



Experimental Design of Physical Unconfined Aquifer for Evaluation of Well Abstraction Effects: Laboratory Approach

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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ABSTRACT

In unconfined aquifer water flows in both horizontal and vertical direction when pumping. So its study during pumping action is more complex. Soil type, porosity, hydraulic conductivity and transmissivity are important parameters that control the specific yield, drawdown and radius of influence on aquifer while abstraction. Due to large extraction of water from the aquifer, the water table drops down and may lead to permanent depletion of yield capacity of aquifer. For practical understanding of water being pumped from aquifer and its impacts on water storage the easiest method is experimental approach. So therefore, this study was planned to carry out the well abstraction from unconfined aquifer of homogeneous sandy soil designed as physical model on rainfall simulator at hydraulic laboratory hall of Campus itself. The catchment dimension is 2.2 meter length, 1 meter width and 0.15 meter depth with impermeable base filled with fine sand as per specification. The simulator was adjusted to make horizontal aquifer. The experimental observations were carried out in two conditions, first was well abstraction with no rainfall after saturation and the second is with rainfall even after saturation condition obtained. The two wells were operated for the abstraction of water simultaneously so that the effect of one well to another could be studied. After observation and data collection, for the analysis of hydraulic conductivity Dupit model. Empirical model and relative effective porosity model (REPM) were used for the

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comparative study. Similarly the radius of influence was estimated by three models (weber, Kusakin and Sichert). For the estimation of transmissivity of the aquifer Thien model was used. Also the general equation (product of hydraulic conductivity and depth of aquifer) was used. Study showed the suitability of the available theories and governing equations for unconfined aquifer. The most important part of the study was to establish the correlation of drawdown and radius of influence with the time period of well abstraction. From the results the correlation coefficient for time and drawdown was of 90% and for time and radius of influence was 97%.

Keywords: Unconfined aquifer; well abstraction.

1. INTRODUCTION

An aquifer is one of the most important ground water resources [1]. Water from aquifer is reliable source for both water supply and irrigation in agricultural fields [2]. More than 60% water demand is supplied from ground water especially in Plain region of Nepal. But rapid growth in population due to urbanization increased the extraction of water from aquifer. The ground water in plain region is in unconfined aquifer form. Due to extensive well abstraction effect on ground water balance condition is increasing [3]. Due to Lack of basic knowledge on groundwater resources and their management there is depletion on the ground water resources. The recharge conditions are decreasing due to deforestation and concrete structure build up in large area of urbanization [4]. Climate change also has significant impacts on ground water [5]. Contamination due to land fill and chemical waste from industry are equally responsible for degradation of quality ground water [6-8]. Unplanned settlement, bored well and deep well constructions are causing to disturbing the water balance condition. The consequences are that boring for well are to be done more than 200 feet to extract drinkable water in plain region and was sufficiently available at 100 feet below ground surface in the past. In many places the water table are so deep into the sub-surface such that a tube well cannot be bored. [9]. Migration of people from many places has increased due to deficiency of drinking water in Nepal. The ground water conditions in neighboring countries India, Pakistan have also been reported to be depleting. Data shows more than 30% ground water is lost from this region. The world ground water condition is decreased unexpectedly during the last decade [10-12]

The knowledge about the ground water resources and its management is fundamental such that people realize themselves the importance of it and try to preserve through

common efforts. Human activities and unplanned development works are the major reason for loss in ground water. So the knowledge about the safe extraction and recharge of water is to be understood on public level [3]. For the development of the basic understanding, the knowledge about ground water, its types, safe yield, recharge process, water loss from the subsurface, flow phenomena and well pumping impacts should be understood. This study is aimed to develop these understanding in easy and practical way through experimental study on laboratory approach making a physical model of an aquifer within a rainfall simulator having catchment tank setup.

2. PURPOSE OF STUDY

The water flow in an unconfined aquifer is a three dimensional flow whose analysis is a complex task. Flow occurs in horizontal and vertical direction when pumping. Equations for confined aquifer and for unconfined aquifer flow analysis are different due to different flow phenomena as confined aquifer has one dimensional flow. In well flow from aquifer due to pumping safe yield, the maximum radius of drawdown of water after abstraction and hydraulic conductivity of soil type and layers are the main parameters to be considered. Commonly, people draw more water from well but do not think about its impact in future [13]. Due to extreme well abstraction the probable effects on drawdown, radius of influence and specific yield capacity of aquifer must be well known. For the purpose the study is to planned to revise available theories, governing equations and their suitability for highly permeable homogenous sandy soil unconfined aquifer and to develop the correlations of, draw down, and radius of influence with time duration of well abstraction on experimental basis at laboratory scale. The unconfined aquifer prepared on the experimental setup represents an artificial catchment on which the artificial rainfall can be generated from the rainfall simulator.

3. GOVERNING THEORIES AND EQUATIONS

The ground water is found in earth as storage under earth surface. The sources are in two forms one is confined and another is unconfined. The storage between two impermeable boundary is confined and if the only bottom is impermeable the aquifer is unconfined which are generally located near earth surface and have no layers of clay or other impermeable geological materials. The uppermost boundary of the ground water within the unconfined aquifer is the water table. Fig. 1 is the unconfined aquifer which shows the pumping effects. The water in this aquifer is more vulnerable to contamination from surface pollution as compared to that in confined aquifer due to easy infiltration process from the earth surface. The fluctuations of water table in unconfined aquifer depend on the rise and fall of water levels in wells. The extraction of water beyond safe yield of the aquifer causes depletion of water from the source [14]. So to know the well effects on this aquifer some terms related to this should be well known which are used in available governing theory and equations for unconfined aquifer [15].

The most important material properties parameters on aquifer are hydraulic conductivity, transmissivity, porosity [16-17]. Safe yield is the most important to be considered while abstraction of water from aquifer the radius of influence and draw down of water level at the well location [18]. Many empirical and mathematical equation have been developed on well abstraction, but it is hard to decide which one is the best for a particular place and location and that depends on the hydrogeology of the particular place. For the hydraulic conductivity estimation Dupit's equation is mostly used for unconfined aquifer. Some of the models equations available in literature are as below.

Dupit's Model: Dupit has given an equation for the hydraulic conductivity which is based on Darcy law for water flow through soil. His model is given as equation 1:

$$\frac{Q}{2\pi K} \ln\left(\frac{R_2}{R_1}\right) = \frac{H_2^2 - H_1^2}{2} \quad (1)$$

Where Q is the discharge from the well, R_2 , R_1 radius from the well section to the piezometer, are H_2 , H_1 the water level in piezometer that indicates the drop in water level due to pumping from well. K is the hydraulic conductivity of soil.

Empirical Model: Many empirical models were developed to estimate the saturated hydraulic conductivity of porous material from grain size analysis [19]. The saturated hydraulic conductivity based on the cozeny-karman is mostly used and given as:

$$K_s = \frac{g}{\mu} \times 6 \times 10^{-4} \times [1 + 10(p - 0.26)] d_e^2 \quad (2)$$

Where $g=9.81\text{m/s}^2$, $\mu = 1.009\text{cP}$ when water is 20°C , P is porosity of material, d_e is the effective grain size.

Relative effective Porosity Model: In 2001, this model was suggested by Suleiman and Ritchie, a simple model for estimating hydraulic conductivity using effective porosity of a soil and also called relative effective porosity model (REPM) the equation is as:

$$K_s = 75 \times \frac{(p-FC)^2}{FC^2} \quad (3)$$

Where p is total porosity and FC is field capacity. P is taken when soil becomes fully saturated and FC is to be estimated after draining out of water from the soil.

Transmissivity (T) (Thien Model): This model estimate the rate of water flow per unit width of soil and is given as:

$$T = \frac{Q}{2\pi(s_1-s_2)} \ln\left(\frac{R_2}{R_1}\right) \quad (4)$$

Also general equation for unconfined aquifer can be used given by product of hydraulic conductivity and depth of aquifer.

Estimation of Radius of Influence: The most important parameter to be considered on pumping from an aquifer is the radius of influence. It is the maximum distance measured at which the drawdown can be detected from the section of well to the unaffected point of water table. It depends on the water discharge from the well. Beyond safe yield the drawdown becomes so high and influence radius becomes so large which affect another well located close by. So while pumping, the radius of influence must be estimated so that the probability of affecting another well can be forecasted. The most common method used in finding the radius of influence is use of empirical formulae. Common available formulas are given below in equation 5, 6, 7 and 8.

Lembke(1886,1887)

$$R = h_0 \times \sqrt{\frac{K}{2N}} \quad (5)$$

Weber (1930)

$$R = 3 \times \sqrt{\frac{h_0 \times K \times t}{ne}} \quad (6)$$

Kusakin (1953)

$$R = 1.9 \times \sqrt{\frac{h_0 \times K \times t}{ne}} \quad (7)$$

Sichardt (1930)

$$R = 3000 \times S_w \times \sqrt{K} \quad (8)$$

Where

N is Ground water Recharge, h_0 is saturated aquifer thickness hydraulic conductivity, ne effective porosity (25%), S_w is draw down at well section and t time of abstraction.

4. MATERIALS AND METHODS

The study is designed to run the test on the unconfined aquifer prepared on the test set rainfall simulator. The simulator is capable to run the test both surface as well as subsurface flow. Catchment prepared of homogenous fine sandy soil at horizontal position works as a physical model of unconfined aquifer. Hence, the study is completely primary data collection approach that follows the flow diagram in Fig. 2.

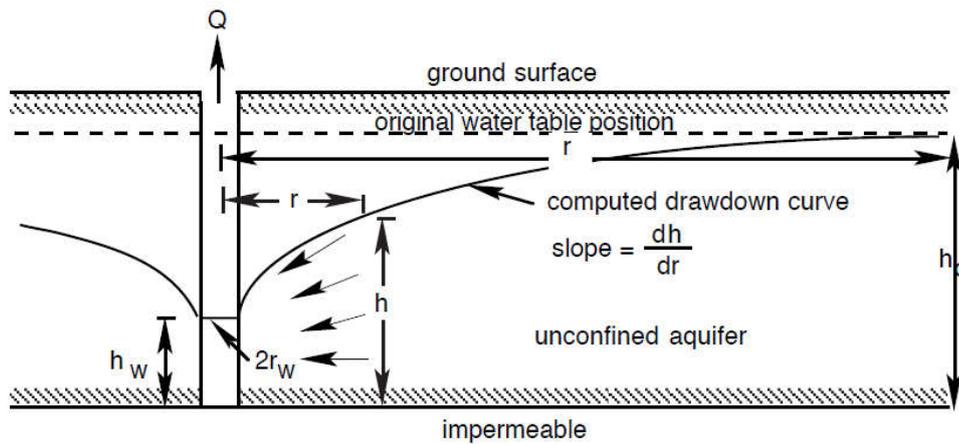


Fig. 1. theoretical section of unconfined aquifer before and after water abstraction

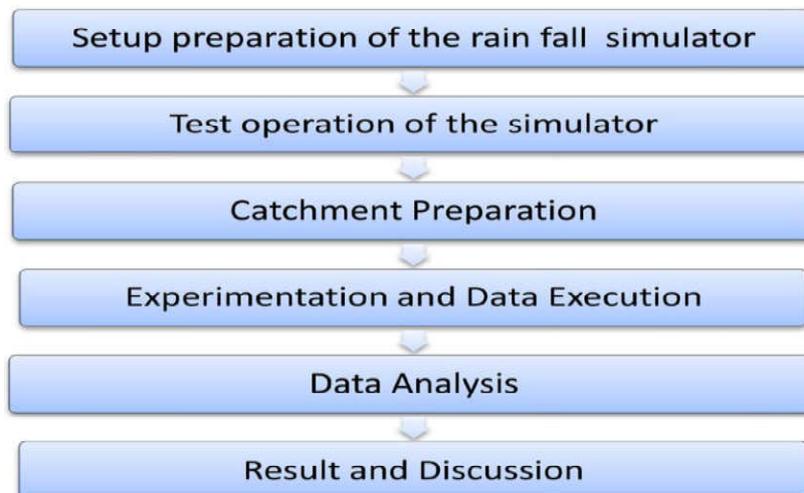


Fig. 2. Flow diagram of the study

4.1 Model Description

The model rainfall simulator product of arm field company Uk is installed in Hydraulics Laboratory hall of Purwanchal campus Dharan, Institute of Engineering Tribhuvan University. The rig is capable to simulate artificial rainfall at the rate of 300 to 1500 LPH over the artificial catchment prepared on the catchment tank. It has capacity to run test for surface hydrology and unconfined aquifer study on well abstraction. As the study is focused for the well abstraction effects on unconfined aquifer water storage, the catchment prepared works as an artificial physical model of

aquifer. The simulator works with the help of electric swamp motor (220 Volt, 50HZ) and simulates rainfall over the catchment. The dimension of the simulator is 2meter length, 1 meter width and 0.15 meter depth. The slope of the catchment is adjustable. For this study, aquifer is made at completely horizontal positions. The setup has two wells and twenty one piezometers to read the water level stored in the catchment soil. The wells are operated under saturated condition of soil without rain and with rain respectively. The Schematic diagram Fig. 3 and Fig. 4 below shows the rig and its complete components [20].



Fig. 3. Simulator Rig set up at hydraulics laboratory hall

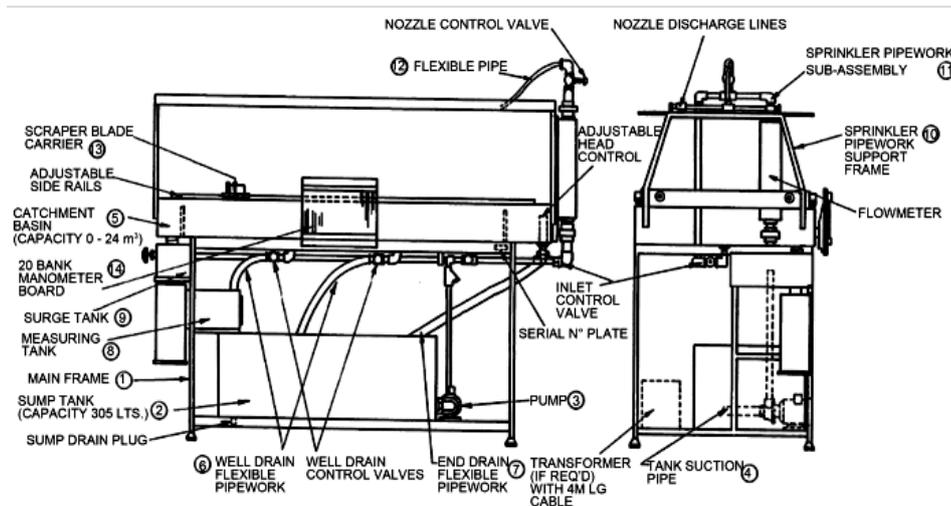


Fig. 4. Schematic Diagram of model Simulator showing all components

4.2 Overview of Physical Model Preparation

After cleaning, adjustment and test operation of the simulator the catchment preparation was carried out of homogeneous clean sand of size (0.2-2 mm) to the level specified of depth 0.15m. The slope of the simulator was adjusted horizontal so that the model aquifer became completely horizontal. The Fig. 5 (a, b) below shows the soil plot prepared (where two wells are located on the center line of the plot) and the manometers position their connections with the soil plot. Manometers are 12 cm apart from each other. For a well there are 6 manometers in both x and y direction on horizontal plane of plot. The total distance between two ends manometers are 36 cm where the width of aquifer model is of 100 cm.

4.3 Test Operation

After the model prepared the test operation were carried out. The first rainfall was given at the rate of 1500 lph up to the time of saturation of the soil. Water table development in permeable sandy soil follows the kinematic storage process during recharging [21]. After saturation rainfall was stopped and the manometers reading were recorded. The wells were closed during the rainfall. After saturation condition for the abstraction of water from the wells the gate valve was opened. The test without rain was carried out first. Water abstraction was carried out at a time interval of 4 minute and the discharge was measured by volume and time relationship. Immediate after 4 minute time of well flow the gate was closed and the manometers reading were recorded. Similarly for the next test operation, after 24 hour gap the rainfall was given at the same rate of 1500lph. The well abstraction was carried out for the same time interval of 4 minute but the rainfall was given

during the test. Immediate after closing of well gate the manometers reading were recorded. Hence the test were carried out for two cases abstraction without rain and with rain after saturation of the aquifer soil. Experimental data collection results were discussed as in result and discussion section as explained below.

5. RESULTS AND DISCUSSION

5.1 Well Abstraction Without Recharge

From the experimental observation and data collection of manometers reading the saturated and drawdown curve after saturation but without rainfall were plotted to obtain the graph shown in Fig. 6. In this test operation both well A and B were opened so that combined well flow occurred. The abstraction water were collected for the time period of 4 minute with abstraction discharge of $5.62 \times 10^{-6} \text{ m}^3/\text{sec}$. The saturation manometer readings were 13 cm. After water abstraction the manometer reading recorded a drop in value. At the well section A the manometer reading was of 5 cm but from the well section the manometer showed increased water level of 13 cm at both end. The draw down curve showed 9cm water level drop- in the well section. The manometer readings were taken width wise of the aquifer so that the water flow effects from length and width wise could be recorded. Similarly for the well B near the outlet of the aquifer, the manometer reading plotted was obtained as shown in Fig. 7. Where the water level was observed 5.5 cm on piezometer at well section and draw down was 8.5 cm which was less than of well A. It is due to the well separation and area of flow for well B is greater than of well A. During well abstraction the most of the water flow was toward well B as it is located at lower part of aquifer area that cover larger area than well A. So water table lowered on well B area was less than that of well A.



Figs. 5. (a) Aquifer model and pump locations (b) manometers positions and connection with soil plot and well

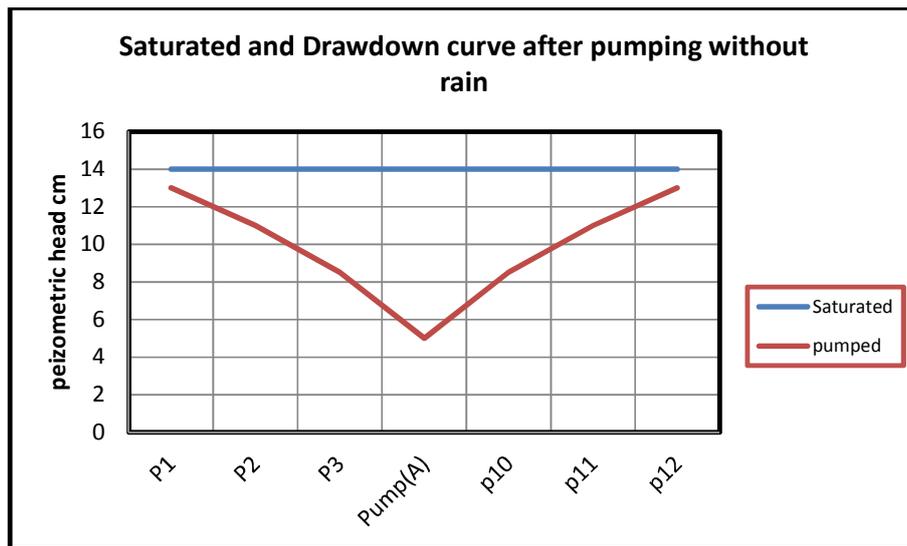


Fig. 6. Draw down curve after well abstraction without rainfall Well (A)

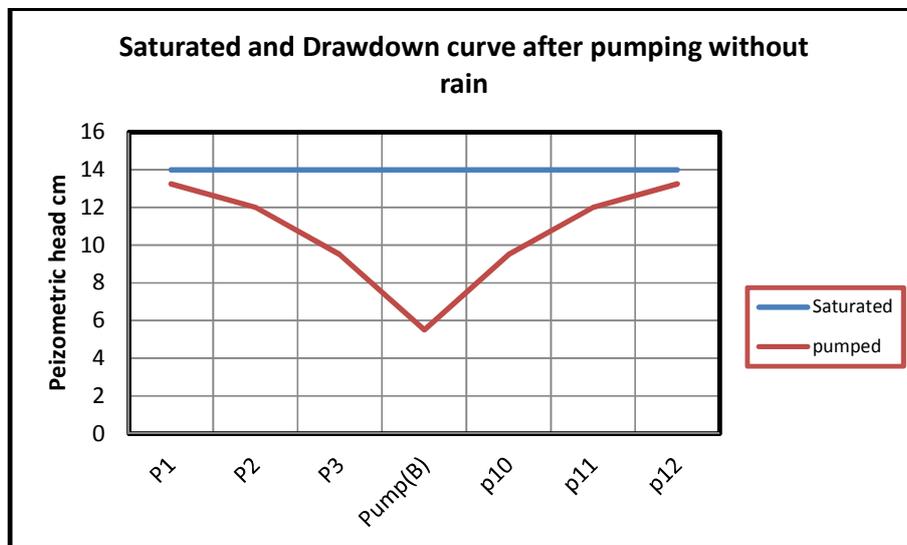


Fig. 7. Drawdown curve after well abstraction without rainfall well (B)

5.2 Well Abstraction with Recharge (Rainfall)

In this case the well abstraction was carried out with the rainfall even after soil saturation so the recharging process was continuous with well abstraction. Both well were opened for the same time period of 4 minutes and manometer readings were recorded with same abstraction discharge of the well flow of $5.62 \times 10^{-6} \text{m}^3/\text{sec}$. After closing the well flow the manometer reading recorded were plotted as shown in Fig. 8 and Fig. 9. In this case the draw down curve was

different to the first case. As the rainfall was recharging the aquifer less effect of abstraction was observed. For the well A the drop in water table was found to be 8.5 cm and for well B it was found to be 6.25cm. This result showed that water level around Well A is more affected due to the operation of Well B. Long water abstraction from wells, will cause well A to lose its yield capacity. So the results could help to make a decision while wells are to be operated the extraction of water without recharge may cause loss of yield capacity of aquifer permanently from an upper area. That is why recharging of aquifer

is important and necessary from upstream side of the aquifer area to maintain the safe yield all the time.

5.3 Time and Drawdown Curve Correlation

In the first test operation the well abstraction and corresponding manometer reading at the well sections were observed at the time interval of 4 min without rain after saturation obtained due to rainfall. The relationship between time and drawdown value (S_w) were plotted for both wells

and the correlation equations were obtained as shown in Figs (10 and 11) below. The equations and R square values obtained were given. R values obtained were acceptable range as they were near around 90% for both wells. The results also showed the data collection after experiments were in good track and controlled making the results more valid and acceptable.

$$(YA = 1.05XA + 5.4, R^2 = 0.882 \text{ for well A})$$

$$(YB = 1.11XB + 6, R^2 = 0.909 \text{ for well B})$$

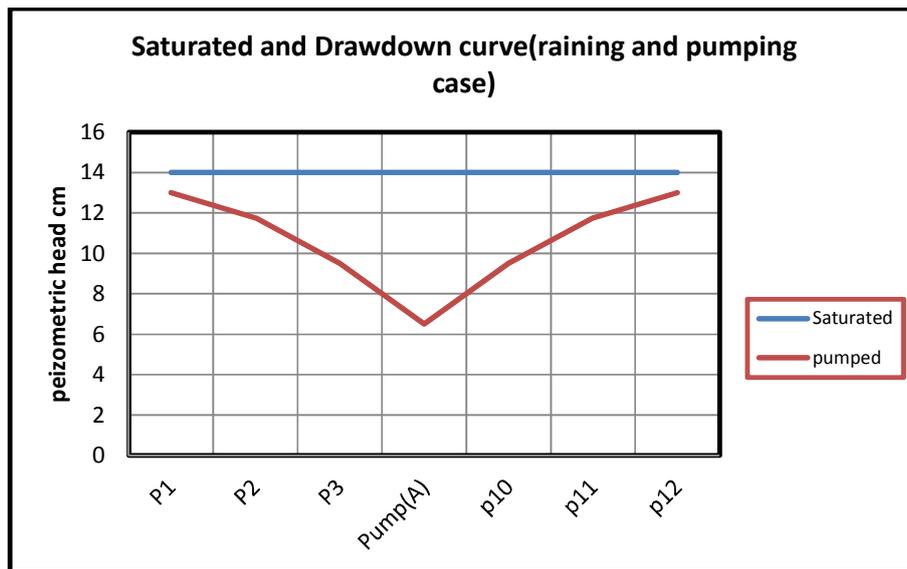


Fig. 8. Draw down curve after well abstraction without rainfall Well (A)

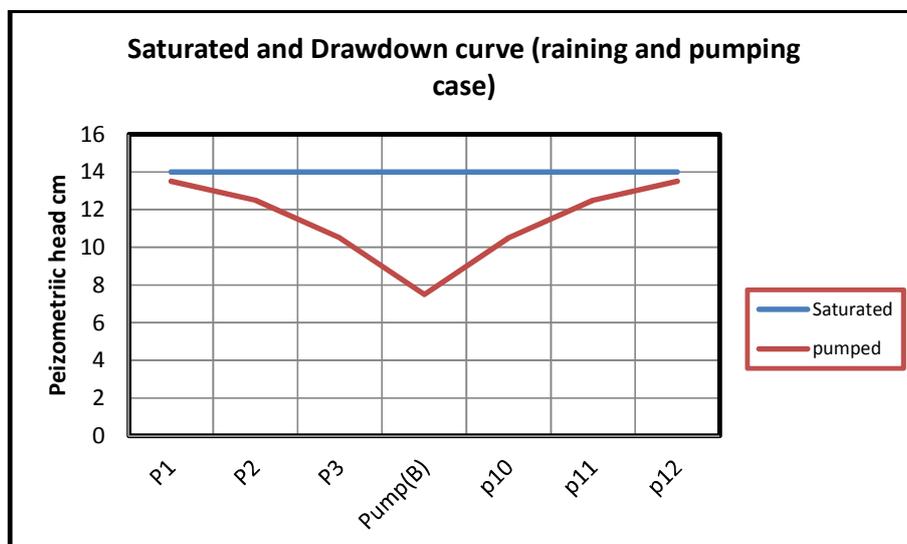


Fig. 9. Draw down curve after well abstraction without rainfall Well (B)

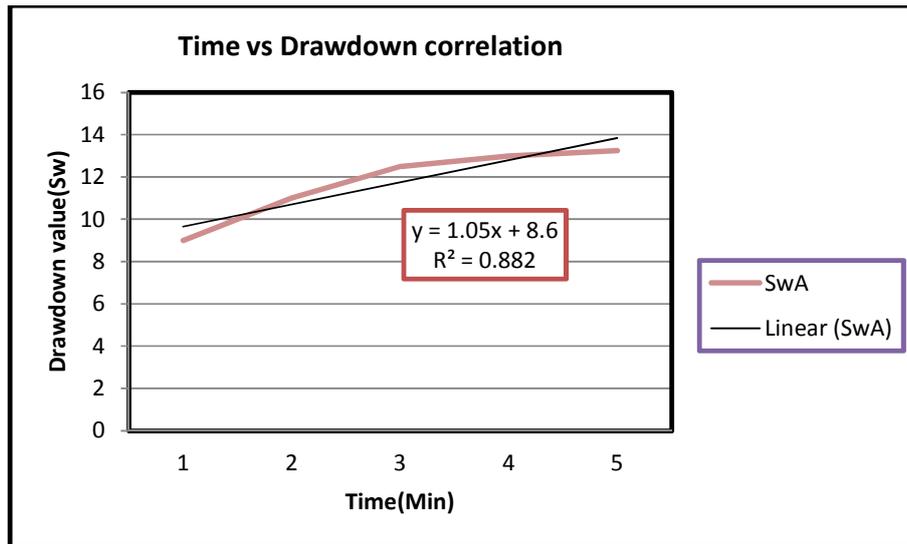


Fig. 10. Time and drawdown correlation graph for well A (without rain)

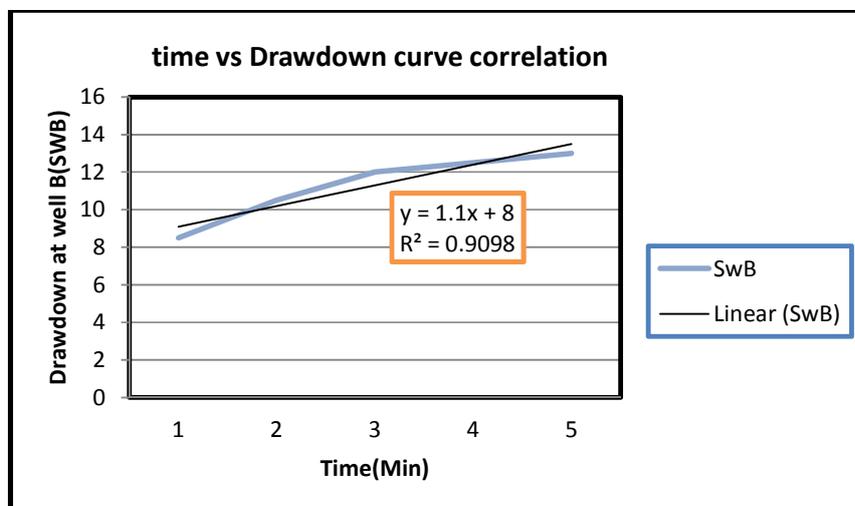


Fig. 11. Time and draw down correlation graph for well B (without rain)

5.4 Hydraulic Conductivity (K)

The hydraulic conductivity at saturation condition was calculated using the equations mentioned. Equation 1,2 and 3)The comparative values from analysis were obtained as shown in Fig. 12. From the results the Dupit value was 2.29 cm/min. Empirical model value was 1.25 cm/min and relative effective porosity model (REPM) value was 0.52 cm/min. These values were seemed higher and lower than the value estimated by Hazen value 1.34 cm/min mentioned in Literature reviewed. [19]. Dupit model is widely used for unconfined aquifer

models, hence, the study made use of its value for the computation of other parameters. Similarly the radius of influences was estimated using three models and the comparative result was as shown in Fig.13. From the result, it was discovered that the value obtained from Sichardt model is more reliable than the weber and kusakin models. These two models underestimated the value of radius of influence as the total distance between two manometers was 36 cm whereas the total width of aquifer model was 100 cm. So the influence radius might reach to the boundary of the aquifer.

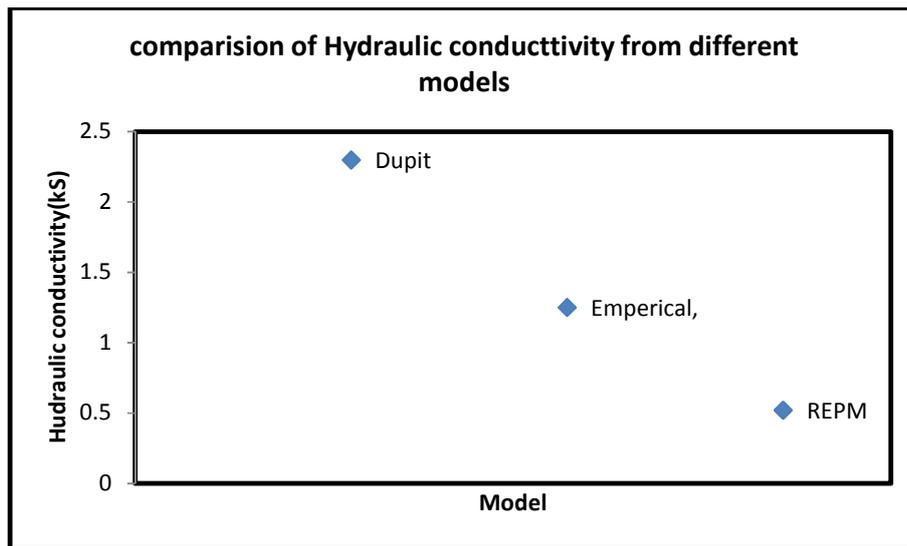


Fig. 12. Comparative hydraulic conductivity of the aquifer soil given by models used

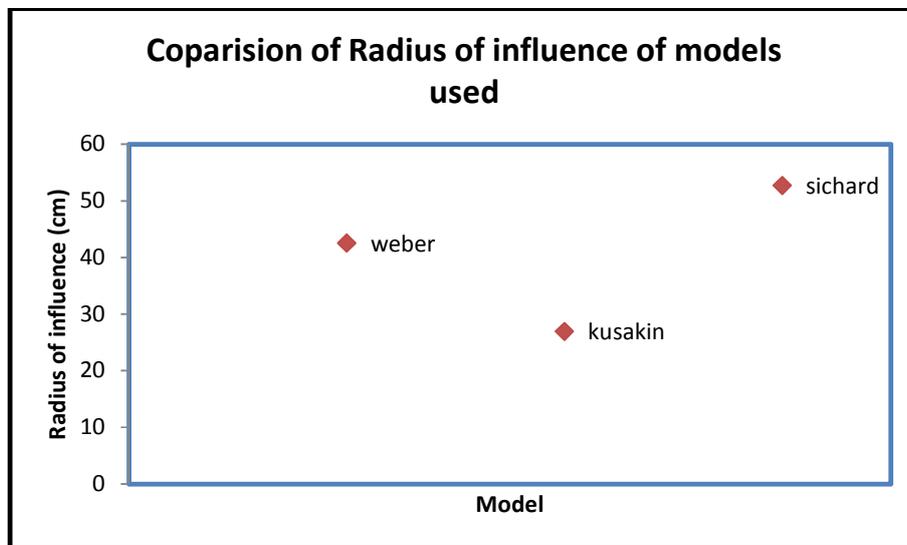


Fig.13. Comparative influence radius values of the three models used

5.5 Correlation between Time of Well Abstraction and Radius of Influence

The radius of influence depends on the drawdown of water table due to well operation and its time duration. How the investigation radius does vary with the drawdown; is an important relation to be established. For this the sichardt model was used to compute the radius of influence with the time period of well operation without rain after saturation. For this model the hydraulic conductivity obtained by Dupit equation was used. At the time interval of 4 min the draw

down were recorded and the corresponding influence radius were calculated both for well A and well B. The correlation graphs of equations obtained are as shown in Figs (14 and 15) below. And the equations were as:

$$(YA = 7.861XA + 46.145, R^2 = 0.9773 \text{ for well A})$$

$$(YB = 8.793XB + 42.485, R^2 = 0.978, \text{ for well B})$$

Since the radius of influence obtained from the Sichadt model were within the aquifer width that were less than 100 cm the experimental data

seemed reliable and the correlation equations of time and influence radius obtained has the R square value greater than 0.97 which showed the linear regression equation obtained from the study were acceptable.

5.6 Transmissivity of the Aquifer Soil

Transmissivity is the most important flow property of soil in aquifer [22]. It is the flow rate of water in horizontal direction per unit width per unit area for unconfined aquifer. In well flow the draw down and radius of influence is dependent

on this. So the transmissivity of soil is to be found out to maintain the safe yield of aquifer. For this study the Thien Model was used for the estimation. From this model the transmissivity value was obtained as 0.33 cm/sec per unit depth. Also from the general equation of transmissivity for unconfined aquifer that is product of hydraulic conductivity and depth of aquifer (Kxh) its numerical value was obtained as 0.35cm/se per unit The value obtained from the two models are found very close to each other and close to the value for sandy soil given in previous research results as 0.5cm/sec/depth.

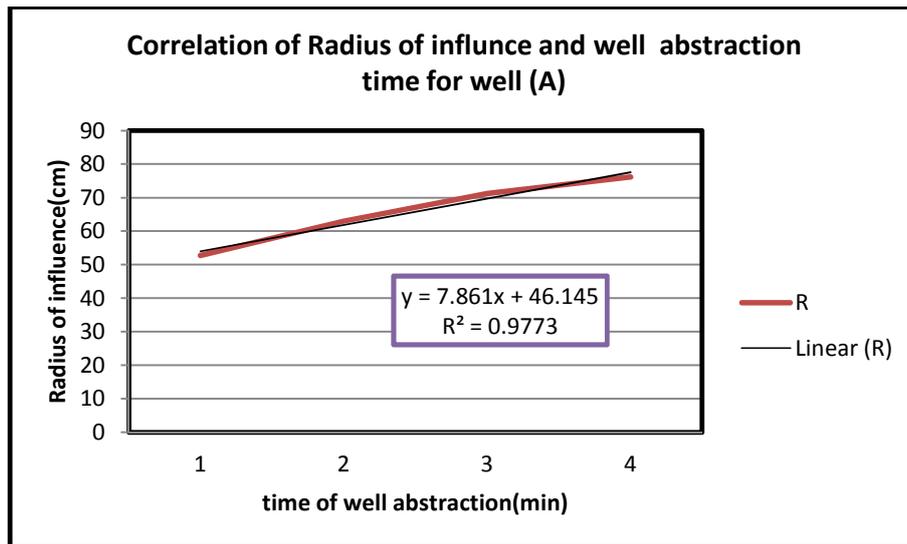


Fig. 14 Correlation between time and radius of influence well (A)

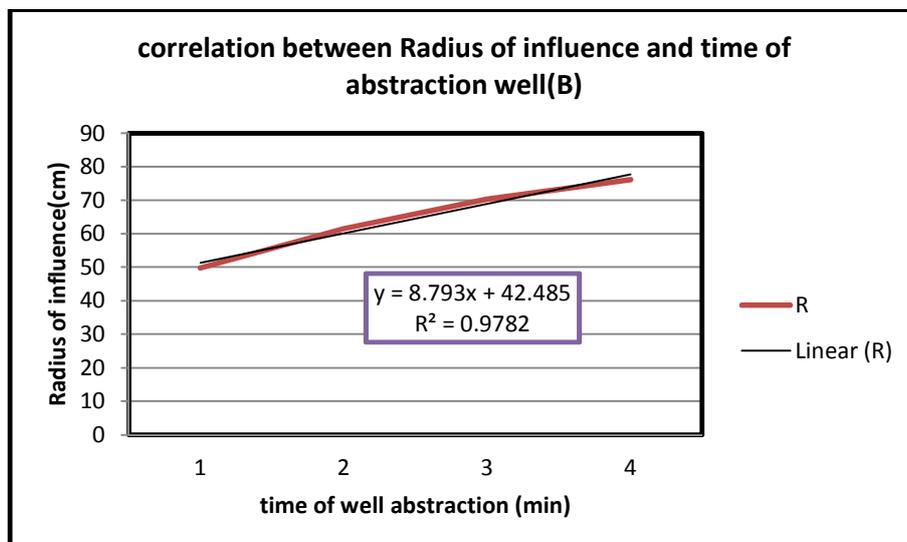


Fig. 15. Correlation between time and radius of influence Well (B)

6. CONCLUSION AND RECOMMENDATIONS

The physical and flow parameters are the most important elements to quantify ground water flow in an aquifer. The hydraulic properties of an aquifer are significantly dependent on soil type and its porosity. The flow of water in the subsurface is a complex phenomenon. The exact yield capacity of aquifer and its sustainability depends upon the abstraction condition. Long abstraction and insufficient recharge may lead to the complete depletion of the groundwater storage in an aquifer. Due to the abstraction the drop in water table is associated with the radius of influence. Radius of influence is function of the time of abstraction and drawdown in water table due to pumping from a well. For the study of well flow in unconfined aquifer having homogenous sand, an experimental approach was planned and observations were carried out in controlled conditions. From the results obtained some sort of conclusions could be insight.

1. Firstly the hydraulic conductivity at saturation conditions were compared using three models Dupit, empirical and relative effective porosity model (REPM). From which the Dupit value was found a bit overestimated to Hazen value which is 1.34 cm/min for fine sand. Empirical and REMP model gave small low value. However the variation was not so high. Dupit value found more appropriate in this study.
2. The hydraulic conductivity was compared from three models. Weber, Kusakin and Sichardt. The Sichardt model gave more acceptable value than others. The radius of influence in this study might go up to 100 cm for maximum well abstraction period. Sichardt value was of 76.99 cm for the largest time period of 16 minute well abstraction. Whereas, the other two model under predicted the radius of investigation,
3. The Transmissivity of the aquifer was found very close to each other from Thien model and general model (kxh) for unconfined aquifer of value 0.33cm/sec/cm and 0.35cm/sec/cm. So a conclusion could be made that the experimental values obtained are acceptable from theoretical value found in literatures for the highly permeable sandy soil.
4. The most important part of the study was to establish the correlation of Time and

drawdown due to well abstraction and the correlation between time and influence radius. From the study the equations obtained are satisfactory and justifiable as the correlation coefficient R square value for both cases are near about 90% and 97%. That's why the equation obtained is acceptable for the unconfined aquifer having sandy homogenous soil for well abstraction due to pumping.

5. Last but not the least, the combined effect of well operations seemed sensitive to each other. The upper well was affected by the down well operation largely. This suggests that the long run of one well abstraction may cause complete depletion of yield of another well if the aquifer loses recharge. So aquifer recharge from upstream side is always important.

7. RECOMMENDATION

Since the study is carried out for only one homogenous soil layer the effect of variation on hydraulic conductivity could not be observed. The study must be carried out at different layers. Also the study of both horizontal and vertical flow on aquifer soil should be carried out for better results

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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