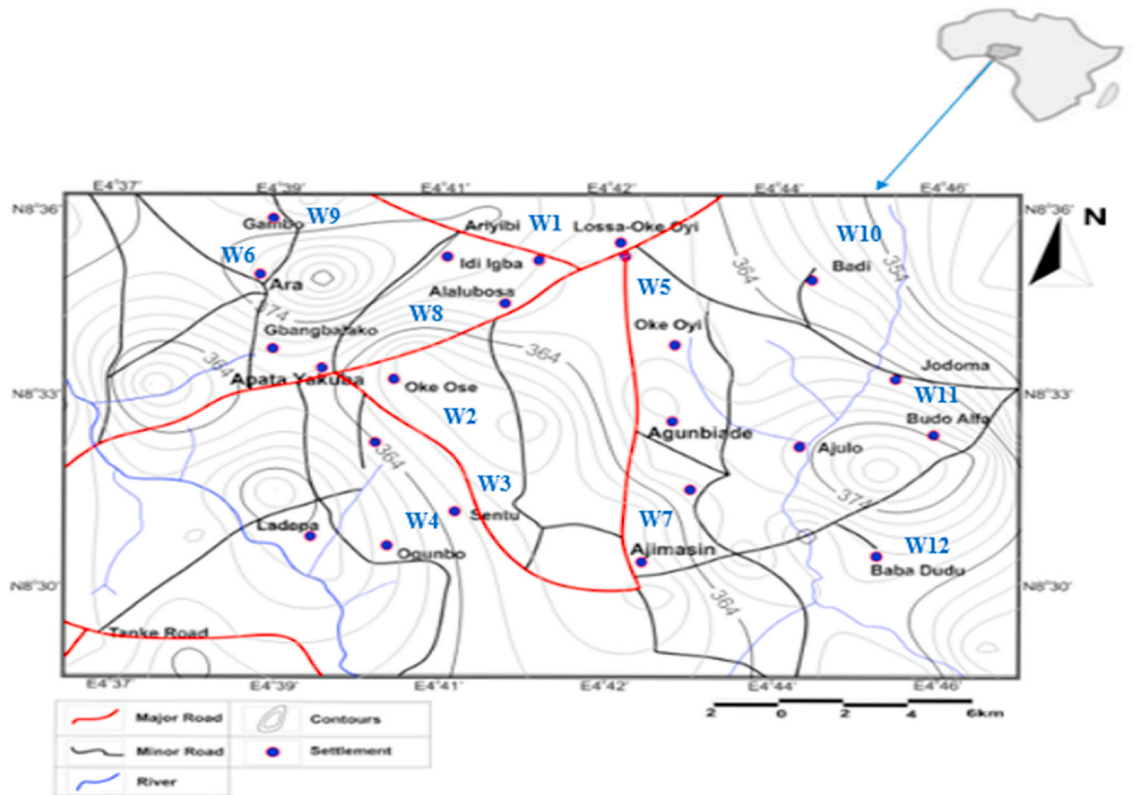

Fig. 5. Nigeria map showing location of study area.

Combining eq. (9) and eq. (10) and integrate:

$$\frac{1}{y}\,dy = \frac{K_a r_w}{r_c^2 \ln\left(\frac{R_e}{r_w}\right)}\,dt \tag{11}$$

Integrated eq. (11):

$$lny = \frac{K_a r_w t}{r_c^2 \ln\left(\frac{R_e}{r_w}\right)} + constant \tag{12}$$

when applying eq. (12), between the limits y_o at $t = 0$ and y_t at t and solve for K_a as follows:

$$lny_0 = \frac{K_a r_w t}{r_c^2 \ln\left(\frac{R_e}{r_w}\right)} + lny_t \tag{13}$$

$$lny_o - lny_t = \frac{K_a r_w t}{r_c^2 \ln\left(\frac{R_e}{r_w}\right)} \tag{14}$$

$$ln\frac{y_o}{y_t} = \frac{K_a r_w t}{r_c^2 \ln\left(\frac{R_e}{r_w}\right)} \tag{15}$$

$$Ka = \frac{r_c^2 \ln\left(\frac{R_e}{r_w}\right)}{r_w}\,\frac{1}{t}\,ln\frac{y_o}{y_t}\ \text{(L/T)} \tag{16}$$

Ka is the apparent hydraulic conductivity (L/T) of the formation. The Ka, r_c, r_w, and R_e in the equation are constants; $(1/t)\ln(y_o/y_t)$ will also be constant. Equation (16) requires plotting a recovery curve as y on log scale against t on linear scale using a semi-log graph where y is the recovery drawdown and t is the time taken. Then to identify the slope where the relationship is approximately linear.

However, due to the inaccessibility to an electric resistance network analogue, and also for the fact that a resistance network could not simulate or account for unsaturated conditions which are important for large-diameter hand-dug wells in unconfined aquifers where unsaturated soil properties are considered as important factors, $\ln\left(\frac{R_e}{r_w}\right)$ is therefore determined using the empirical equation developed by Rupp et al., 2011, Rupp et al. (2011) and Uribe et al. (2014). This will improve the estimations of apparent hydraulic conductivity by accounting for the unsaturated zone and useful in the developing areas of the world where there is no access to software for numerical analysis. The equation was specifically based on the textural characteristics of the soil/rock materials surrounding the aquifer.

$$\ln\left(\frac{R_e}{r_w}\right) = \frac{C_1 + C_2 ln\left(\Lambda\left({d}/{r}\right)^2\right)}{1 + C_3\left(\frac{(D-d)}{D}\right)^{\frac{1}{2}}\left(\frac{d}{r}\right)^{-5/8}} \tag{17}$$

The capillary parameter Λ in the equation is a function of water retention of soil materials in the well (unsaturated zone) surrounding the aquifer which was determined in the laboratory from textural properties of the soil/rock materials and interpreted using soil's water retention properties (Rupp et al., 2011, 2011) i.e. for an unconsolidated soil/rock media, C_1, C_2 and C_3 are constants. For units in metres, $C_1 = 1.839$, $C_2 = 0.209$ and $C_3 = 1.614$.

The estimated Ka using the proposed equation is relatively a low hydraulic conductivity of the aquifer formation because the flow into the well is not horizontal, there will be a reduce in flow due to energy loss, also there will be a time difference in recharge through the base of the well and the direction of the flow moves against the force of gravity. To account for the gaps in the stated above facts, the horizontal hydraulic conductivity K of the aquifer formation will be determined based on

Fig. 6. Showing recovery test in unscreened well in study area.

Darcy's law using Bouwer and Rice (1976) method which will take into account the horizontal flow into the well. The estimated K is expected to reflect true flow characteristics of the aquifer formation.

3. Application of the proposed method

To test the viability of the proposed method, the field recovery tests were conducted in twelve (12) un-screened concrete wells in two stages: The first recovery tests were conducted in un-screened concrete wells to determine apparent hydraulic conductivity Ka (Fig. 6) and then screening was added for the second recovery tests to estimate horizontal hydraulic conductivity K (Fig. 7).

The study was carried out in the rural areas of Ilorin Northcentral Nigeria as shown in Fig. 5. The well radius, well depth, and static water of the wells were recorded before the commencement of the field test as presented in Table 1. These included the well depth (m), referred to as the distance from the land surface to the bottom of the well, r_c called the radius of the unscreened part of the well where the head is rising (m), and r_w is the distance from the centre of the well to the undisturbed aquifer. These wells are concrete-lined large-diameter hand-dug wells having depths between 8.6 m and 10.6 m and well radius ranges from 0.68 m to 0.78 m.

3.1. Field recovery tests

To achieve this objective, the field tests were conducted by pumping the wells to draw the water level down, the pump was then turned off while the well was monitored up to 90% of recovery. Since the aquifer was unconfined, the water level in the well was lowered to no more than 10% of the aquifer thickness (Herbert and Kitching, 1981; Mace, 1999). The measured recovery water level at specific time interval was used to calculate the recovery drawdown as shown in Table 2 and Table 3, while the recovery drawdown – time data in un-screened and screened wells were used to estimate apparent hydraulic conductivity Ka and horizontal hydraulic conductivity of the aquifer formation.

4. Results and discussions

The calculated recovery drawdown, y (m) from the field recovery tests conducted in un-screened and screened wells are presented in Tables 2 and 3 below.

Table 1
Location coordinates and physical dimensions of test wells.

Well no.	Well depth (m)	Well radius r_c (m)	Static water level (mbgl)*	Depth of concrete-lined well (m)	r_w (m)	Aquifer Type
W1	9.4	0.68	3.1	9.36	0.71	Unconfined
W2	9.8	0.75	3.4	9.73	0.77	Unconfined
W3	8.9	0.75	2.7	8.86	0.72	Unconfined
W4	9.1	0.66	2.9	9.07	0.71	Unconfined
W5	8.7	0.72	2.8	8.64	0.75	Unconfined
W6	10.6	0.75	3.7	10.53	0.77	Unconfined
W7	9.8	0.75	3.2	9.75	0.74	Unconfined
W8	10.3	0.72	3.5	10.26	0.76	Unconfined
W9	8.8	0.73	2.9	8.76	0.76	Unconfined
W10	8.6	0.78	2.8	8.51	0.81	Unconfined
W11	9.2	0.72	3.3	9.13	0.76	Unconfined
W12	10.4	0.75	3.6	10.35	0.72	Unconfined

*Where mbgl is defined as metres below ground level.

Fig. 7. Showing some screened wells in study area.

Table 2
Calculated recovery drawdown, y (m) in un-screened concrete wells.

Time (min)	y (m) Well 1	y (m) Well 2	y (m) Well 3	y (m) Well 4	y (m) Well (5)	y (m) Well 6
0	0.342	0.260	0.194	0.310	0.338	0.408
10	0.274	0.212	0.160	0.264	0.280	0.348
20	0.212	0.176	0.130	0.232	0.232	0.298
30	0.156	0.136	0.092	0.188	0.186	0.246
40	0.090	0.102	0.064	0.148	0.154	0.198
50	0.034	0.064	0.032	0.112	0.126	0.152
60	–	0.026	–	0.078	0.098	0.108
70	–	–	–	–	–	0.058
Time (min)	**y (m) Well 7**	**y (m) Well 8**	**y (m) Well 9**	**y (m) Well 10**	**y (m) Well 11**	**y (m) Well 12**
0	0.266	0.302	0.380	0.284	0.264	0.348
10	0.218	0.246	0.322	0.236	0.218	0.302
20	0.178	0.196	0.266	0.184	0.176	0.256
30	0.140	0.146	0.220	0.138	0.134	0.216
40	0.098	0.098	0.176	0.092	0.090	0.170
50	0.054	0.052	0.122	0.046	0.048	0.126
60	0.022	–	0.076	–	–	0.086
70	–	–	0.028	–	–	0.046

Table 3
Calculated recovery drawdown, y (m) in screened wells.

Time (min)	y (m) Well 1	y (m) Well 2	y (m) Well 3	y (m) Well 4	y (m) Well (5)	y (m) Well 6
0	0.344	0.262	0.196	0.312	0.340	0.412
10	0.302	0.234	0.176	0.286	0.306	0.374
20	0.266	0.212	0.156	0.254	0.266	0.338
30	0.224	0.182	0.134	0.226	0.224	0.298
40	0.186	0.154	0.112	0.196	0.184	0.258
50	0.136	0.122	0.086	0.166	0.156	0.218
60	–	0.096	–	0.132	0.128	0.188
70	–	–	–	–	–	0.146
Time (min)	**y (m) Well 7**	**y (m) Well 8**	**y (m) Well 9**	**y (m) Well 10**	**y (m) Well 11**	**y (m) Well 12**
0	0.268	0.306	0.384	0.286	0.268	0.352
10	0.236	0.270	0.354	0.260	0.234	0.324
20	0.200	0.228	0.312	0.224	0.198	0.288
30	0.172	0.188	0.272	0.188	0.166	0.244
40	0.148	0.146	0.232	0.154	0.132	0.208
50	0.128	0.108	0.188	0.126	0.092	0.174
60	0.098	–	0.142	–	–	0.136
70	–	–	0.098	–	–	0.097

4.1. Analysis of recovery drawdown trends

The recovery drawdown obtained un-screened and screened wells were plotted on direct linear regression graphs as shown in Fig. 8. The well recovery is proportional to the flow rate of the well, and increases as the flow of the well increases. In screened wells (K), groundwater enters the well with a minimal amount of energy loss, and well recovery after pumping is generally rapid, and may sometimes exhibit near full recovery up to the static water level. Conversely, in un-screened wells (Ka) exhibits excessive energy losses and well recovery and the time after pumping is slower.

4.2. Estimation of the apparent hydraulic conductivity (Ka)

To estimate the apparent hydraulic conductivity (Ka), the calculated recovery drawdown data was plotted against recovery drawdown time. Derived from Equation (16) above, K, r_c, r_w and R_e are constants, and $(1/t)\ln(y_o/y_t)$ is also constant; therefore, it is required that the recovery drawdown y is plotted against time t on a semi-log graph (drawdown on the logarithmic and time on a linear scale). A best-fit straight line through the set of data points was plotted. The straight line plotted was also used to calculate the value of $(1/t)\ln(y_o/y_t)$. Fig. 9 shows a semi-log plot of recovery drawdown against time in Well 5 for Ka estimation.

The values obtained from the plotted curves, along with other well parameters, were substituted into the proposed equation (16), as derived above in order to estimate the apparent hydraulic conductivity (Ka) of the aquifer formation in concrete-lined large-diameter hand-dug wells.

from equation (16) above i.e. $Ka = \frac{r_c^2 \ln\left(\frac{R_e}{r_w}\right)}{r_w} \frac{1}{t} ln\frac{y_o}{y_t}$Where:

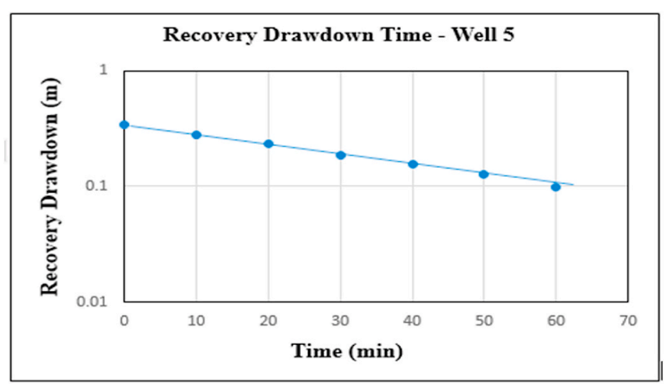

Fig. 9. Semi-log plot of recovery drawdown against time recorded in Well 5.

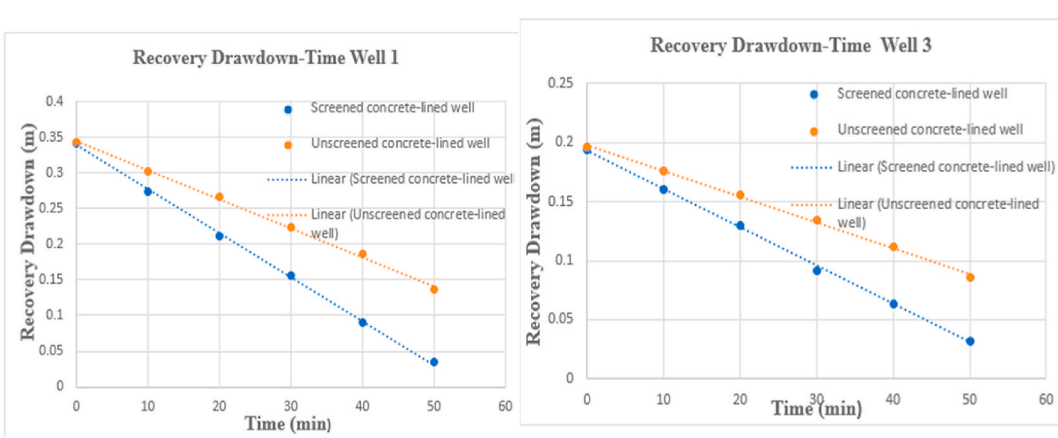

Fig. 8. A linear regression plots of recovery drawdown and time for Well 1 and Well 3 for un-screened and screened wells.

Table 4
Calculated ln (R_e/r_w) for un-screened wells.

Well	A	R	D	a/r	(a/r)^2	Λ(a/r)^2	ln (Λ (a/r)^2)	((d-a)/d)	((d-a)/d)^1/2	(a/r)^(-(5/8))	C1+C2(ln (Λ (a/r)^2))	1 + C3 (((d-a)/d)^1/2)* (a/r)^(-(5/8)))	ln (Re/rw)
1	0.04	0.68	6.3	0.058824	0.00346	0.001419	−6.558024807	0.993651	0.996820342	5.875307153	0.468372815	10.45259385	0.0448
2	0.07	0.75	6.4	0.093333	0.008711	0.003572	−5.634754048	0.989063	0.994516214	4.4027803	0.661336404	8.067119142	0.0819
3	0.04	0.75	6.2	0.053333	0.002844	0.001166	−6.753985624	0.993548	0.996768974	6.246342518	0.427417005	11.04902292	0.0387
4	0.03	0.66	6.2	0.045455	0.002066	0.000847	−7.073683026	0.995161	0.997577711	6.902623339	0.360600248	12.11384775	0.0297
5	0.06	0.72	5.9	0.083333	0.006944	0.002847	−5.861411419	0.989831	0.994902261	4.725940818	0.613965013	8.588784616	0.0715
6	0.06	0.75	6.9	0.08	0.0064	0.002624	−5.943055408	0.991304	0.995642681	4.848068619	0.59690142	8.790687674	0.0817
7	0.05	0.75	6.6	0.066667	0.004444	0.001822	−6.307698521	0.992424	0.99620492	5.433216825	0.520691009	9.735932094	0.0534
8	0.04	0.72	6.8	0.055556	0.003086	0.001265	−6.672341635	0.994118	0.997054486	6.088990769	0.444480598	10.79868367	0.0411
9	0.04	0.73	5.9	0.054795	0.003002	0.001231	−6.699928279	0.99322	0.996604404	6.141709816	0.43871499	10.87906006	0.0403
10	0.09	0.78	5.8	0.115385	0.013314	0.005459	−5.210566618	0.984483	0.992211045	3.856182313	0.749991577	7.175400747	0.1045
11	0.07	0.72	5.9	0.097222	0.009452	0.003875	−5.553110059	0.988136	0.994050096	4.291869767	0.678399998	7.885862356	0.0860
12	0.04	0.75	6.8	0.053333	0.002844	0.001166	−6.753985624	0.994118	0.997054486	6.246342518	0.427417005	11.05190133	0.0536

- r_c is radius of the unscreened part of the well at which the head is rising (m)
- r_w is called the distance from the well centre to undisturbed aquifer (m)
- t is the time taken (min)
- the straight line plotted was used to evaluate $(1/t)\ln(y_o/y_t)$
- y_o is the water depth below water table at beginning of test
- y_t is the depth to water or drawdown, at time *t*
- R_e is the radial distance over which the difference in head is dissipated in the flow system of the aquifer

To calculate the radial distance R_e, the equation of Rupp et al., 2011 and Uribe et al. (2014) for a large-diameter well was used as given in equation (17) above.

from equation (17) above i.e. $\ln\left(\frac{R_e}{r_w}\right) = \frac{C_1 + C_2 \ln\left(\Lambda\left(\frac{a}{r}\right)^2\right)}{1 + C_3\left(\frac{(d-a)}{d}\right)^{\frac{1}{2}}\left(\frac{a}{r}\right)^{-5/8}}$ Where:

- r is well radius (m)
- C_1, C_2 and C_3 are constants (m)
- a is the well base for recharge (m)
- d is distance from the water table to the well base (m)

The calculated effective radius (R_e) for the tested wells is presented in Table 4 while Table 5 shows the calculated data from equation (17) for the twelve concrete-lined large-diameter hand-dug wells.

4.3. *Estimation of horizontal hydraulic conductivity (K) from apparent hydraulic conductivity (Ka)*

The horizontal hydraulic conductivity (K) was determined, which take into account the horizontal flow into the well following the Darcy's law (1856). The K is expected to give a true reflection of flow characteristics of the aquifer formation. To achieve the above objective, the method of Bouwer and Rice (1976), developed for an unconfined aquifer of large-diameter wells, was considered following the field recovery tests conducted in screened wells, as discussed above. The recovery field tests were equivalent to slug tests of Bouwer and Rice (1976) because the pumping period t_p to lower the water level in the well was short when compared with recovery period (Herbert and Kitching, 1981; Rushton and Holt, 1981; Mace, 1999). The measured recovery water levels at specific time intervals were used to calculate the recovery drawdown as shown in Table 3 above.

To estimate the horizontal hydraulic conductivity (K), the calculated recovery drawdown data was plotted against time (Fig. 10). According to Bouwer and Rice (1976), the K, r_c, r_w, R_e, and L_e are constants, and $(1/t)\ln(y_o/y_t)$ is also constant. Therefore, on a semi-log paper, the recovery drawdown y was plotted against time t (recovery drawdown on the logarithmic and time on a linear scale). Then a best-fit straight line was made through the set of data points plotted. Fig. 10 shows a semi-plot of recovery drawdown against time for Well 7. The straight line plotted was used to calculate values for the $(1/t)\ln(y_o/y_t)$.

The values obtained from the plotted curves along with other well properties were substituted into the Bouwer and Rice (1976) equation (18) to estimate horizontal hydraulic conductivity (K) of the aquifer formation for screened wells.

$$K = \frac{r_c^2 \ln \frac{R_e}{r_w}}{2L_e} \frac{1}{t} \ln \frac{y_o}{y_t} \qquad (18)$$

where:

- K = true hydraulic conductivity (K) of aquifer formation (m/day)

Table 5
Calculated apparent hydraulic conductivity using proposed method.

Well no.	r_c (m)	r_c^2 (m)	r_w (m)	ln (R_e/r_w)	t (sec)	1/t	ln (y_o/y_t)	Ka (m/s)	Ka (m/d)
W1	0.68	0.462	0.71	0.045	3000	0.00033	0.688	6.65×10^{-6}	0.6
W2	0.75	0.563	0.77	0.082	2400	0.00042	0.577	1.45×10^{-5}	1.3
W3	0.75	0.563	0.72	0.039	3000	0.00033	0.693	6.97×10^{-6}	1.5
W4	0.66	0.436	0.71	0.030	3600	0.00028	0.788	4.06×10^{-6}	0.4
W5	0.72	0.518	0.75	0.072	2400	0.00042	0.604	1.24×10^{-5}	1.1
W6	0.75	0.563	0.77	0.082	3600	0.00028	0.875	1.47×10^{-5}	1.3
W7	0.75	0.563	0.74	0.053	3600	0.00028	0.793	8.50×10^{-6}	0.7
W8	0.72	0.518	0.76	0.041	3000	0.00033	1.054	9.77×10^{-5}	0.8
W9	0.73	0.533	0.76	0.040	3000	0.00033	0.788	7.30×10^{-6}	1.3
W10	0.78	0.608	0.81	0.105	2400	0.00042	0.385	1.27×10^{-5}	1.1
W11	0.72	0.518	0.76	0.086	3000	0.00033	0.750	1.45×10^{-5}	1.3
W12	0.75	0.563	0.72	0.0535	3000	0.00033	0.718	9.91×10^{-6}	0.9

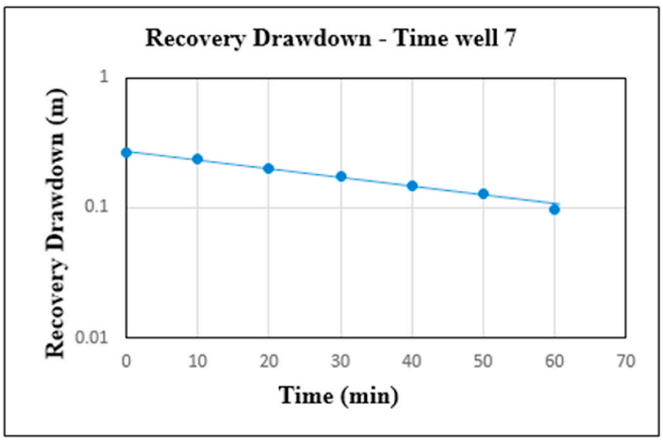

Fig. 10. Semi-log plot of recovery drawdown against time recorded in Well 7.

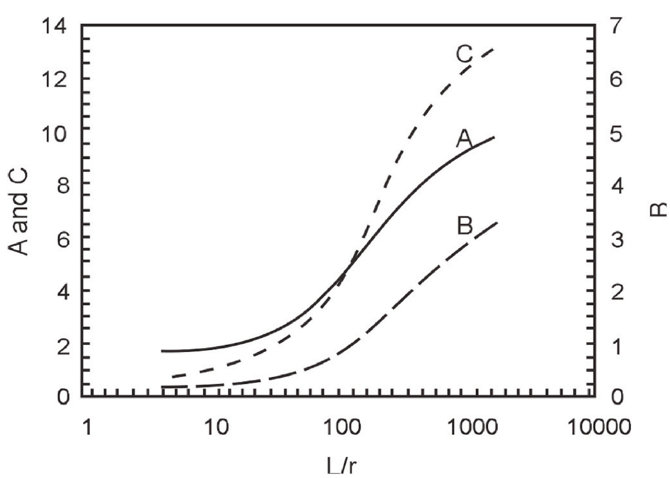

Fig. 11. A, B, and C as a function of L_e/r_w.

- r_c = inner well radius (m)
- r_w = distance from the well centre to the undisturbed aquifer (m)
- L_e = length of the screen or open portion of the well (m)
- t = time taken (s)
- y_o = well water depth below water table at the beginning of test (m)
- y_t = depth to water or drawdown, at time t (m)
- R_e = is the radial distance over which the difference in head is dissipated in the flow system of the aquifer.

Bouwer and Rice (1976) determined the values of R_e experimentally using a resistance network analogue for different values of r_w, L_w, L_e and D. The L_w, the length of the well in aquifer, was equal to the distance from the water table to the bottom of the well, D, (Fig. 10); the effective radius R_e was calculated using equation (19) according to Bouwer and Rice (1976):

$$ln\frac{R_e}{r_w} = \left(\frac{1.1}{ln\frac{L_w}{r_w}} + \frac{C}{\frac{L_e}{r_w}}\right)^{-1} \quad (19)$$

L_e/r_w from equation (19) was obtained from the curve generated by Bouwer and Rice (1976) as shown in Fig. 11. The calculated effective radius (R_e) for screened wells is presented in Table 6.

The calculated data from the curves and estimated horizontal hydraulic conductivity (K) of aquifer formation in screened wells using Bouwer and Rice (1976) method is shown in Table 7.

The estimated horizontal hydraulic conductivity (K) of aquifer formation using the Bouwer and Rice (1976) method in Table 7 shows that the estimated K-values are higher than the Ka-values as compared in Table 8. This is reasonable considering the difference in flow pattern between the wells.

Descriptive statistical correlation was determined between the estimated Ka and K-values taken at different parts of the site. Specifically, this strategy was carried out to describe the strength and direction of the relationship existing between the estimated values of Ka and K. The degree of relationship or association between the estimated Ka and K-values was measured by a correlation coefficient, denoted by r. It is sometimes referred to as the Pearson correlation coefficient and was used to measure the linear relationship or association.

The Pearson correlation coefficient between estimated Ka and K-values was determined using SPSS software as presented in Table 9. The Pearson moment (r-cal.) is 0.88, with the Pearson level of significance value of 0.00, which simply indicates that there is a significant strong positive relationship between the estimated Ka and K-values.

Further information on the relationship or association between estimated Ka and K-values was made from a regression analysis with the use of bivariate plots as shown in Fig. 12. The regression analysis was determined from best straight line to summarise the relationship between K and Ka values. This also helps to show how one variable or value changes on average with another.

As shown in Fig. 12 above, there is a linear regression between the estimated Ka and K values taken from different areas, having $R^2 = 0.775$ with a linear equation as presented in equation (20).

$$y = 0.71x + 0.87 \quad (20)$$

The linear equation (21) shows the regression between two variables (Ka and K) which implies that a change by 0.71 unit in one variable results in one unit change in another. The usefulness of this is that once the apparent hydraulic conductivity Ka is estimated, it is possible to estimate horizontal hydraulic conductivity K of the aquifer formation using equation (21) below:

Table 6
Calculated ln (R_e/r_w) for screened wells.

Well	d	r_w	B	c	d/r_w	In(d/r_w)	(1.1/ln (d/r_w))	b/r_w	$c/(b/r_w)$	ln Re/r_w=((1.1/ln (d/r_w))+(c/(b/r_w)) ^ (-1)
1	6.3	0.71	6.3	1.4	8.8732394	2.1830399	0.503884505	8.8732394	0.1577778	1.511345027
2	6.1	0.77	6.1	0.8	7.9220779	2.0696535	0.531489924	7.9220779	0.1009836	1.581093835
3	5.9	0.72	5.9	0.9	8.1944444	2.1034564	0.522948795	8.1944444	0.1098305	1.580329815
4	6.1	0.71	6.1	1	8.5915493	2.1507791	0.511442579	8.5915493	0.1163934	1.59277258
5	5.6	0.75	5.6	0.5	7.4666667	2.0104487	0.547141549	7.4666667	0.0669643	1.628383811
6	6.4	0.77	6.4	1.2	8.3116883	2.1176628	0.519440594	8.3116883	0.144375	1.506442464
7	6.2	0.74	6.2	1.1	8.3783784	2.1256544	0.517487701	8.3783784	0.1312903	1.541359239
8	6.4	0.76	6.4	1.1	8.4210526	2.1307348	0.516253821	8.4210526	0.130625	1.545884589
9	5.4	0.76	5.4	0.4	7.1052632	1.9608358	0.56098527	7.1052632	0.0562963	1.620006258
10	5.5	0.81	5.5	0.2	6.7901235	1.9154691	0.574271851	6.7901235	0.0294545	1.656379455
11	5.5	0.76	5.5	0.5	7.2368421	1.9791849	0.555784343	7.2368421	0.0690909	1.600319419
12	6.2	0.72	6.2	1.3	8.6111111	2.1530534	0.51090234	8.6111111	0.1509677	1.510870527

Table 7
Calculated horizontal hydraulic conductivity using Bouwer and Rice (1976) method.

Well no.	r_c^2 (m)	L_e (m)	ln (R_e/r_w)	D(m)	t (sec)	1/t	ln (y_o/y_t)	K (m/s)	K (m/d)
W1	0.462	6.3	1.51	6.3	3600	0.00028	0.880	1.36E-05	1.179
W2	0.563	6.4	1.58	6.4	1800	0.00056	0.536	2.09E-05	1.802
W3	0.563	6.2	1.58	6.2	1800	0.00056	0.507	2.04E-05	1.759
W4	0.436	6.2	1.59	6.2	3000	0.00033	0.742	1.37E-05	1.183
W5	0.518	5.9	1.63	5.9	2400	0.00042	0.631	1.90E-05	1.639
W6	0.563	6.9	1.51	6.9	2400	0.00042	0.693	1.79E-05	1.549
W7	0.563	6.6	1.54	6.6	1800	0.00056	0.432	1.59E-05	1.373
W8	0.518	6.8	1.55	6.8	1800	0.00056	0.489	1.62E-05	1.397
W9	0.533	5.9	1.62	5.9	2400	0.00042	0.747	2.29E-05	1.983
W10	0.608	5.8	1.66	5.8	1800	0.00056	0.425	2.07E-05	1.789
W11	0.518	5.9	1.60	5.9	2400	0.00042	0.765	2.26E-05	1.950
W12	0.563	6.8	1.51	6.8	1800	0.00056	0.495	1.73E-05	1.497

Table 8
Estimated values for apparent hydraulic conductivity andhorizontal hydraulic conductivity of the aquifer formation.

Well No.	K_a (m/day)	K (m/day)
W1	0.6	1.179
W2	1.3	1.802
W3	1.5	1.759
W4	0.4	1.183
W5	1.1	1.639
W6	1.3	1.549
W7	0.7	1.373
W8	0.8	1.397
W9	1.3	1.983
W10	1.1	1.789
W11	1.3	1.950
W12	0.9	1.497

Table 9
Pearson correlation between the estimated apparent hydraulic conductivity and true hydraulic conductivity values.

Correlations		K	Ka
K	Pearson correlation	1	0.880*
	Sig. (two-tailed)		0.000
	N	12	12
Ka	Pearson correlation	0.880*	1
	Sig. (two-tailed)	0.000	
	N	12	12

* Correlation is significant at the 0.01 level (two-tailed).

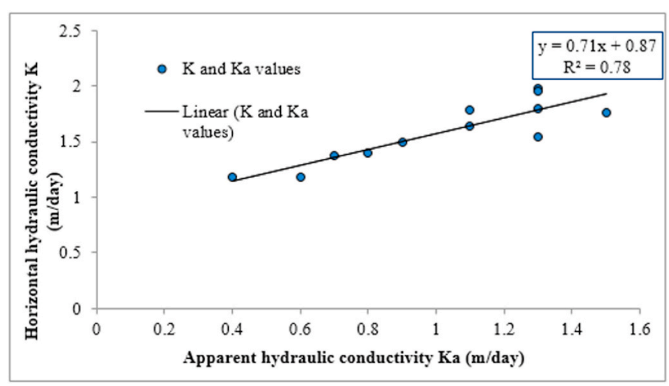

Fig. 12. Bivariate plot of horizontal hydraulic conductivity against apparent hydraulic conductivity.

$$K = 0.71Ka + 0.87 \quad (21)$$

where:

- K is the horizontal hydraulic conductivity of aquifer formation (L/T)
- Ka is the estimated apparent hydraulic conductivity of aquifer formation (L/T).

5. Conclusion

The use of un-screened concrete lining in the construction of large-diameter hand-dug wells will prevent the horizontal water flow to the well and this makes Darcy-based methods not suitable for estimation of horizontal hydraulic conductivity in un-screened concrete-lined large-diameter hand-dug wells. The recovery test method proposed in this study can be used to estimate horizontal hydraulic conductivity (K) from apparent hydraulic conductivity (Ka) in un-screened concrete-lined large-diameter hand-dug wells. The application of the proposed method showed that the estimated Ka values were lower than K values which shows the effect of un-screened concrete-lining. A relationship between Ka and K values was established with a correction factor for the estimation of K from Ka by a regression analysis with the use of a bivariate Pearson correlation coefficient using SPSS software. The Pearson moment (r-cal.) was 0.88 with the Pearson level of significant value of 0.00, which implies a significant strong positive relationship between the estimated Ka and K values.

The estimated horizontal hydraulic conductivity K is useful to determine well yield and to evaluate water resources coverage and distribution for water management and sustainability most especially in developing rural areas of sub-Saharan African countries and for other developing rural areas of the world where concrete-lined large-diameter hand-dug wells are mostly being used.

Declaration of competing interest

We write to inform you that there is no conflict of interest for this submitted article. Thanks.

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