Original Article

Estimation of hydraulic diffusivity and associated hydraulic parameters using pumping test and lithological data in Wasinmi residential community, south-west Nigeria

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Abstract

Pumping tests were conducted on existing 50 wells (twenty five each) with constant rate pumping test for boreholes and recovery method test for hand-dug wells within district to evaluate aquifer hydraulic parameters and estimate hydraulic Diffusivity within Wasinmi district, South-West Nigeria adopting standard methods of Cooper and Jacob straight line solution to time-drawdown data collected from observation wells. The depth range of 4.3m to 2.4m with a mean depth of 8.3m; mean static water level (SWL) of 1.59m and mean drawdown (DD) of 0.85m while the boreholes tapped fresh water from weathered sandstone aquifer with a depth range of 35m to 75m with a mean depth of 51m, SWL of 17.8m and DD of 8.17m. Borehole discharge varied from 1.0×10^{-2} l/s to 11.0×10^{-2} l/s with a mean of 4.0×10^{-2} l/s with exhibited transmissibility that varied from 1.0×10^{-2} m^2/s to 9.20×10^{-2} m^2/s with an mean of 4.5×10^{-1} m^2/s (40,500 m^2/day) while discharge from hand-dug wells ranged from 1.0×10^{-4} to 6.0×10^{-2} l/s with a mean of 2.3×10^{-2} l/s with exhibited transmissibility that varied from 1.0×10^{-1} (8.64 m^2/day) to 5.10×10^{-1} m^2/s(44,064 m^2/day) with a mean of 1.42×10^{-1} m^2/s (12,269 m^2/day). The hydraulic conductivity varied from 87.96m^2/day to 4397.76 m^2/day in the boreholes and 594.432 m^2/day to 7762.18 m^2/day in the hand-dug wells. The mean recovery period of 2254 and 9446 seconds were reported for Wasinmi boreholes and hand-dug wells respectively. Output from the two water sources revealed that the auriferous zones were classified as very high in potentials in the designation of transmissivity magnitudes of 38,880 and 12,269 m^2/day for the boreholes and hand-dug wells respectively; based on standard aquifer potentiality classification. This correlates well with the lithological description of the study area displaying fractured shale/clay-shale/clayey sand and weathered sandstone as groundwater bearing unit releasing water into the well with good correlation coefficient between transmissibility and specific capacity (R^2= -0.74 and R^2= 0.715) respectively reported for Wasinmi boreholes and hand-dug well Hydraulic diffusivity varied from 11.816 m^2/s to 13,022.87 m^2/s in Wasinmi Boreholes and 4.06 m^2/s to 6467.26 m^2/s in Wasinmi hand-dug wells with the regions of higher hydraulic diffusivity values were comparatively favourable for groundwater development.

Key words: Specific capacity; cone of depression; residual drawdown; hydraulic diffusivity; fractured-shale

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Citation: Ishola, S.A. 2025. Estimation of hydraulic diffusivity and associated hydraulic parameters using pumping test and lithological data in Wasinmi residential community, south-west Nigeria. *Naturalis Scientias*, 2 (2): 586-622. DOI: https://doi.org/10.62252/NSS.2025.1035. www.naturalisscientias.com.

1. Introduction

There have been decades of great challenges in groundwater environment since the values of specific yield estimated from pumping test data in an unconfined aquifer is lower than expected; delayed field experience in yield above the declining water table has been attributed as the primary cause of reported uncertainties in specific yield. Specific yield is a significant hydraulic parameter for the assessment of groundwater storage in a specified unconfined aquifer. The principal drainable source of groundwater is abstracted from the declining hydraulic head[1-3]. Hydraulic diffusivity is relevant to well yield as it dictates how quickly water can move through the pumping. A higher diffusivity means faster water movement and a quicker response to well pumping potentially leading to a higher well yield. Diffusivity is primarily influenced by hydraulic conductivity and specific storage. Understanding hydraulic diffusivity is crucial for well design. A well in an area with high diffusivity might be able to support a higher pumping rate without causing excessive drawdown whereas a well in an area with low diffusivity might have a limited yield and require more careful management. Hydraulic diffusivity is a fundamental parameter in transient groundwater flow simulations which are essential for predicting how well yield might change over time under different pumping scenarios[4]. The volume of the specific yield has great influence on well yields, solute transport and rates of water level declination[5-6]. Specific yield is also a critical hydraulic parameter in the estimation of evapotranspiration from diurnal water-level fluctuation readings[7-8]. Challenges observed in quantifying changes in three-dimensional regional aquifer storage are often caused by the sparseness and low reliability of availability specific yield values[9]. Depletion in stream flow induced by groundwater pumping has been reported to be the potential cause of potential water recourse management issue in the High Plains Region of the United States and has functioned as sensitive parameters in the computations of depletion in stream caused by a constructed pumped well in a thin aquifer[8-11]. The most commonly utilized techniques for the estimation of specific yields are measurement of the drainage of aquifer materials and pumping tests. Though Johnson summarized quite a number of laboratory methods for the determination of specific yield[12], one of the earliest researches on determination of specific yield of alluvial aquifers from pumping test analyses from published literature was the work of Wenze et al.[13]; this test was undertaken on eighty-three (83) observation wells at a nearby site within Platte river valley, Nebraska. Also, the published work of Nwankwor et al.[14] reinvigorated more curious interest in groundwater hydrological techniques in the estimation of specific yield from the pumping test data because the specific yield determined from pumping test data remarkably differed from the specific yield obtainable from other techniques. In the course of pumping tests, observed decline in hydraulic head in permeable alluvial aquifers is often far smaller than expected. According to the reported pumping test output in the Platte river valley of Nebraska[13-16], the recorded drawdown from observation wells between 8m to 20m from the pumping well were found to vary between 1.22 to 0.8m irrespective of the adopted large pumping rate of 2m3/min that lasted for significant time greater than 48 hours. In the course of the pumping operations, drainage occurrence was only observed on the aquifer constituents found above the declining hydraulic head[8 & 17-18]. Therefore, pumping tests conducted for a limited duration (several number of days for instance) are the ones that often proffer the estimation of the specific yield for limited thickness of the aquifer materials only near the water table.

Therefore, the estimation of the specific yield for the aquifer constituents in a large thickness is highly profitable for water resources evaluation.

Precise documentation of variation in specific yield is scarce although 19. Nwankwor et al.[19] reported that specific yield possess variable values that are significantly high for a given test site; this is principally due to the fact that the expensive state for the construction of observation wells as well as the few available number of observation wells for a pumping test thereby preventing a spatial output for characterization of aquifer specific yield. Hence, a less-exorbitant approach for the determination of the spatial variation of specific yield in an unconfined aquifer is highly necessary. Nwankwor at al.[20] in consonance to this concluded that short-term pumping tests are not too reliable approaches for specific yield determination while small-scale laboratory tests may result to values of specific yield that are otherwise reasonable. The specific yield determined from laboratory drainage by Nwankwor et al.[14] has been utilized as a bench mark for the Borden aquifer whose values were determined from repacked aquifer materials; in the course of sampling and repacking of subsurface materials; the original sedimentary structures and particle framework were destroyed[8]. If the specific yield can alternate very largely in its magnitude for an unconfined aquifer, the hydraulic conductivity will also be heterogeneous. Though, the documentation of spatial variation of horizontal hydraulic conductivity is commonly available, the analysis of spatial variation of the vertical hydraulic conductivity is scarce (Butler et al., 2002). Pumping testing operations undertaken at Borden site[2 & 14–22] to the work of Cape-Cod site in the USA[11] were often used to illustrating the procedures for determination of specific yield or for demonstrating the drainage processes in the course of water table decline during pumping. The unconfined aquifer is largely composed of medium-grained sand of glacio-deltaic or glacio-fluvial deposits at the Borden site while highly permeable sand and gravel of glacial outwash were primary constituents of the Cape-Cod[2 & 11]. The hydraulic Estimation for Hydraulic Diffusivity and Associated Hydraulic Parameters using Pumping Test and Lithological Data in Wasinmi community of Ewekoro Local Government Area of Ogun state was necessitated as a result of daily increase in water demand potentially straining the available water resources and leading to water scarcity and water quality issues. If water resources cannot keep up with the growing demand, water scarcity can occur which has led to conflicts and challenges for communities while over–extraction of groundwater to meet the needs of the growing population can lead to the depletion of aquifers making it harder to access water in the future. The increase in population with resultant pressure on water resources can lead to increase in pollution from human activities including industrial waste and improper sanitation can contaminate water sources making them unsafe for consumption. The presence of different cement manufacturing companies like Larfage WAPCO, Dangote cement, and other associated industries in Ewekoro where larger members of staff reside in Wasinmi community due to its proximity to the industries has increased the daily demand on the limited resources[23]. Also, the output of the public surface water system and the few existing domestic wells and boreholes are quite insufficient to meet the needs of the growing population leading to the reliance on groundwater sources, which can be unsustainable. Therefore, the field experience of uncertainty is a revelation that the hydrodynamics of Wasinmi groundwater system are not quite understood which makes this research tasks and efforts necessary. In this work, constant rate, single well pumping tests were undertaken by the authors in boreholes and hand-dug wells located in Wasinmi autonomous residential communities within Ewekoro Local Government Area of Ogun State, South-West, Nigeria. The acquired field data from these tests were consequently harnessed in computing the necessary hydraulic parameters namely transmissibility, hydraulic conductivity and specific discharge, among others; this would also go a long way in the selection of appropriate pump size needed for ultimate sustainability of groundwater abstraction from the boreholes extracting water from the aquifer thereby forestalling future borehole failure and meeting the needs of the ever increasing population of the dwellers since the advent of cement manufacturing companies that have increased the number of residents in Wasinmi.

2. Study area

2.1 Physiographic and geological settings

Wasimi is located in parts of Dahomey basin in Ewekoro Local Government Area of Ogun State at an elevation of 79 metres above sea level with coordinates of 6°58'0" N and 3°28'60" E in DMS (Degrees Minutes Seconds) or 6.96667 and 3.48333 (in decimal degree) and its population amounts to 536,068. The history of the people reveals that culture and tradition play a central role in their indigenous beliefs system. The neighbourhood include Ogun state sport academy, an under construction industrial factory site, the proposed Ogun State Cargo, international airport in Wasinmi and so on[24]. Over fifty percent of the land area of southwestern Nigeria lies within the coastal plain where the relief is generally low with average elevation of about 200 m – 400 m above sea level[25]. Three major landform units, namely the hills, plains and river valleys, dominate the study area. The hills are the most striking feature, although they constitute less than 30 % of the total surface area. The plains are the most striking landform system in the investigated areas (with an average elevation of 64m above sea level) which ranges between 46 m and 107 m in Wasinmi. The river valleys are the narrowest landform in the area. The rivers in the study area display are in form of sluggish perennial streams in dry season but are turbulent during the wet season. This relief can be described as undulating and the drainage is dendritic[24-26].

Ewekoro formation is the local geology in the study area which is generally consistent with the regional geology of eastern part of the Dahomey Basin; predominantly comprises of the non-crystalline and highly non-fossiliferous limestone and thinly laminated fissile and probably non-fossiliferous shale[25-27]. Ewekoro formation consists of intercalations of argillaceous sediment. The rock is soft and friable but in some places cement by ferruginous and siliceous materials. The lithological units in Ewekoro formation are clayey sand, clay, shale, marl, limestone and sandstone. The lithology of Ise and Afowo formations as defined by Omatsola and Adegoke[27] showed a high degree of similiarity. Both are essentially sands and sandstones, but the latter contains thick interbeds of shales. This difference is not sufficient to warrant the establishment of separate lithostratigraphic units[**25**]. The two formations were considered synonymous by Okosun[26]. In that study, it was observed that the Ise, Afowo and Abeokuta formations have similar lithologic and electric log characters. The uppermost beds of Abeokuta formation which crop out in Ijebu Ode area and in the shallow boreholes at Itori, Wasimi and Ishaga onshore consist mainly of fine to coarse grained sand and interbeds of shale, mudstone, limestone and silt. These lithofacies correlate well with the upper portion of the neostratotype in Ojo-1 borehole[25-26].

The Abeokuta formation was found to consist of grits, loose sands, sandstones, kaolinitic clay and shale and was further characterized as usually having a basal conglomerate or basal ferruginized sandstone. The Abeokuta formation on surface outcrops comprises mainly sand with sandstone, siltstone, silt, clay, mudstone and shale interbeds[25]. It usually has a basal conglomerate which may measure about 1m in thickness and usually consists of poorly rounded quartz pebbles with silicified and ferruginized sandstone matrix or a softly gritty white clay matrix. In outcrops where there is no conglomerate, a coarse, poorly sorted pebbly sandstone with abundant white clay constitutes the basal bed[25]. The overlying sands are coarse grained clayey, micaceous and poorly sorted and indicative of short distances of transportation or short duration of weathering and possible derivation from the granitic rocks located to the north. Figure 1 shows the Geology map showing the study area in South-West Nigerian part of Dahomey Embayment, Figure 2 is the data acquisition map which shows the investigated locations in Wasinmi study area within Ewekoro Local Government area (LGA) of Ogun state, South-West, Nigeria, Figure 3 is the inset map showing the study areas in within Nigeria continental domain while Figure 4 is the data acquisition map showing each investigated locations in Wasinmi study area within Ewekoro LGA, Southwest Nigeria.

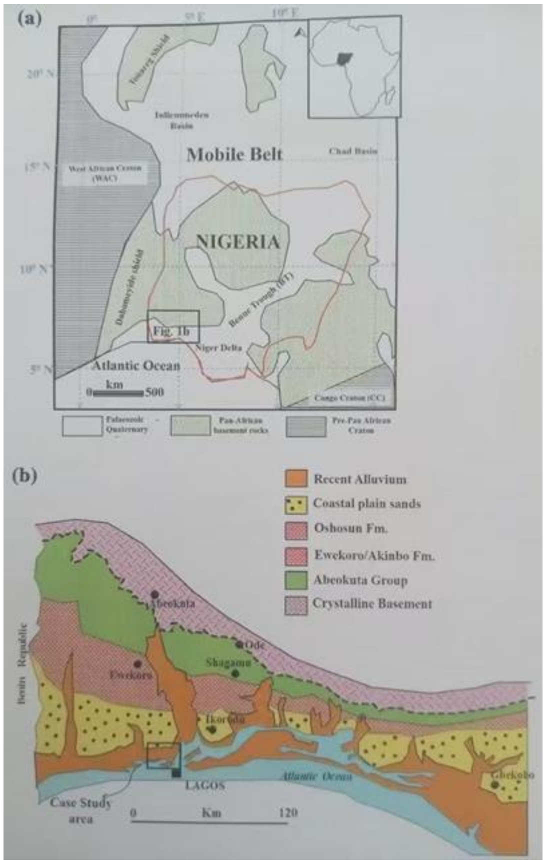

Figure 1. Geological map showing the study area within the South-West Nigerian part of Dahomey embayment[24 & 28]

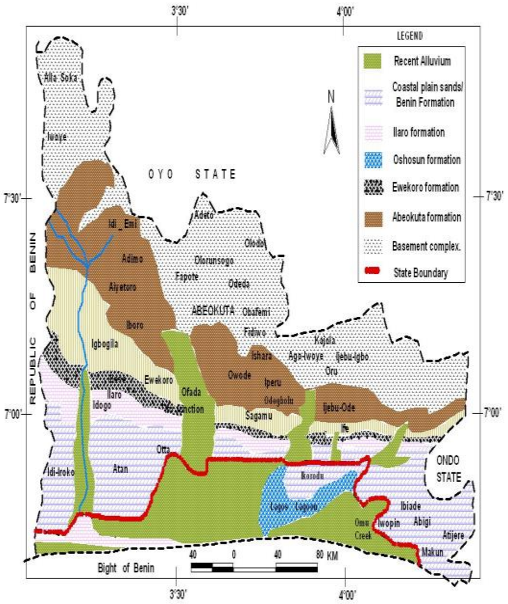

Figure 2. A map of Ogun State showing the geology of the study areas (after Kehinde-Phillips and Obiora & Onwunka)[30 & 39]

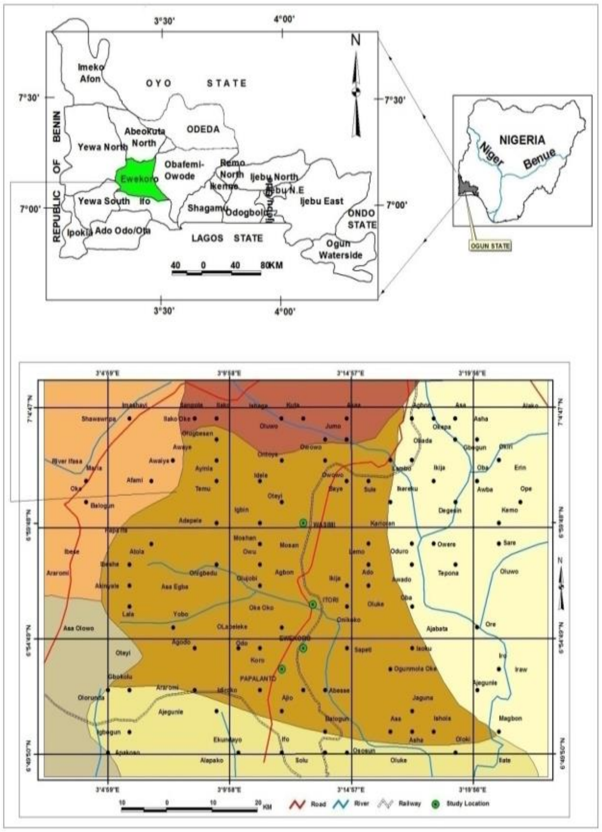

Figure 3. Inset map showing the study areas in Ogun State within Nigeria continental domain using Esri - data/nigeria political information in Arcview GIS 3.2A environment[24]

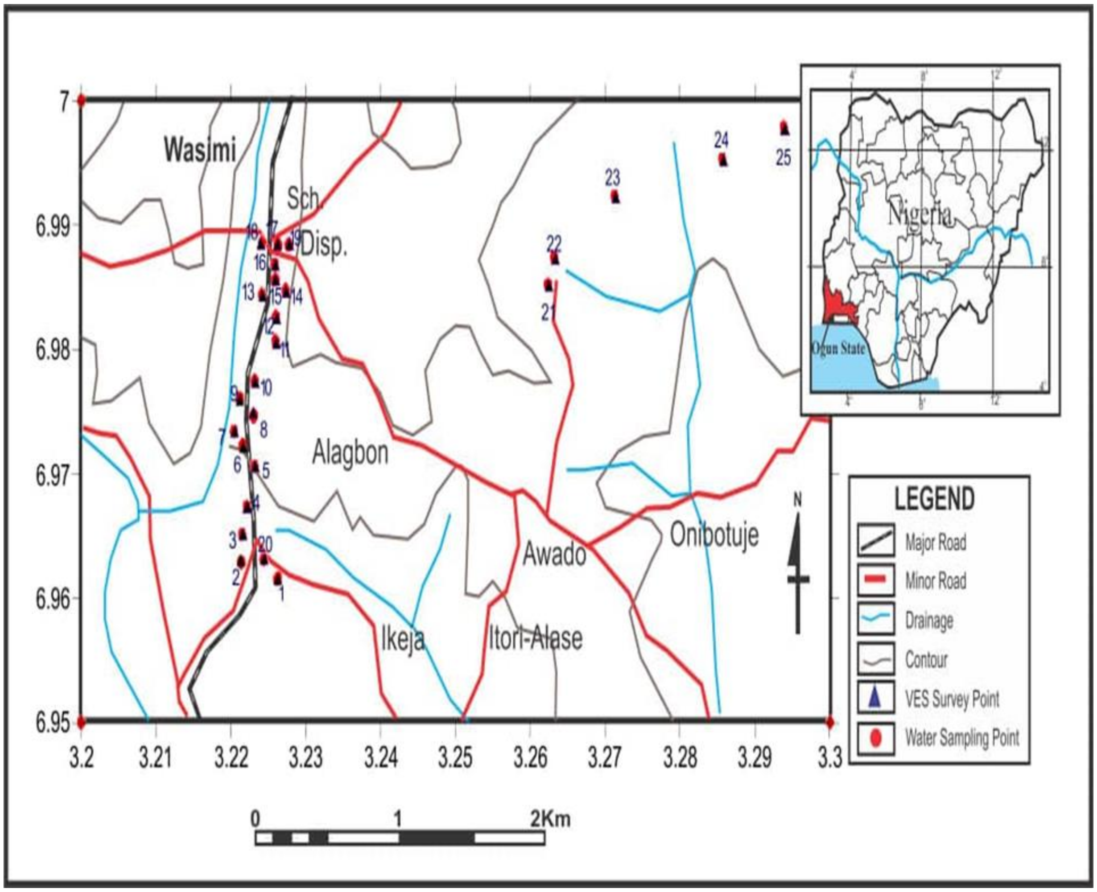

Figure 4. Data acquisition map showing the investigated locations in the Wasinmi study area within Ewekoro LGA, Southwest Nigeria[24]

3. Materials and methods

3.1 Theoretical background

Specific yield is a measure of the volume of water in which an aquifer takes into or releases from a given storage per unit area of the aquifer per unit change in the water table depth[31-34].

$$S_Y = \frac{V_w}{(A.\ \Delta H)} \qquad 1$$

Where S_Y stands for specific yield of aquifer, V_w represents the volume of the water extracted from the groundwater, A represents the aquifer coverage area, and ΔH represents the alteration in water table. More specific expression is given by Dos-Santos and Youngs[35] who stated that the specific yield is the ratio of water flux per unit area via the water table due to the resultant effect of water taken up or released by the unsaturated soil to the rate of the rise or fall of the water table. One of the commonly utilized definitions of specific yield is the ratio of the volume of water that saturated rock or soil yields by gravity to the total volume of the rock or soil[18 & 36-38] where

$$S_Y = P_s - S_r \qquad 2$$

Equation 2 depicts that specific yield stands as the difference between porosity (P_s) and specific retention (S_r) where porosity is the capability of the rock to contain void spaces while specific retention is the actual volume of the retained water by the soil or rock[39] which could also be represented by either field capacity[40-41] or the residual moisture content[42-43]. Duke[44] reported that the utilization of the field capacity and the residual moisture content serves as veritable attempt for the description of the lower limit of water content at which the water is significantly mobile.

3.2 Variability of aquifer specific yields

The introduction of the capillarity as well as the subsurface water distribution for the detailed understanding of variability of specific yield cannot be overemphasized. These idealized variables are symbolized as ΔH, P_s , P_r and S_r. There is an existence of a small zone above the water that is completely saturated under negative pressure. It is observed that in this zone, the closer the water table, the closer the pressure head tends to zero and the pressure head of the water table is zero; this pressure head is technically called matric potentials[16]. The occurrence of this saturated zone is a resultant effect of the impact of surface tension exhibited on the water as well as the attractive forces of the sediments a with capacity to wicking up water from the water table and holding it in place in the pore spaces. This zone is therefore referred to as tension saturated zone. In consonance with the concept of capillary fringe, two definitions are recognized; tension-saturated zone exemplified by Duke, Abdul & Gillham, Sophocleous, and Shah & Ross[44-47] and space ranging from water table to the maximum capillary rise height as exemplified in the work of Mccarthy & Johnson[48]. The significant contribution of the impact of the capillary fringe in water table and storage change computations have been reported in previous published literature namely Li et al., Nielsen & Perrochet, and Cartwright et al.[49-51] among others while numerous studies have equally revealed the variation of specific yield with water table and time[35-44 & 52-59]. It is only when the water table is deep enough and the time interval is close enough for the attainment of the complete drainage process by gravity or attaining the state of static equilibrium condition that the ultimate specific yield which serves as constant value is regarded as being valid[43-57] while Fahle & Dietrich[60] stated that restriction should be placed on specific yield to function under a specified time window at specified field situations.

3.3 Expressions of specific yield as a function of water table depth

When equilibrium is attained with enough time, the specific yield is found to be equal to the difference in water content between the initial and final equilibrium soil moisture horizon integrated in vertical manner ranging from land surface to the final water table depth divided by the encountered in water table depth with the assumption that no water sources or sinks are resident in the vadoze zone[52-61]. The water content as observed between two equilibrium moisture horizons changes with water table depth. 62. Childs[62] utilized a hypothetical moisture profile for the description of the variation in specific yield with depth of the water table. Under a deep declining water table where the static equilibrium soil moisture horizon is above the initial water table denoted as IWT while the re-attained equilibrium is defined as observed horizon after IWT declined by ΔH to the final water table denoted as FWT. The static equilibrium horizon can be represented by a water-retention curve like Van-Genuchten curve model or the Brooks-Corey curve model[63-64]. The volume of the water released per unit area by mathematical deduction is equal to (P_s $-S_r$). ΔH while that of the specific yield value per unit area is equal to (P_s $-S_r$). Under a shallow water table situation, the released water is found to be much smaller than (P_s $-S_r$). ΔH unlike in the declining deep water table situation because the closer the water table is to the ground surface, the smaller the specific yield is[64]. As the capillary fringe zone possesses little or no storage capacity making the specific yield to be tending to zero or almost equal to zero once the water table is found to be sufficiently close to the ground surface; implying that a small amount of downpour can have significant causing a rapid and great change in water table response[54]. In view of the above discourse on water table depth dependence, we have ultimate specific yield (deep water-table case) and the apparent specific yield (shallow water table case) or depth dependence or depth-compensated specific yield[56-65]. It is worthy of note that some researchers have utilized the ultimate specific yield concept for both deep and shallow water table situations[56-59].

When the water table depth is deep enough, the effect of capillary fringe can be ignored and thus apparent specific yields consequently equals the ultimate specific yields. The depth needed to attain the ultimate specific yield is related to the soil texture. The ultimate specific yield can be attained when the water level is deeper than 1m for coarse-textured sediment such as sand[58]; loamy soil[43]; peat sediment[57] and a mixture of sand, silt, clay and lateritic[66] while a given depth exceeding 10m is required for fine-textured sediments to attain ultimate specific yield status[67]. The necessity of expressing the empirical formulae for the computation of apparent specific yield in this work cannot be underestimated. Equation 3 depicts a function of water table depth for the apparent specific yields as proposed by Abdul & Gillham[44] and Neuman[16] with three assumptions stated; presence of a static equilibrium soil moisture profile above the IWT, possible instantaneous re-attainment of the static equilibrium profile after a change is observed in the water table and the porous medium must be uniform[42].

$$S_Y = (P_s - S_r).\left[1 - \left(\frac{h_a}{H}\right)^{\lambda}\right] \qquad 3$$

Where H represents the depth to water-table h_a represents the air-entry pressure head (bubbling pressure) and λ represents the index of pore-size distribution. Furthermore, an improved formular was introduced by Nachabe[40] to enhance the computation of the apparent specific yield for the primary purpose of addressing the earlier set limitation that Nachabe expression is only valid when the FWT is small in comparison with the IWT depth[40]. Nachabe formula is valid regardless of the water table fluctuation[40].

$$S_Y = \frac{(P_s - S_r)}{\Delta H}.\left[\Delta H + \frac{h_a}{1-\lambda}\left\{\left(\frac{h_a}{H_i}\right)^{\lambda-1} - \left(\frac{h_a}{H_f}\right)^{\lambda-1}\right\}\right] \qquad 4$$

Where H_i and H_f are the corresponding parameters for the initial water table depth (IWT) and final water table depth (FWT) respectively. It is worthy of note that Abdul & Gillham[44] and Nachabe[40] functions are jointly centred on Brooks-Corey water retention curve. The Van-Genuchten has equally been harnessed in the analytical expression of apparent specific yield. Crosbie et al.[42] went further to explaining that Duke[44] functions cannot be applied in a layered soil. Therefore, a more generally acceptable solution was proposed in equation 4 centred on a static equilibrium profile featured by the Van-Genuchten curve while a similar expression to equation 5 was equally achieved using the Van-Genuchten water retention curve by Duke[44] and Cheng[59].

$$S_Y = (P_s - S_r) - \frac{(P_s - S_r)}{\left[1 + \{\alpha(\frac{H_i + H_f}{2})\}\}^{n}]^{m}\right]} \qquad 5$$

Where α is related to the air-entering value of the Van-Genuchten curve in reverse order and n is a dimensionless parameter in the Van-Genuchten curve that is restricted generally to values greater than 1, and m is consequently expressed as

$$m = 1 - \frac{1}{n} \qquad 6$$

3.4 Expressions of specific yield as a function of time

Since the water in the soil medium is not instantaneously mobile, the shorter the accumulated time, the smaller the value of the specific yield[16]. After the commencement of the water table change, the soil medium near the water would attain the static equilibrium first due to the capability of the capillary fringe in making the medium close to the water table in order to possess appreciable water supply[40 & 68]. However, it takes a very long time, potentially several months or years to extract completely the entire vadoze zone[8-14]. For instance, Prill[69] and Meizhao et al.[16] discovered that it would take over a year for a 1.71m long column of medium grained sand to attain static equilibrium while 0.6m at the bottom of the column attained the static equilibrium barely 5hrs interval after the commencement of drainage. This is an absolute indication that the specific yield is time-dependent most specifically when the water table is shallow and the soil is fine-textured with high air-entry pressure[70]; if the introduced time-step model is longer than the required time to attaining static equilibrium, the apparent specific yield can be justifiably adopted[40]. However, the time-step in land surface model is usually short (less than an hour) and the static equilibrium condition seldom occurs in such a short time step. Contrary to the apparent specific yield, the transient specific yield is time-dependent. The transient specific yield should therefore be obtained from the initial and time-varying moisture profiles. The theoretical formula for the transient yield was proposed by Martinez-Santos et al.[71] and expressed in equation 7.

$$S_Y = \frac{\Delta W^I}{\Delta t} \bigg/ \frac{\Delta H}{\Delta t} + \alpha(\mathrm{H,t}) \qquad 7$$

where $\frac{\Delta W^I}{\Delta t}$ accounts for the change encountered in the shape of the moisture profile above the water table over time, $\frac{\Delta H}{\Delta t}$ is the change rate of the water table and α(H,t) is the air constant at the surface at any given time which can be obtained from the measured moisture profile curves. For the static equilibrium condition ($\frac{\Delta W^I}{dt} = 0$), the equation is in line with Duke formula[44].

Based on the Brooks-Covey curve, the transient specific yield in Nachabe[40] was computed in equation 8 where

$$S_Y = \frac{K_{sat}}{\Delta H}(\Theta_b{}^n - \Theta_{surf}{}^n)\mathrm{t} + (P_s - S_r)(1 - \Theta_b) \tag{8}$$

where K_{sat} is the saturated hydraulic conductivity; n is an exponent that can be projected to set at ${(2+3\lambda)}/{\lambda}$; a normalized water content Θ is defined as

$$\frac{(P - S_r)}{(P_s - S_r)} \tag{9}$$

Θ_b is accordingly the temporal evolution of water content profile and Θ_{surf} is the water content occurring at the surface and empirically equal to

$$\left(\frac{2h_a}{H_i + H_f}\right) \times \lambda \tag{10}$$

Where equation 10 is a typical case description of an instantaneous drop in the encountered water table[40-43]. In addition, this expression has several limitations; the initial moisture profile is assumed to be in the static equilibrium condition[40]. The alteration in water table should be recognized and there should be no downward or upward flux in the unsaturated[16]. As observed in the above expression, the static equilibrium status is quite uncommon especially in the category of short time-step models. A significant formula was proposed by Pozdniakov et al.[70] for the purpose of predicting the dynamic specific yield under periodic water table oscillations either via seasonal or diurnal responses. For a vertical column of porous medium with L_0 with the assumption that the lower boundary of the column is saturated fully and the impenetrable upper boundary, the water-head H at time t can be expressed further as

$$\mathrm{H}\,(\mathrm{t})|_{z=}L_0 = m_0 + \Delta H_{max} \sin \frac{2\pi t}{T} \tag{11}$$

Where m_0 represents the attained height of the column with full water saturation above the column bottom, ΔH_{max} represents the amplitude of the oscillation where 2. $\Delta H_{max} <$ m) and T is the period of oscillation. The mean value for half of the period value of the specific yield can be computed by equation 12.

$$S_Y(\mathrm{T}) = \frac{\Delta V}{\Delta Z_{gw}} \tag{12}$$

$$\Delta Z_{gw} = Z_{gw}\,(t_{mins} + \frac{T}{2}) - Z_{gw}(t_{mins}) \tag{13}$$

$$\Delta V = \int_{t_{mins}}^{t_{mins}+\frac{T}{2}} K \frac{\partial H}{\partial Z}\Big|_{z=L_0} \partial t \qquad 14$$

Where Z_{gw} represents the water table level, t_{mins} is the time marker at which the point is in the lower position and K is the hydraulic conductivity determinable with respect to the outcome of Van-Genuchten curve. It should be pointed out that the initial soil moisture profile should be in hydrostatic distribution and that the values of the period of oscillation and the corresponding amplitude are obtained.

3.5 Varying techniques of field utilization for specific yield evaluations

The principal challenge often encountered in evaluating the specific yield is to quantify the amount of water that is gained or otherwise lost[72]. A number of varying field techniques has been proposed for the evaluation of specific yield. Among the conventional techniques include the laboratory drainage technique, pumping testing, the numerical technique, the texture based techniques, water table fluctuation technique and slug-test. Aside from these aforementioned field techniques, newer techniques were proposed in the latter years namely geoelectrical technique, magnetic resonance sounding, and rainfall-water table response techniques. Nevertheless, estimation of specific yield is circumscribed with uncertainty[73-74]. Therefore, the determination of an appropriate specific yield value in the field still remains a huge task[75-76]. There is no widely accepted available technique for the estimation of specific yield due to the fact that the various methods often produce values that are somewhat inconsistent in relation to sediment types thereby defining their respective area of application[11,39,42,58 & 77]. In this study aquifer pumping testing technique was utilized which necessitated the instalment of pumping as well as observation wells.

3.6 Field data acquisition

Pumping tests were conducted on 25 selected boreholes and 25 hand-dug wells cut across Wasinmi area, with the view to assessing and ascertaining the hydraulic performance in terms of yield-drawdown characteristics of the wells. The results of this study will go a long way to enhancing the water resource management planning**.** Two principal data sources were utilized in this study. These are primary and secondary data sources. The primary data source comprised of visual inspection and reconnaissance survey where personal visits to locations of existing boreholes and hand-dug wells in the study area; identifying sampling points and collecting well inventories. Borehole drilling contractors and site engineers were equally consulted in Wasinmi on core samples information regarding drilled holes and hand-dug wells in the study area. Existing drilled boreholes and hand-dug wells were identified across the study areas and where there were no boreholes the existing hand-dug wells were used. The depth of the boreholes and the overburden thickness were measured using dip-meter while GPS was used to acquire the coordinates used in producing the data acquisition map of the study area displayed above in Figure 4. Two different methods were used in conducting pumping tests on the selected boreholes and hand dug wells. These methods are constant rate pumping test and recovery method test.

3.6.1 Constant rate pumping test

Constant rate pumping tests were conducted on the selected boreholes. The materials used for these tests included; 60-litre gallons as a standard measure, generating set to power the pump, stop watch to record time intervals and rubber hose connected to the pipe from the borehole to discharge the water into the gallons. In conducting this test, the initial or static level of the water in the boreholes was measured using a dip-meter. The generating set was thereafter switched on to start the pumping. The pumping was allowed to run continuously for a long period of two hours before the rate of pumping was adjusted for the boreholes to maintain constant discharge. At this point, the water level response in terms of dynamic drawdown was measured to know the drawdown and a calibrated 60-litre gallon was then filled from the constant discharge from the boreholes while a stopwatch was simultaneously set to record the time taken, in seconds, to fill the gallons. This process was repeated for four hours for each of the selected boreholes. It was therefore observed that the water level and the drawdown in the boreholes were constant throughout the four hours pumping. With the constant discharge from the boreholes, a state of equilibrium was maintained between the rate of discharge and the rate of recharge from the aquifer. In this condition of equilibrium, the rate of pumping or discharge is directly proportional to the yield of the borehole or well at the constant drawdown. In other words, the discharge per unit time in litre per second gives the yield of each of the selected boreholes at the constant drawdown[78]. This test was adopted because of the relatively easier field operations, economic advantage, overall logistics and technical ease of rapid computation of aquifer parameters including K and T of auriferous zone of interest at every investigated location. Estimation of aquifer parameters was accomplished by adapting to Cooper et al.[79] straight-line solution to time-Drawdown data acquired in the observation well which serves as adjustment to Remson and Lang[80] non-equilibrium well equation as stated below

$$T = \frac{2.3S_Y}{4\pi\Delta S} \qquad 19.0$$

$$C_s = \frac{S_Y}{s_m} \qquad 20.0$$

$$K = \frac{T_r}{A_{thic}} \qquad 21.0$$

Where S_Y = Specific yield (m^3/day), C_s = Specific capacity, T_r = Transmissivity (m^2/day)
s_m = mean drawdown, ΔS = change in draw-down over one log cycle, A_{thic}= saturated thickness of the aquifer. Pumping test of wells serves as the most reliable method for the estimation of hydraulic conductivity[64-65 & 81-84].

$$K = \frac{S_Y}{2\pi A_{thic}(h_1 - h_2)} \qquad 22.0$$

$$D_H = \frac{T}{s} = \frac{KB}{s} = \frac{K}{S_s} \qquad 23.0$$

Equation 21.0 and 22.0 are respectively representing hydraulic conductivities for borehole and hand-dug wells where $h_1$is the initial water level before pumping, h_2 is the final water level after pumping also known as drawdown and π is the mathematically constant approximately equal to 3.14159 while equation 23.0 represents hydraulic diffusivity denoted with D_H. The analyses of drawdown and recovery data are utilized to determine the aquifer storage coefficient (S). The storage coefficient can be calculated by using the formula expressed in equation 24.0 while specific storage (S_s) is then calculated through equation 25.0.

$$\mathrm{S} = S_s \times A_{thic} \qquad 24.0$$

$$S_s = \frac{\mathrm{S}}{A_{thic}} \qquad 25.0$$

Hydraulic Diffusivity (D_H) is a fundamental parameter in studying groundwater flow being an analytical solution for groundwater flow within a finite length of one-dimensional aquifer. It is a key parameter in groundwater development, determination of how quickly disturbances like starting a well or change in recharge, pumping or changes in boundary conditions propagate through an aquifer with great impact on groundwater management and resource engineering. It is computed as the ratio of transmissibility (T) to storability (S). Hydraulic diffusivity is highly relevant in groundwater studies due to its contributions and applications in Transient groundwater flow system, aquifer disturbance propagation, groundwater management, environmental management, and resource engineering practices. It is highly utilized in pumping tests, numerical modelling and tidal response analysis.

3.6.2 Recovery method Test

Recovery method test was carried out on the identified hand-dug wells by monitoring the recovery status of water levels on the cessation of pumping; dip-meter, generating set and stop watch among others were the materials used for this test. Dip-meter was first released and dipped into the well for the purpose of determining the overall depth of the well and the water level by measurement before outset of pumping. The pump was therefore powered by the generating set and the water in the well was pumped out until it gradually reached the bottom of the well. The stop watch was simultaneously set to record the time taken for the pumping as the reduction in water level was observed at different depth interval. As soon as the bottom level of the pumped well was attained, the well was left undisturbed creating space for recharge while the stop watch equally recorded the time taken for the water replenishment back to previous level before pumping started. The volume of the pumped water pumped was computed by utilizing the diameter and the overall depth measurement of the well. The ratio of the volume of water abstracted to the time taken in the course of abstraction gave the pumping rate in litre per second while the volume per day (m^2/day) resulted to the yield of the well. In the course of the field measurement, three wells comprising of WASWW23 to WASWW25 were found to be completely dried. So, field pump testing could not be performed on them; they were denoted as Not Available for Measurement in Table 2.

Cone of depression are created in aquifer when groundwater is pumped from a well[84]. This represents an actual depression of the observed water levels in an unconfined aquifer while but represents a reduction in the pressure head in the neighbourhood of the pumped well. The land area scaling above the cone of depression is referred to as the area of influence while the distance covered from the centre of the well to the edge of the observed cone of depression is referred to as the radius of influence. In the exploratory well site investigation, the radius of influence grants an insight about the well spacing to be adopted[85-87]. In this study, proposed equation from Bear[88] and applied by Shahinuzzaman et al.[84] was utilized in the determination of the radius of influence as presented in equation 26.0

$$R = 1.5\sqrt{\frac{T}{S}} \qquad 26.0$$

Where R is the radius of influence for both confined and unconfined aquifer, T and S are stated as transmissivity and storage coefficient in a respective order. Drawdown (DD) is the recorded difference between the initial static water level (SWL) and the pumping water level (PWL) at any specified period of time during pumping operation.

$$DD = SWL - PWL \qquad 27.0$$

The specific capacity (Cs) represents the pumping flow-rate (Q) per unit drawdown produced in the well.

$$Cs = \frac{Q}{DD} \qquad 28.0$$

The specific drawdown (SDD) as a parameter is defined in well hydraulics as the inverse of specific capacity (Cs) as denoted in equation 29.0 and is of paramount significance in the study of aquifer properties.

$$SDD = \frac{1}{Cs} \qquad 29.0$$

4. Results

The results of the basic well inventories and hydraulic properties of the aquifers in the study area presented as summary in Tables 1 and 2 for boreholes and hand-dug wells respectively. In the evaluation of the aquifer characteristics in the study area, groundwater supply to boreholes were abstracted from fractured sandstone whose depth ranged from 35m to 75m with a mean depth of 51m, the static water level ranged from 8.45m to 37.4m with a mean value of 17.8m while the drawdown observed varied between 3.67m to 11.4m with mean drawdown of 8.17m. Fractured shales released groundwater into the hand-dug wells whose depth varied between 4.3m to 21.4m with the mean depth of 8.28m while the static water level ranged from 0.24m to 5.42m with the mean static water level of 1.59m.

Table 1. Hydraulic parameters of studied aquifer systems of Wasinmi boreholes

	BASIC HYDRAULIC PARAMETERS						**ESTIMATED HYDRAULIC PARAMETERS**				
Locations	**Well Head (m)**	**Borehole Depth BHD (m)**	**Borehole diameter BHDT (mm)**	**Static Water Level SWL (m)**	**Residual Draw-Down DD (m)**	**Time (s)**	**Specific Discharge Q (l/s)**	**Specific Capacity Cs (m^2/s)**	**Well Loss WLC (s^2/m^5)**	**Transmissibility Tr (m^2/s)**	**Optimum Operating Capacity OOC**
WASBH1	0.28	40	125	11.9	5.83	850	10.6×10-2	1.817×10-2	5.189×104	2.180×10-2	1.926×10-3
WASBH2	0.25	35	125	8.75	3.67	1026	0.772×10-2	2.390×10-2	4.771×104	2.868×10-2	2.097×10-3
WASBH3	0.42	50	125	17.8	6.48	1170	7.692×10-2	1.187×10-2	10.951×104	1.425×10-2	9.132×10-4
WASBH4	0.42	50	125	17.1	4.28	2635	3.415×10-2	7.980×10-3	36.693×104	9.576×10-2	2.726×10-4
WASBH5	0.25	55	110	8.45	8.45	2981	3.019×10-2	3.573×10-3	19.983×104	42.88×10-2	1.079×10-4
WASBH6	0.28	42	110	8.82	8.15	2992	3.008×10-2	3.691×10-3	90.051×104	44.23×10-2	1.111×10-4
WASBH7	0.15	45	110	10.45	9.22	2884	3.121×10-2	3.385×10-3	94.649×104	40.63×10-2	1.057×10-4
WASBH8	0.61	55	25	22.59	10.53	3067	2.934×10-2	2.787×10-3	122.298×104	33.44×10-2	8.177×10-5
WASBH9	0.28	55	125	26.12	6.48	3409	2.640×10-2	4.074×10-3	92.982×104	48.89×10-2	1.076×10-4
WASBH10	0.36	46	110	13.12	8.32	2491	3.613×10-2	4.342×10-3	63.747×104	52.11×10-2	1.569×10-4
WASBH11	0.30	42	25	11.4	10.16	2596	3.467×10-2	3.413×10-3	84.506×104	40.95×10-2	1.183×10-4
WASBH12	0.30	36	110	10	8.57	2635	3.415×10-2	3.985×10-3	73.472×104	47.82×10-2	1.361×10-4
WASBH13	0.45	42	25	10.75	11.15	1350	6.667×10-2	5.979×10-3	25.087×104	71.75×10-2	3.986×10-4
WASBH14	0.30	43	25	12.9	10.89	1415	6.361×10-2	5.841×10-3	26.911×104	70.10×10-2	3.716×10-4
WASBH15	0.25	50	125	22.95	4.25	2984	3.016×10-2	7.096×10-3	46.732×104	85.15×10-2	2.140×10-4
WASBH16	0.04	60	25	24.06	10.32	2430	3.704×10-2	3.589×10-3	75.233×104	43.07×10-2	1.329×10-4
WASBH17	0.45	70	25	29.95	11.15	1393	6.460×10-2	5.794×10-3	26.719×104	69.52×10-2	3.743×10-4
WASBH18	0.43	45	25	9.07	10.25	1879	4.789×10-2	4.673×10-3	44.693×104	56.07×10-2	2.238×10-4
WASBH19	0.28	70	25	32.9	11.35	3431	2.040×10-2	1.798×10-3	272.651×104	21.57×10-2	3.668×10-5
WASBH20	0.28	40	25	8.92	11.26	2675	3.365×10-2	2.988×10-3	99.459×104	35.86×10-2	1.005×10-4
WASBH21	0.45	40	125	21.75	6.45	3128	2.877×10-2	4.460×10-3	77.931×104	53.52×10-2	1.283×10-4
WASBH22	0.42	52	110	18.08	7.85	1541	5.841×10-2	7.441×10-3	23.081×104	74.41×10-2	4.346×10-4
WASBH23	0.36	55	110	22.04	8.82	1606	5.605×10-2	6.355×10-3	28.071×104	76.26×10-2	3.562×10-4
WASBH24	0.28	75	125	37.42	4.15	2840	3.169×10-2	7.635×10-3	41.335×104	91.62×10-2	2.419×10-4
WASBH25	0.32	74	125	26.48	6.25	947	9.506×10-2	1.521×10-3	6.917×104	18.26×10-2	1.446×10-4
MEAN	0.33	51	84.80	17.8	8.17	2254	4.0×10^{-2}	6.3×10^{-3}	5.98×10^{4}	4.5×10^{-1}	02.52×10^{-4}
MAX	0.61	.00	125.00	37.4	11.4	3431	11.0×10^{-2}	2.0×10^{-2}	2.73×10^{6}	9.2×10^{-1}	2.20×10^{-3}
MIN	0.04	35.00	25.00	8.45	3.67	850	1.0×10^{-2}	1.0×10^{-4}	4.77×10^{4}	1.00×10^{-2}	1.00×10^{-6}
S.D	0.11	11.58	46.18	8.47	2.49	838	2.0×10^{-2}	5.0×10^{-2}	5.60×10^{4}	2.6×10^{-1}	1.00×10^{-4}
CV (%)	33	23	55	48	31	37	50	79	94	58	40

Table 2. Hydraulic parameters of studied aquifer systems of Wasimi hand-dug wells

	BASIC HYDRAULIC PARAMETERS						ESTIMATED HYDRAULIC PARAMETERS				
Locations	**Well Head (m)**	**Well Depth WD (m)**	**Well diameter MWD (m)**	**Static Water Level SWL (m)**	**Residual Draw-Down DD (m)**	**Time (s)**	**Specific Discharge Q (*l*/s)**	**Specific Capacity Cs (m^2/s)**	**Well Loss WLC (s^2/m^5)**	**Transmissibility T (m^2/s)**	**Optimum Operating Capacity OOC**
WASWW1	0.62	5.5	1.00	1.68	0.29	3312	27.17×10-3	9.37×10-2	0.0394×104	11.244×10-2	3.381×10-6
WASWW2	0.48	7.6	1.86	1.32	0.13	1620	55.66×10-3	42.70×10-2	0.0042×104	51.288×10-2	4.026×10-7
WASWW3	0.83	4.4	0.65	0.32	0.86	9814	9.171×10-3	10.66×10-3	1.0225×104	1.28×10-2	4.034×10-6
WASWW4	0.72	7.3	0.79	3.22	0.32	1728	52.08×10-3	10.85×10-2	1.1797×104	13.02×10-2	1.456×10-5
WASWW5	1.43	12.6	0.86	2.82	1.72	3708	24.27×10-3	1.41×10-2	0.2920×104	1.69×10-2	3.245×10-6
WASWW6	1.48	4.3	0.74	0.66	0.13	1699	52.97×10-3	40.75×10-2	0.0046×104	48.90×10-2	1.101×10-6
WASWW7	1.62	4.5	0.91	0.58	0.17	2250	40.00×10-3	23.53×10-2	0.0106×104	28.24×10-2	1.155×10-6
WASWW8	0.72	8.7	0.83	1.71	0.19	2268	39.68×10-3	20.89×10-2	0.0121×104	28.24×10-2	1.145×10-6
WASWW9	0.43	9.3	1.67	2.39	0.69	15172	5.92×10-3	8.59×10-3	1.9662×104	1.03×10-2	7.856×10-7
WASWW10	0.46	7.5	0.38	0.82	1.65	17532	5.13×10-3	3.11×10-3	6.2612×104	3.73×10-3	7.889×10-7
WASWW11	0.28	6.8	0.46	1.07	1.99	15775	5.71×10-3	2.87×10-3	6.1142×104	3.44×10-3	1.298×10-6
WASWW12	1.85	6.2	0.78	0.78	0.14	1717	52.42×10-3	37.44×10-2	0.0051×104	44.92×10-2	1.167×10-6
WASWW13	1.80	6.8	0.82	0.54	0.25	3132	28.74×10-3	11.49×10-2	0.0303×104	13.79×10-2	6.862×10-6
WASWW14	1.28	8.8	0.78	0.57	0.14	1541	58.40×10-3	41.72×10-2	0.0073×104	50.06×10-2	7.122×10-6
WASWW15	0.90	8.5	0.78	1.12	0.17	9151	9.84×10-3	5.79×10-2	0.1757×104	6.942×10-2	2.186×10-5
WASWW16	0.92	6.5	0.69	0.35	0.79	9302	9.68×10-3	1.23×10-2	0.8439×104	1.469×10-2	2.657×10-6
WASWW17	1.22	5.5	0.69	0.52	1.04	11988	7.51×10-3	7.25×10-3	1.8363×104	8.704×10-3	7.093×10-6
WASWW18	1.50	6.8	0.65	0.24	1.88	20275	4.43×10-3	2.36×10-3	5.2526×104	2.833×10-3	3.016×10-6
WASWW19	0.95	16.2	0.62	4.27	1.26	24610	3.66×10-3	2.90×10-3	9.4213×104	3.483×10-3	3.428×10-6
WASWW20	0.93	21.4	0.58	5.42	1.65	18389	4.89×10-3	2.97×10-3	6.8889×104	3.559×10-3	3.320×10-6
WASWW21	0.82	9.7	0.63	3.03	1.59	19721	4.56×10-3	2.87×10-3	7.6343×104	3.444×10-3	3.629×10-6
WASWW22	0.65	7.2	0.66	1.48	1.19	13115	6.86×10-3	5.77×10-3	2.5270×104	5.767×10-3	5.877×10-6
WASWW23	0.95	3.6	1.02	**NAFM**	**NAFM**	**NAFM**	**NAFM**	**NAFM**	**NAFM**	**NAFM**	**NAFM**
WASWW24	0.90	3.4	0.86	**NAFM**	**NAFM**	**NAFM**	**NAFM**	**NAFM**	**NAFM**	**NAFM**	**NAFM**
WASWW25	0.75	3.2	0.78	**NAFM**	**NAFM**	**NAFM**	**NAFM**	**NAFM**	**NAFM**	**NAFM**	**NAFM**
MEAN	0.995	8.277	0.8105	1.59	0.83	9446	2.3×10^{-2}	1.4×10^{-1}	2.342×104	1.42×10^{-1}	3.20×10^{-3}
MAX	1.85	21.40	1.86	5.42	1.99	24610	6.0×10^{-2}	5.8×10^{-1}	9.421×104	5.10×10^{-1}	3.48×10^{-2}
MIN	0.28	4.30	0.38	0.24	0.13	1541	1.0×10^{-4}	1.0×10^{-4}	0.004×104	1.00×10^{-1}	1.00×10^{-8}
S.D	0.461	3.994	0.3402	1.39	0.68	7584	2.1×10^{-2}	1.8×10^{-1}	3.046×104	1.86×10^{-1}	3.78×10^{-3}
CV (%)	46	48	42	87	82	80	89	133	100	131	118

NAFM: Not available for measurement (completely dried wells)

5. Discussion

In Wasinmi Boreholes, the sedimentary aquifer released up to 11.0×10^{-2} l/s with depths to aquifer found to vary between 35m to 75m with the mean of 51m (Table 1). Ewekoro, the closest community to the study area exhibited a yield of 6.0×10^{-2} l/s and the accompanied depth to water found to vary between 35m and 100m with a mean depth of 60.32[23]; Ilorin basement had 17m to 60m with a mean of 32.9m in borehole depth[89-90]; Ado-Ekiti basement had 40m to 120m and Malawi basement had 24m to 75m with a mean value of 24m[91-93]. The influence of depth on the observed yield was not totally dependent but other parameters like porosity and permeability played significant roles. The specific yields particularly for an unconfined aquifer varied in standard of 0.01 to 0.3[94]. The observed high value is a reflection of the aquifer potential for a high storage in relation to the water holding capacity of the rock. This is due to the abundance of clayey materials; possessing a high capacity for water storage but low capacity for water transmission. The auriferous zone in the study area is as a result of the effect of weathering of the saturated sandstone and partly cavernous karst limestone in the area[95-96]. Borehole discharge varied from 1.0×10^{-2} l/s to 11.0×10^{-2} l/s with a mean of 4.0×10^{-2} l/s (Table 1) as compared with Ewekoro aquifer that ranged from 3.0×10^{-2} to 6.0×10^{-2} l/s with an average of 4.0×10^{-2} l/s; Ilorin basement complex ranged from 2.4×10^{-1} l/s to 25.0×10^{-1} l/s with an average of 8.9×10^{-1} l/s; Ado-Ekiti basement ranged from 2.6×10^{-1} l/s to 0.26×10^{-1} l/s and Malawi basement ranged from 2.5×10^{-3} l/s to 5.0×10^{-1} l/s with a mean of 0.078×10^{-1} l/s. The study area exhibited transmissibility that varied from 1.0×10^{-2} m^2/s to 9.20×10^{-2} m^2/s with a mean value of 4.5×10^{-1} m^2/s (38,880 m^2/day) as compared to the closest community (Ewekoro aquifer) whose transmissibility varied between 8.04 to 6912 m^2/day with a mean of 776.6 m^2/day; Ilorin basement complex had 2.0 to 35 m^2/day while upper gravelly coastal plain sandy aquifer of Akpabuyo, South-South Nigeria possessed transmissibility value range of 3.61 to 11.4m^2/day[97]. The residual drawdown in the investigated location ranged from 3.67m to 11.4m with a mean of 8.17 (Table 1) while the mean static water level was 17.8m with an interval of 8.45m to 37.4m. Average specific capacity (Cs) and Well loss were respectively found to be 6.3×10^{-3} m^2/s and 5.98×10^{4} $s^2/m^{5.}$ The longest recovery period was 3431 seconds (WASBH19) and shortest recovery was 850 seconds (WASBH1) with a mean recovery period of 2254 seconds (37.57 minutes). Among the investigated hydraulic parameters in the study area, Borehole Depth is the least variable identified parameters having the coefficient of variation (CV) of 23% (Table 1). This was accompanied by Residual Drawdown (RDD) and Well Head possessing a CV of 31% and 33% respectively (Table 1). In Wasinmi hand-dug wells, the sedimentary auriferous zones produced up to 6.0×10^{-2} l/s with a mean of 2.3×10^{-2} l/s while depths to the well varied from 4.30 to 21.40m with the mean depth of 8.3m. Water discharge from the well ranged from 1.0×10^{-4} to 6.0×10^{-2} l/s with an average of 2.3×10^{-2} l/s. The transmissibility varied from 1.0×10^{-1} (8.64 m^2/day) to 5.10×10^{-1} m^2/s (44,064 m^2/day) with a mean of 1.42×10^{-1} m^2/s (12,269 m^2/day). The RDD varied between 0.13m to 1.99m with a mean of 0.83m, the mean SWL was found to be 1.59m within a range of 0.24m to 5.42m while the mean Cs and WLC were respectively reported as 1.4×10^{-1} m^2/s and 2.34×10^{-4} s^2/m^5. The shortest recovery period was 1541 seconds (WASWA14) while the longest recovery period was 24,610 seconds (WASWA19) with the average of recovery period of 9446 seconds (157.43 minutes). Among all the hydraulic parameters investigated in Papalanto hand-dug wells, measured well diameter is the least variable parameter with value of 42% followed by Well head alongside well depth possessing CV of 46% and 48% in respective order (Table 2).Transmissibility is a very significant hydraulic property of an aquifer which serves as the ratio of dominating density and drained density via a unit width of an aquifer subjected to a unit hydraulic head. It is a function of liquid properties, porous media and the accompanied thickness of the porous media[98]. The plots of specific capacity (Cs) against Transmissibility

(T) on Semilog Scale are in Figure 5a and 5b for Wasinmi Borehole and hand-dug well sites.

High transmissibility values are suggestive of high potentiality which in turn determines the production capacity. Groundwater in the study area exhibited very high transmissibility in both water sources; 4.5×10^{-1} m^2/s (38,880 m^2/day) in Boreholes and 1.42×10^{-1} m^2/s (12,269 m^2/day) According to potentiality classification, transmissibility values greater than 500 m^2/day are considered high potentials[99-102]. According to transmissibility classification scheme of Krasny[103] adopted by Jika & Tse[104]; the auriferous zone in the study area are classified as high in potentials in the designation of transmissivity magnitude for boreholes and hand-dug wells jointly presented in Table 3.

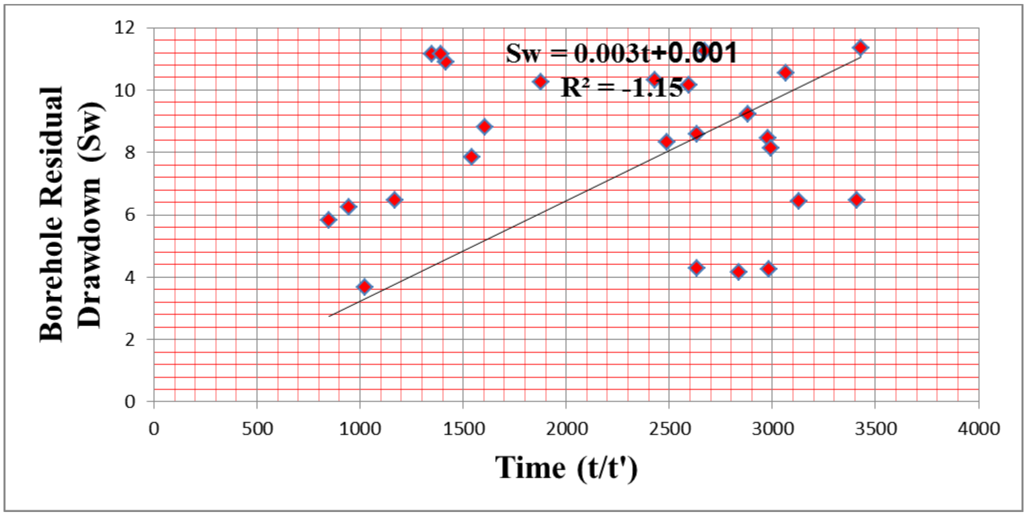

Figure 5a. Plot of residual drawdown (Sw) and time (T) on Semilog scale for Wasinmi borehole sites

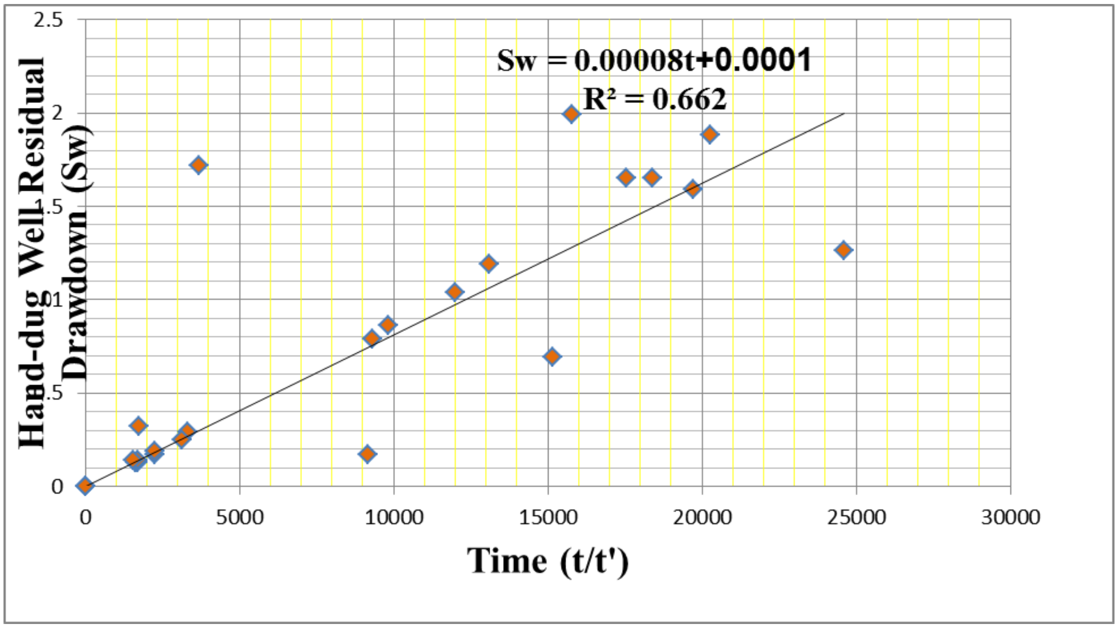

Figure 5b. Plot of residual drawdown (Sw) and time (T) on Semilog scale for Wasinmi Hand- dug well Site

Table 3. Transmissibility potentials of the aquifer system[99 & 103-107]

Coefficient of Transmissibility (T) Range (m^2/day)	Classification magnitude	Magnitude designation		Coefficient of Transmissibility (T) Range (m^2/day)	Classification magnitude	Magnitude designation
> 500	I	High Potentials		> 1000	I	Very High
100−500	II	Good Potentials		100 – 1000	II	High
50−100	III	Moderately Potentials		10 – 100	III	Intermediate
5−50	IV	Low Potentials		1 – 10	IV	Low
0.5−5	V	Very Low Potentials		0.1 − 1.0	V	Very Low
<0.5	VI	Negligible Potentials		0 – 0.1	VI	Imperceptible

As obtained from the drilling outputs and lithological description of the boreholes drilled in the study area, the saturated thickness of the aquifer were 14m (26m-40m) and 17m (8m-25m); 17m (13m-30m) and 9m (3-12); 25m (5m-30m) and 22m (2m-24m); 50m (12m-62m) and 22m (2.0m-24m); and 63m (7.0-70m) and (2m and 22m) respectively recorded for boreholes and hand-dug wells in location 1 to 4; 5 to 8; 9 to 12; 13 to 16; 17 to 20 and 21 to 25 as displayed in Figure 6a to 6f in respective order. The aquifer thickness as well as the static water level are both veritable information to be considered by drillers and borehole contractors on the selected numbers of casing/screens to be utilized while the depth would equally enhanced the driller preparation towards the preparation of cost estimates for drilling operations being dependent on the length of metre drilled[108]. Other associated parameters are also of great significance in terms of drilling operation and water management scheme to be adopted and installed be it manpower (manual) on motorized well pumping system[23]. The plots of specific capacity and transmissibility are displayed in Figures 5a and 5b; respectively for Wasinmi Borehole and hand-dug wells. Good correlations are conspicuously observed between transmissibility and specific capacity with correlation coefficient (R^2 = -0.33 and R^2 = 1.00) respectively reported for Wasinmi boreholes and hand-dug wells (Figure 5a and 5b). This output is a revelation that the higher value of specific capacity of an aquifer and its transmissibility, the greater the prolificacy or production capacity of the well. Hydraulic conductivity values in the study area were found between 1.018×10^{-3} m^2/s (87.96 m^2/day) and 50.90×10^{-3} m^2/s (4397.76 m^2/day) in Wasinmi boreholes and between 0.688×10^{-3} m^2/s (594.432 m^2/day) and 89.84×10^{-3} m^2/s (7762.18 m^2/day) in Wasinmi hand-dug wells; this is rated as being very high when compared with the work of Jika & Tse[104] who reported range of values between 6.1×10^{-2} and 6.45×10^{-1} m^2/s in Konshisha, North Central Nigeria. The hydraulic properties of the aquifers in the study area are strongly influenced by weathered sandstone which serve as the aquifer materials for the borehole and the presence of shale/clay shale/clayey sand for the hand-dug wells; groundwater from the shallow hand-dug wells are abstracted from the fractured shales/clay-shale/clayey sand because the required depth for fresh water were not reached at the time of the termination of drilling depth. Shale is a sedimentary rock hydraulically known for its fissility; though highly porous its water transmission capability is very poor. Shale does not transmit water in any way except it is fractured[104]. These are evident in boreholes and well locations of high transmissibility (WASBH24) and

(WASWW14) exhibiting transmissibility values of 9.2×10^{-1} m^2/s (79488 m^2/day) and 50.06×10^{-2} m^2/s (43,251.84 m^2/day) respectively around northeast of Onibotuje and north-west of Alagbon. The potentiality of aquifer in the study area is hydraulically high; according to Daniel[109] and Jika & Tse[104], an aquifer with a transmissibility value of less than 12.4 m^2/day (0.5 m^2/hr. or 1.44×10^{-4} m^2/s) can supply sufficient water to meet domestic needs of households but with higher values can altogether serve domestic, industrial and irrigation purposes. The exhibited high aquifer yield in the study area is an implication that the productive capacities from both water sources can be enhanced and sustained, better when high horse power pumps are preferably installed. Hydraulic conductivity in the range of 40.8 to 49.0 m^2/day has been reported to be of favourable sites for groundwater development in eastern part of Kushtia district of Bangladesh[84] while the Hydraulic conductivity values that ranged from 6.1×10^{-2} to 6.45×10^{-1} have also been reported in Konshisha area in the middle Benue trough of North Central Nigeria[104] and the value range of 9.7 to 27.9 m/day has been reported for upper gravelly aquifer of coastal plain sandy aquifer of Akpabuyor, south-south Nigeria[97]. Hydraulic conductivity is a significant parameter in hydrogeological studies and has been immensely useful for effective groundwater management, protection and prediction for contaminant transportation.

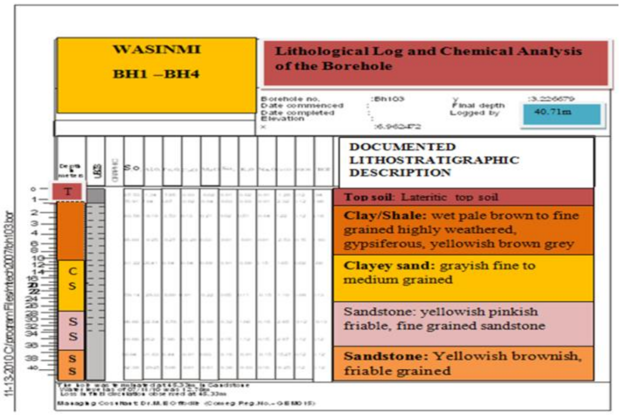

Figure 6a. Lithological description of Wasinmi subsurface around Locations WASBH1 to WASBH4

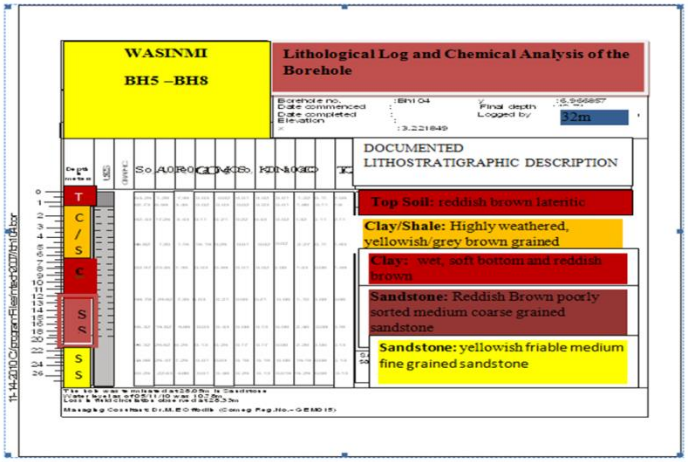

Figure 6b. Lithological Description of Wasinmi Subsurface around Locations WASBH5 to WASBH8

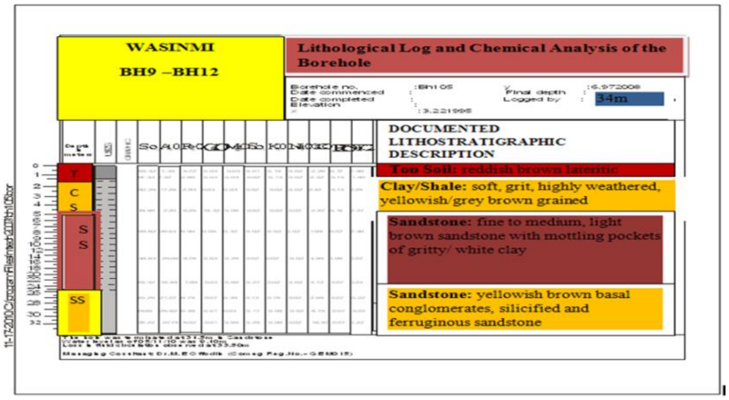

Figure 6c. Lithological description of Wasinmi subsurface around Locations WASBH9 to WASBH12

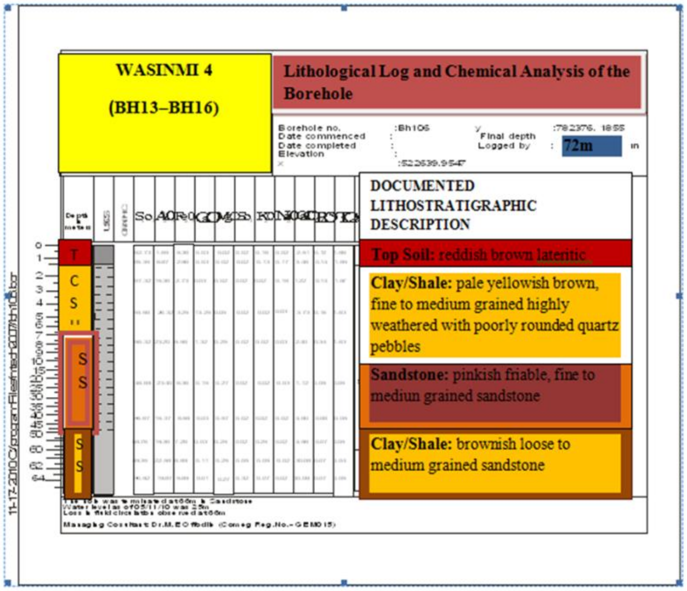

Figure 6d. Lithological description of Wasinmi subsurface around Locations WASH13 to WASBH16

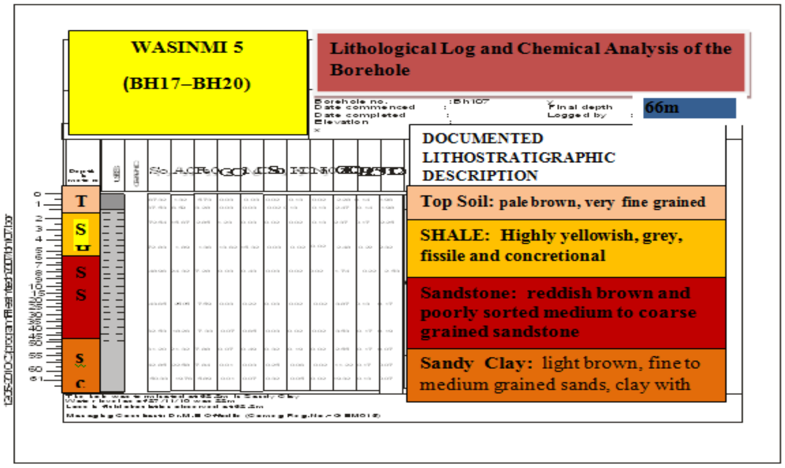

Figure 6e. Lithological description of Wasinmi subsurface around Locations WASBH17 to WASBH20

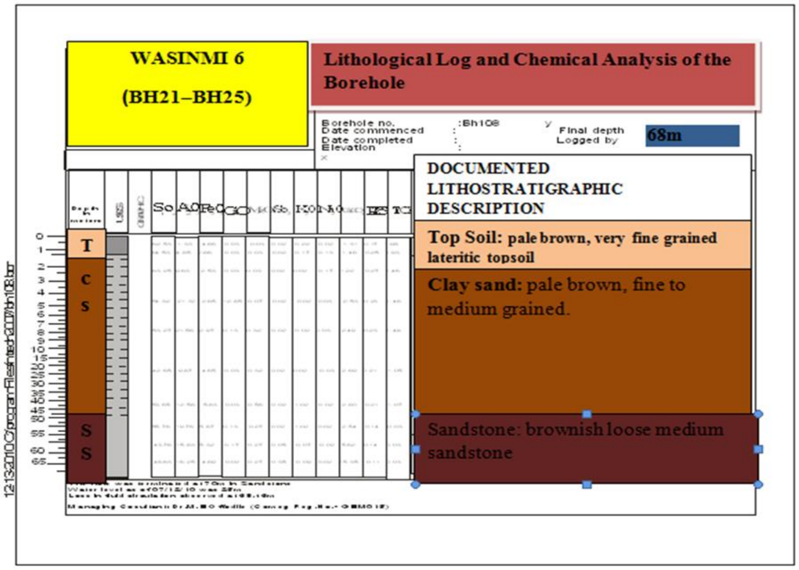

Figure 6f. Lithological description of Wasinmi subsurface around Locations PAPBH21 to PAPBH25

It determines the ease at which the fluids flow via the soil matrix system under a unit hydraulic gradient per unit time[23]. The hydraulic conductivity status of the study area is dependent on the size of the soil grains, the structure of the soil matrix, class of soil fluid as well as the degree of saturation of soil matrix. Hydraulic conductivity varies with particles size for unconsolidated porous media; clayey and partly shaly materials are responsible for the area that exhibited low values of hydraulic conductivity whereas sandy and gravelly aquifers displayed higher values of hydraulic conductivity. Hydraulic diffusivity varied from 11.816 m^2/s (1,020,902.4 m^2/day) to 13,022.87 m^2/s (1,125,175,968 m^2/day) in Wasinmi Boreholes and varied from 4.06 m^2/s (350,784 m^2/day) to 6467.26 m^2/s (558,771, 264 m^2/day) in Wasinmi hand-dug wells. The regions of higher hydraulic diffusivity values are comparatively favourable for groundwater development because of the accompanied higher degrees of flow as well as transport connectivity[84]. The output and consequent understanding of hydraulic diffusivity in the study area would go a long way in assisting well-site contractors and engineers to make predictions on the influence of new and prospective wells on the water levels in the neighbourhood of existing wells; it would reveal how quickly water moves through the aquifer thereby equipping farmers on how irrigation practices can be optimized to ensure efficient utilization of groundwater resources; and it would also serve as essential tool for designing an effective correction measures and remediation strategies for the sanitization of possible contaminated groundwater system. Figures 7a and 7b revealed that the output of hydraulic diffusivity in the study area is a reflection of transmissibility output due to their direct connectivity while Figures 8a and 8b showed the distribution of hydraulic conductivity versus hydraulic diffusivity in 3D line/wireframe contour representations in both water contour sources. Therefore, distribution of hydraulic diffusivity is highly significant in aquifer potential assessment of the study area.

The radius of influence in the study area ranged from 4.89m to 64.80m in Wasinmi boreholes and 3.18m to 49.13m in Wasinmi hand-dug Wells (Table 4). Higher values of radius of influence that ranged from 638m to 760m have been reported in eastern part of Kushtia district of Bangladesh[84]. The size of radius of influence in groundwater studies and well testing practices is primarily a tripartite function namely hydrogeological features like aquifer heterogeneities, presence of faults and recharge rates; aquifer properties like aquifer thickness, porosity and specific yield, and aquifer type (either confined or unconfined); pumping conditions like drawdown, pumping duration among others.

The specific drawdown varied from 0.116m (WABH2) to 2m (WASBH25) in Wasinmi Boreholes and 0.017m (WASWW2) to 0.833m (WASWW11) in Wasinmi hand-dug wells (Table 4). Since drawdown exhibit inverse relationship with specific capacity where low drawdown reflects a high specific capacity and a high drawdown is an indication of low specific capacity. Therefore, wells with similar rate of discharge will abstract less quantity of water from the wells emplaced in the vicinities of high specific drawdown than that of wells occupied in the region of low-valued specific capacity. Higher Specific drawdown of 57m to 126m was reported for Kushtia aquifer[84].

Table 4. Yield determinant parameters of the Wasinmi groundwater systems

Wasinmi Boreholes							**Wasinmi Hand-Dug Wells**					
Locations	**K** (m^2/s)	**Ss** (l/s)	D_H (m^2/s)	**R** (m)	**SDD** (m)		**Locations**	**K** (m^2/s)	**Ss** (l/s)	D_H (m^2/s)	**R** (m)	**SDD** (m)
PAPBH1	1.557×10^{-3}	1.319×10^{-4}	11.816	5.156	0.578		**PAPWW1**	5.918×10^{-3}	9.711×10^{-5}	60.94	7.553	0.056
PAPBH2	1.914×10^{-3}	9.571×10^{-6}	200.00	21.95	0.116		**PAPWW2**	26.99×10^{-3}	2.505×10^{-5}	106.49	49.134	0.017
PAPBH3	1.018×10^{-3}	9.564×10^{-5}	18.716	4.893	0.739		**PAPWW3**	6.74×10^{-4}	1.226×10^{-6}	549.76	35.157	0.284
PAPBH4	6.843×10^{-3}	4.252×10^{-5}	160.94	19.03	0.732		**PAPWW4**	6.853×10^{-3}	5.695×10^{-5}	120.33	16.454	0.066
PAPBH5	21.45×10^{-3}	2.125×10^{-5}	1008.9	47.65	1.538		**PAPWW5**	2.113×10^{-3}	1.333×10^{-4}	15.85	5.973	0.349
PAPBH6	22.12×10^{-3}	2.123×10^{-5}	1043.2	48.45	1.486		**PAPWW6**	61.13×10^{-3}	3.401×10^{-4}	179.73	20.109	0.018
PAPBH7	20.32×10^{-3}	2.95×10^{-5}	925.51	45.63	0.179		**PAPWW7**	35.30×10^{-3}	2.068×10^{-4}	170.63	19.594	0.027
PAPBH8	16.72×10^{-3}	9.28×10^{-6}	1801.7	20.13	1.944		**PAPWW8**	35.30×10^{-3}	2.261×10^{-4}	156.20	18.747	0.030
PAPBH9	19.56×10^{-3}	1.048×10^{-5}	1866.0	64.80	1.261		**PAPWW9**	2.06×10^{-3}	3.868×10^{-4}	53.26	3.462	0.283
PAPBH10	20.84×10^{-3}	1.436×10^{-5}	1451.5	57.15	1.384		**PAPWW10**	7.46×10^{-3}	1.656×10^{-4}	45.05	3.184	0.728
PAPBH11	16.38×10^{-3}	6.848×10^{-6}	2391.9	23.20	1.725		**PAPWW11**	0.688×10^{-3}	1.511×10^{-4}	4.56	3.202	0.833
PAPBH12	19.13×10^{-3}	1.469×10^{-6}	13,023	17.12	1.466		**PAPWW12**	89.84×10^{-3}	7.936×10^{-4}	113.21	15.960	0.019
PAPBH13	13.54×10^{-3}	3.015×10^{-5}	450.40	10.05	1.366		**PAPWW13**	11.49×10^{-3}	1.332×10^{-4}	86.28	18.578	0.047
PAPBH14	13.23×10^{-3}	2.876×10^{-5}	459.91	32.17	1.366		**PAPWW14**	41.72×10^{-3}	1.603×10^{-4}	260.24	24.200	0.018
PAPBH15	16.07×10^{-3}	2.698×10^{-5}	5954.8	36.60	0.774		**PAPWW15**	5.785×10^{-3}	2.701×10^{-5}	214.18	21.953	0.054
PAPBH16	8.126×10^{-3}	1.653×10^{-5}	491.62	10.52	0.170		**PAPWW16**	1.224×10^{-3}	3.014×10^{-4}	4.06	9.559	0.253
PAPBH17	14.48×10^{-3}	3.560×10^{-5}	406.78	30.25	1.387		**PAPWW17**	1.741×10^{-3}	1.296×10^{-4}	13.43	5.498	1.036
PAPBH18	11.68×10^{-3}	2.640×10^{-5}	442.47	31.56	1.481		**PAPWW18**	5.666×10^{-3}	8.140×10^{-5}	69.61	3.958	0.892
PAPBH19	4.494×10^{-3}	1.125×10^{-5}	399.47	29.98	2.512		**PAPWW19**	6.972×10^{-4}	7.076×10^{-5}	61.96	3.930	0.660
PAPBH20	7.471×10^{-3}	2.013×10^{-5}	371.14	28.90	1.941		**PAPWW20**	7.122×10^{-4}	1.015×10^{-4}	70.15	3.973	0.745
PAPBH21	29.73×10^{-3}	2.183×10^{-5}	1362.0	55.36	1.203		**PAPWW21**	8.00×10^{-5}	1.237×10^{-6}	6467.26	12.071	0.744
PAPBH22	41.34×10^{-3}	5.061×10^{-5}	816.82	42.87	1.027		**PAPWW22**	1.340×10^{-3}	1.775×10^{-6}	75.49	13.037	0.454
PAPBH23	42.37×10^{-3}	1.856×10^{-5}	2282.7	71.68	1.178		**PAPWW23**	NAFM	NAFM	NAFM	NAFM	NAFM
PAPBH24	50.90×10^{-3}	9.222×10^{-6}	5519.4	35.24	0.737		**PAPWW24**	NAFM	NAFM	NAFM	NAFM	NAFM
PAPBH25	10.14×10^{-3}	2.767×10^{-5}	366.61	28.72	6.410		**PAPWW25**	NAFM	NAFM	NAFM	NAFM	NAFM

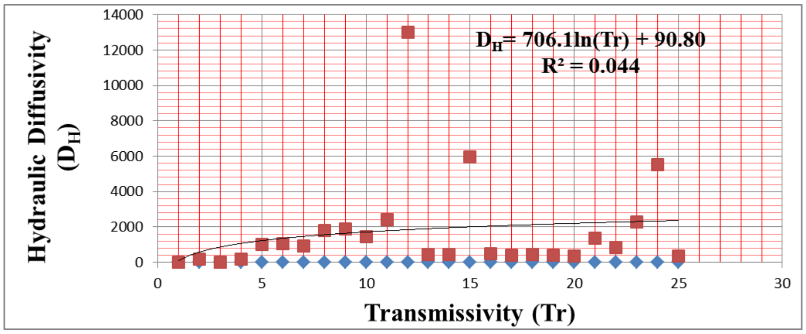

Figure 7a. Plot showing the trends and connectivity between hydraulic diffusivity and Transmissivity on Semilog scale for Wasinmi borehole sites

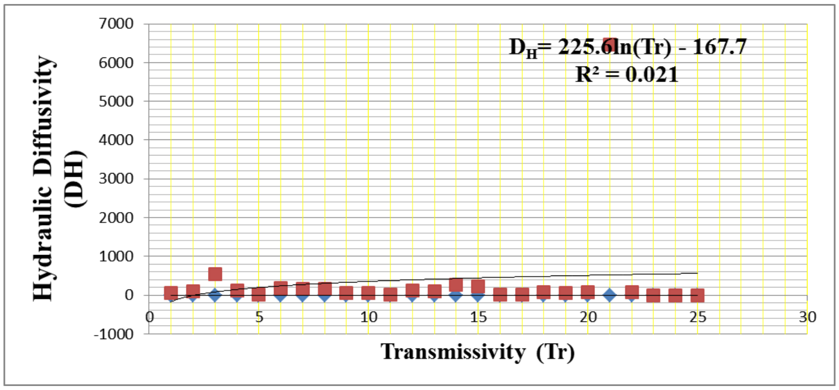

Figure 7b. Plot showing the trends and connectivity between hydraulic diffusivity and Transmissivity on Semilog scale for Wasinmi hand-dug well sites

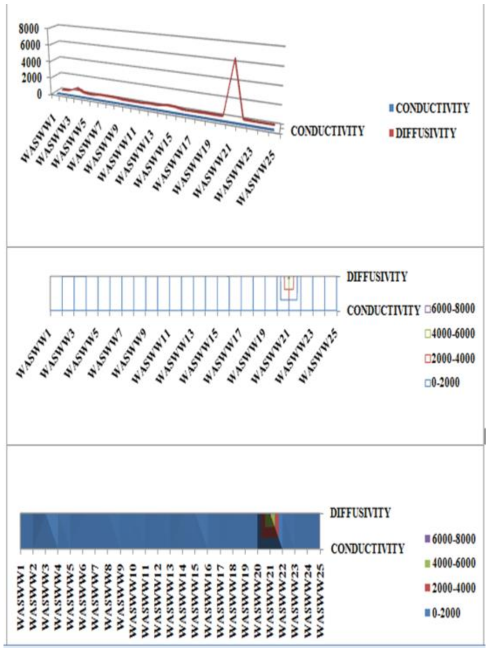

Figure 8a. Plot showing the distribution of hydraulic conductivity versus hydraulic diffusivity in 3D line/wireframe contour representations in Wasinmi borehole sites

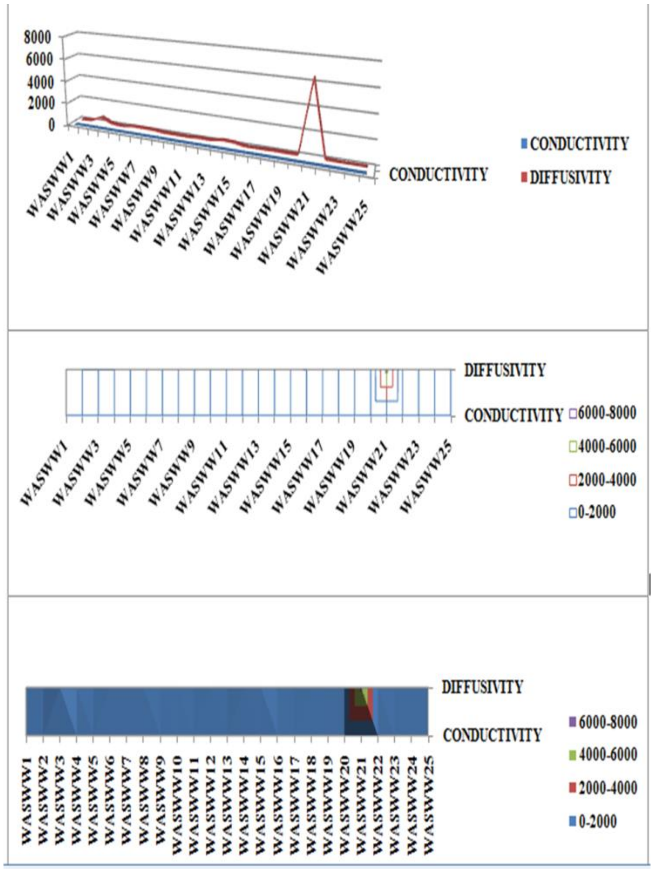

Figure 8b. Plot showing the distribution of hydraulic conductivity versus hydraulic diffusivity in 3D line/wireframe contour representations in Wasinmi hand-dug well Sites.

In Papalanto boreholes, the lowest specific yield of 0.772×10^{-2} l/s at WASBH2 and highest specific yield of 10.62×10^{-2} l/s at WASBH1 recorded around northwest of Ikeja (Figure 4). The lowest specific storage of 9.57×10^{-6} l/s was recorded at WASBH2 and the highest specific storage of 1.319×10^{-4} l/s at WASBH1; this is complemented with the observed variation in yields sites as displayed in Figure 4. It can be inferred from the observed values of specific yield and specific storage that groundwater can be abstracted at varying proportions over all the investigated sites while the variation in the observed specific capacity is significant because it measures the productive capacity of boreholes and helps in the appropriate selection of pump for groundwater abstraction[23-25 & 89].

The specific yield for Wasinmi hand-dug wells ranged between 3.66×10^{-3} l/s at WASWW19 and 58.40×10^{-3} l/s at WASWW14 (Figure 4) while the lowest specific storage of 1.23×10^{-6} l/s at WASWW2 and the highest specific storage of 7.94×10^{-4} l/s at WASWW12 (Table 4 and figure 4). Just like the borehole sites, it can be inferred that fresh groundwater can be tapped at varying quantity in Wasinmi hand-dug well sites especially when higher drilled depths are undertaken. The specific storage was found to be generally much smaller than the specific yield in both Wasinmi water sources where specific yield is the volume of water released from storage by a unit volume of an unconfined aquifer under a unit change (Figure 9a and 9b); because the subsurface hydrogeological conditions of the study area are reflections of the elastic compression of the aquifer and constituting water while the specific yield is a representation of the water released due to gravity drainage in an unconfined aquifer which is much larger volume. The observed values of specific storage are in general representative of the amount of time for drainage.

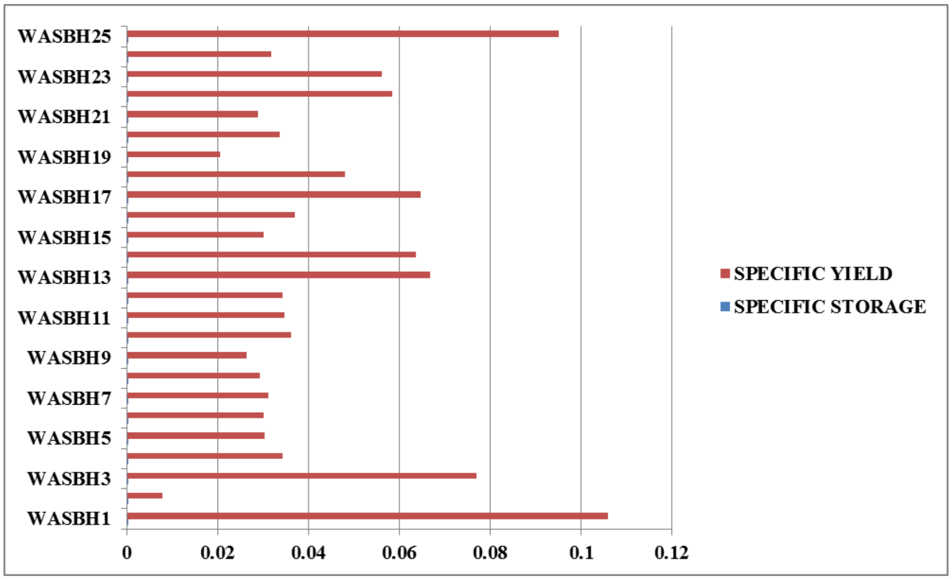

Figure 9a. Variation of specific yield versus specific storage in Papalanto Borehole well-sites

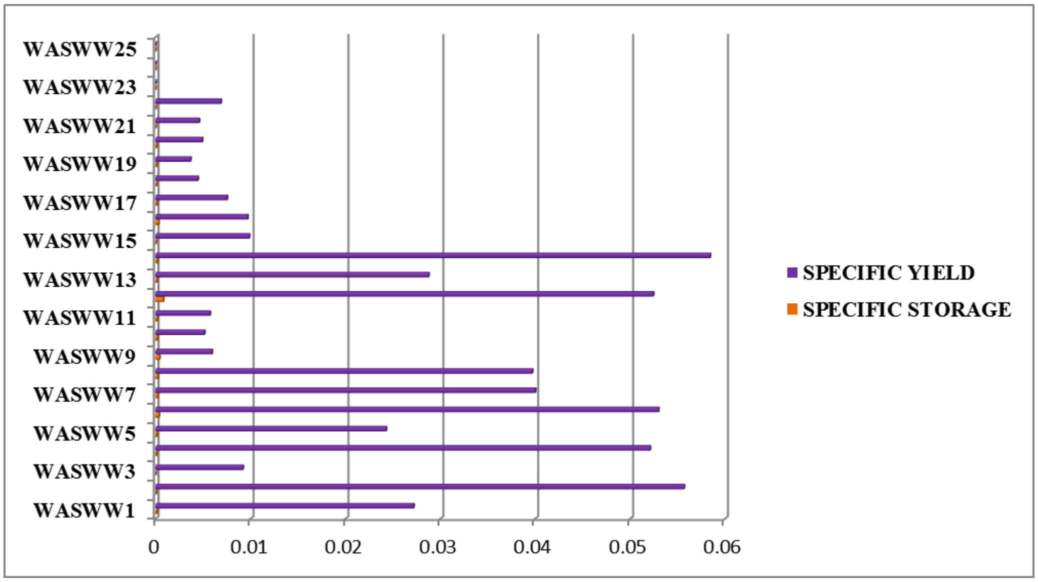

Figure 9b. Variation of specific yield versus specific storage in Papalanto hand-dug well sites

Therefore, as the water content decreases from saturation, the large pores which are most effective in conducting water are the first to drain out. Similarly, the tortuosity of the flow paths may increase while the average properties principally density and viscosity of the soil solution may change. These factors are strong contribution to a rapid decrease of in hydraulic conductivity relative to hydraulic diffusivity with decreasing yield as respectively observed in WASBH12 alongside WASBH13, WASBH16 alongside WASBH25 (Figure 8a) and WASWW21 alongside WASWW22 (Figure 8b) in Wasinmi borehole and

Wasinmi hand-dug wells. Another plausible reason attributable to the sudden decrease or change in the observed hydraulic conductivity relative to hydraulic diffusivity is the type of cationic species in the sediment solution and consequent changes in the hydraulic conductivity of the sediments containing significant quantity of clay most notably, swelling clay[109-112].

6. Conclusions

Groundwater has been of immense contribution to the residents of Wasinmi communities despite its varying supply challenges. Pumping test has proving not only as effective but reliable estimation technique for the characterization of aquifer properties. Groundwater system in the study area has been characterized geohydraulically with parameters displaying varying outputs from two water sources namely boreholes and hand-dug wells and their varying contributions to groundwater yields. The weathered sandstone constituted the aquifers from which water are abstracted for boreholes while fractured shale/clayey sand/shale-clay and partly clay are typically responsible for water supply via hand-dug wells due to the fact that the required depth from fresh water aquifers were not reached. The outputs of the estimated hydraulic parameters are highly significant for groundwater productivity and sustainability most specifically high hydraulic conductivity, transmissibility and high specific yields among others. Borehole discharge ranged from 1.0×10^{-2} l/s (864 L/day) to 11.0×10^{-2} l/s (9504 L/day) with a mean of 4.0×10^{-2} l/s (3456 L/day) with exhibited transmissibility that varied from 1.0×10^{-2} m^2/s (864 m^2/day) to 9.20×10^{-2} m^2/s (7949 m^2/day) while discharge from hand-dug wells ranged from 1.0×10^{-1} l/s (8640 L/day) to 6.0×10^{-2} l/s (5184 L/day) with an average of 2.3×10^{-2} l/s (1987.2 m^2/day) with transmissibility ranging from 1.0×10^{-1} l/s (8640 m^2/day) to 5.10×10^{-1} l/s (44064 m^2/day). The hydraulic conductivity of the study area ranged from 87.96 m^2/day to 4397.76 m^2/day in Wasinmi boreholes and ranged from 1541 m^2/day to 24,610 m^2/day in Wasinmi hand-dug wells. The recorded mean recovery period of 2254 seconds and 9446 seconds were attained by Wasinmi boreholes and hand-dug wells respectively. The two water sources revealed that the auriferous zones are classified as very high in potentials in the designation of mean transmissibility magnitude for boreholes (38,880 m^2/day) and hand-dug wells (12,269 m^2/day) based on the comparison of their results with standard aquifer potentiality classification. The status of the hydraulic diffusivity is an indication that the zones possessing greater values are comparably favourable for groundwater abstraction and development because of the greater degree of flow they exhibited. In Wasinmi boreholes, the lowest specific yield of 0.772×10^{-2} l/s at WASBH2 and highest specific yield of 10.62×10^{-2} l/s at WASBH1 around northwest of Ikeja and Awado while the lowest specific storage of 9.57×10^{-6} l/s and the highest specific storage of 1.319×10^{-4} l/s at respectively at the same location; revealing that groundwater can be abstracted at varying proportions over the investigated sites. The variation in the observed specific capacity is significant because it measures the productive capacity of boreholes and is of immense assistance for appropriate pump selection. The hydraulic parameters in the area revealed that the auriferous zones for hand-dug well are constituent of fractured shale /clay-shale/clayey sand materials of lower yields than boreholes because the required depths were not reached but the large diameter hand-dug well enhanced the transmission of fluids into the well. The generally observed high yields in the borehole revealed that the aquifer materials are sufficiently fractured; typical weathered sandstone. In view of this, the observed high yields from both water sources due to high transmissibility necessitates the recommendation of high horse power pumps of about 7.0 to 13.0 h.p. preferably for installation in order to ensure sustainable groundwater withdrawal, effective water management and control in the study area. The results of the specific yield gives an inference that fresh groundwater can be sourced at varying amount in Wasinmi hand-dug well sites especially when higher required depths are undertaken; it is a general reflection of the optimum period of time for drainage. Specific storage of an aquifer is often influenced by the compressibility of the aquifer matrix and compressibility of the water. The specific storage was found to be generally much smaller than the specific yield in both water sources. Well spacing has been proposed for the study area based on the outputs of the estimated radius of influence utilizing an empirical formula under unconfined condition since the aquifer the aquifer in the area is largely unconfined; observed minimum and maximum radius of influence of the area were 5m to 65m and 3m to 49m for hand-dug wells and boreholes respectively. The overall variation of the estimated hydraulic properties in Wasinmi groundwater system is an indication that the study area is hydrogeologically favourable for groundwater development provided other requirements and boundary conditions are met. Therefore, based on the geohydraulic investigation of the study area, results of this study should be utilized as a comprehensive guide for effective groundwater planning and development in the study area coupled with other pre-drilling and post drilling hydrogeological techniques.

7. References

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Acknowledgement

The author is grateful to the Ogun-Oshun River Basin Development Authority (OORBDA) and Federal Ministry of Water Resources for their permission to use the lithological data/core sample description and field logistics. Also, the traditional ruler of Wasinmi; His Royal Majesty, Oba Emmanuel Babatunde Osuntogun Fasoyin, Oniwasinmi of Wasinmi, Owu Kingdom, Abeokuta and the entire autonomous communities within Wasinmi district of Ewekoro Local Government Area for their permission and assistance.

Data availability

The data that support the findings of this study are available from the author upon reasonable request.

Declaration of competing interest

The author declares that he has no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI tools declaration

The author declares that he has not used Artificial Intelligence (AI) tools in the creation of this article.