Journal of Environmental Science and Technology

ISSN 1994-7887

science alert

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OPEN ACCESS Journal of Environmental Science and Technology

ISSN 1994-7887
DOI: 10.3923/jest.2017.215.219

Research Article
Potential of Aquifers for Groundwater Exploitation Using Cooper-Jacob Equation

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Abstract
Background and Objective: Groundwater is critical to Indonesia's water supply. This resource should be properly managed. In this study, a method is proposed for determining sustainable limits to the exploitation of aquifers and identifying their lithology. **Materials and Methods:** The proposed method is based on constant rate pumping tests. These tests were performed on four wells in Tampan District, Pekanbaru, Indonesia. The measured values of the drawdown were analyzed using Cooper-Jacob method in order to derive the hydraulic transmissivity and conductivity of the aquifer. From these parameters, the lithology and the potential of the tested aquifer for sustainable groundwater exploitation were determined. **Results:** The drawdown for the well A, B, C and D were 2.861, 1.462, 1.225 and 2.274 m, respectively. These values correspond to a 150 min pumping duration and 0.125 L s^{-1} pumping rate. Within the assumption of a homogeneous and isotropic earth lithology, the mean values of the aquifer hydraulic transmissivity and conductivity were computed to be 12.24 m^2 day^{-1} and 1.68 m day^{-1}, respectively. **Conclusion:** From the values of the transmissivity and conductivity, it was determined that the lithology of the studied aquifer consists of fine sand and that it can be used as a sustainable water supply for a small community.

Key words: Aquifer, sustainability, transmissivity, conductivity, lithology

Received: March 10, 2017 Accepted: May 24, 2017 Published: June 15, 2017

Citation: Muhammad Juandi, Antonius Surbakti, Riad Syech, Krisman and Syahril, 2017. Potential of aquifers for groundwater exploitation using cooper-jacob equation. J. Environ. Sci. Technol., 10: 215-219.

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Groundwater is a crucial source of water throughout the world and specifically in Indonesia. It is stored in geological formations known as aquifers[1]. The relatively constant characteristics of groundwater over time is a strong asset[2]. However, its availability is uneven. It depends on the rainfall, vegetation, topography and the degree of porosity and permeability of the rocks making up the aquifer[3]. In the context of water resources management, the groundwater extraction rate is another factor that must be considered. Indeed, it is often pumped much faster than it is replenished naturally. In the long term, excessive extraction can lead to the depletion of groundwater[4-6]. Therefore, it is vital to establish sustainable limits to the exploitation of an aquifer.

A possible approach to investigate the potential of an aquifer for groundwater exploitation relies on the analysis of pumping tests data. Pumping tests consists in measuring the drawdown, i.e. the lowering of the water level, resulting from the pumping process in a well[7,8]. The pumping test data can then be analyzed using statistical models such as the Cooper Jacob equation to derive the hydraulic transmissivity and conductivity of the aquifer[9-11]. These hydraulic properties depend on the size, shape, composition, compaction and thickness of its constitutive grains. Finally, using the classification established by Krasny[12], the transmittivity of an aquifer can be related to its capabilities in terms of groundwater exploitation. In a similar fashion, the lithology of an aquifer can be determined from its hydraulic conductivity and tabulated classifications given in the literature[13]. Based on these results, it possible to set limits to the amount of groundwater that can sustainably be extracted from an aquifer and thus avoid over exploitation.

MATERIALS AND METHODS

Constant rate pumping tests were performed in 4 private wells located in Tampan district, Pekanbaru city, Indonesia. The geographical coordinates of this district are 101°22 '45 "BT-101°23' 09" E and 0°28 '41 "N-0°29' 09" N. It occupies an area of 59.81 km^2. It is geologically homogeneous and consists of minas formations surrounded by young alluvium along the Siak River and old swampy alluvium. Rainfall ranges from 1,408-4,344 mm year^{-1} with an average of 2,938 mm year^{-1}. This district exhibits a rather flat topography with slopes between 0-8%. The population in 2017 is about 362.299 inhabitants. The water consumption is 17,607,731.4 m^3 year^{-1}. The water demand increases in parallel with the population and the industrial growth of Pekanbaru[14]. Most of the water consumed in Tampan district is directly obtained from groundwater reserves.

Experimental procedure: The experimental procedure was as follow:

- The wells to be studied were chosen and their absolute location recorded
- The well was verified to be in equilibrium, i.e. the water level should remain constant in the absence of pumping
- The water level in the wells prior to the pumping test was measured with a measuring tape combined with water detection sensors
- The appropriate discharge rate to be used during the constant rate pumping tests was determined by performing a preliminary step-drawdown measurement[15,16]
- The constant rate pumping test was started for a minimum duration of 100 min in order to get measurements over a full log cycle
- The water level was measured 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 40, 50, 60, 75, 90, 105, 120 and 150 min after the start of the pumping process

Statistical analysis: The Cooper Jacob method was used to analyze the data from the pumping tests. The following assumptions are inherent to that method[17]:

- The aquifer has a seemingly infinite areal extent
- The aquifer is homogeneous, isotropic and of uniform thickness
- The control well penetrates the entire thickness of the aquifer
- Prior to pumping, the water table is horizontal over the area influenced by the test
- The aquifer is confined and leak free
- The flow to the well did not reach steady state
- The water is released instantaneously from the storage when the hydraulic head declines
- The diameter of the pumping well is very small so that storage in the well can be neglected

Within these assumptions, the drawdown s(m) can be expressed as Eq. 1[16], where Q (m^3 s^{-1}) is the pumping rate, T (m^2 s^{-1}) is the aquifer transmissivity and u is the well function:

$$s = \frac{Q}{4\pi T}\int_{u}^{\infty}\frac{e^{-u}du}{u} \quad (1)$$

Table 1: Potential water usage for various ranges of the transmissivity T[12]

Transmissivity (m^2 day^{-1})	Potential groundwater usage	Expected debit (l s^{-1})
T>1.000	Water supply for a large population	>50
1000>T>100	Water supply for a smaller population	5-50
100>T>10	Water supply for a small community	0.5-5
10>T>1	Water supply for a single house	0.05-0.5
1>T>0.1	Limited private consumption	0.005-0.05
0.1>T	Little practical use	<0.005

Table 2: Conductivity K for various types of rocks and materials[13]

Geological classification	K (m day^{-1})	Classification
Unconsolidated material		
Clay	10^{-8}-10^{-2}	Slow
Fine sand	1-5	Medium
Medium sand	5-2×10^{1}	Fast
Rough sands	2×10^{1}-10^{2}	Fast
Gravel	10^{2}-10^{3}	Fast
Sand and gravel mixture	5-10^{2}	Fast
Clay, sand and gravel mixture	10^{-3}-10^{-1}	Slow
Rocks		
Sandstone	10^{-3}-1	Slow
Carbonate stone with secondary porosity	10^{-2}-1	Medium
Flakes	10^{-7}	Slow
Thick solid rock	<10^{-5}	Slow

Table 3: Location of the measurement wells

Well label	Location name	North latitude	East longitude
A	Pondokan Rohul	00°28'11.61"	101°22'41.84"
B	Perumahan Delta Karya	00°27'09.42"	101°23'13.23"
C	Perumahan Oce Regency II	00°28'41.60"	101°21'39.46"
D	Perumahan Bukit Raya	00°28'38.46"	101°24'45.81"

The Cooper-Jacob straight-line time-drawdown equation derived from Eq. 1 can be used to calculate the transmissivity as indicated in Eq. 2, where Δs (m) is the drawdown over one log cycle of the pumping duration:

$$T = \frac{2{,}30Q}{4\pi\Delta s} \tag{2}$$

Once the transmissivity of the aquifer is known, its conductivity K can be computed as given in Eq. 3, where B is the thickness of the aquifer:

$$K = \frac{T}{B} \tag{3}$$

The capabilities of the aquifer in terms of groundwater exploitation can be found from its transmissivity and the classification given in Table 1. In a similar manner, the lithology of the studied aquifer can be deducted from its conductivity and the data of Table 2.

RESULTS

The 4 measurement wells were located at the coordinates given in Table 3. The level of water in the wells before pumping was measured. A preliminary step-drawdown measurement was performed in each well. In this measurement, the well was pumped at a low constant rate until the drawdown stabilized. The pumping rate was then ramped up and the well pumped again till the drawdown stabilized. From these tests, it was determined that an appropriate discharge rate for the constant pumping rate test was 1.25×10^{-4} m^3 s^{-1}.

The results of the measurements of the drawdown with a constant pumping rate of 1.25×10^{-4} m^3 s^{-1} are given in Fig. 1. The drawdown was measured at different time intervals after the initiation of the pumping phase, as indicated by the markers. The data were then fitted to a straight line, excluding the first data points which do not satisfy the conditions of Cooper Jacob approximation. The drawdown per logarithmic cycle Δs, i.e. the drawdown between 10 and 100 min of pumping, is also indicated in the figure. Δs was 19.1, 15.3, 13.9 and 22.6 cm for well A, B, C and D, respectively. The total drawdown after a pumping time of 150 min was 2,861, 1,462, 1,225 and 2,274 m for well A, B, C and D, respectively.

DISCUSSION

As can be seen from Fig. 1, the drawdown increased during the first 4 min of the pumping tests. This is caused by the sudden aquifer pressure drop when the water starts to be pumped out of the well. After this initial phase, the drawdown continued to increase but at a reduced and constant rate. The Cooper Jacob approximation is valid during that phase. A similar behavior was observed by Wu *et al.*[18] and Sarma and Xu[19]. In contrast, Shen *et al.*[20] observed in experiments involving a low pumping rate that the drawdown increased slower in the initial phase than in the second. If pumping had continued for a long time, the system would have reached steady state and the drawdown would have stabilized to a constant value. Steady state is attained when the amount of water discharged by the aquifer into the well equates that pumped out of the well. The drawdown after 150 min of pumping was not the same for the 4 wells. These differences were related to small variations in the lithology of the soil around the test wells. However, to simplify our analysis, the soil properties were assumed homogeneous and isotropic over the whole studied area.

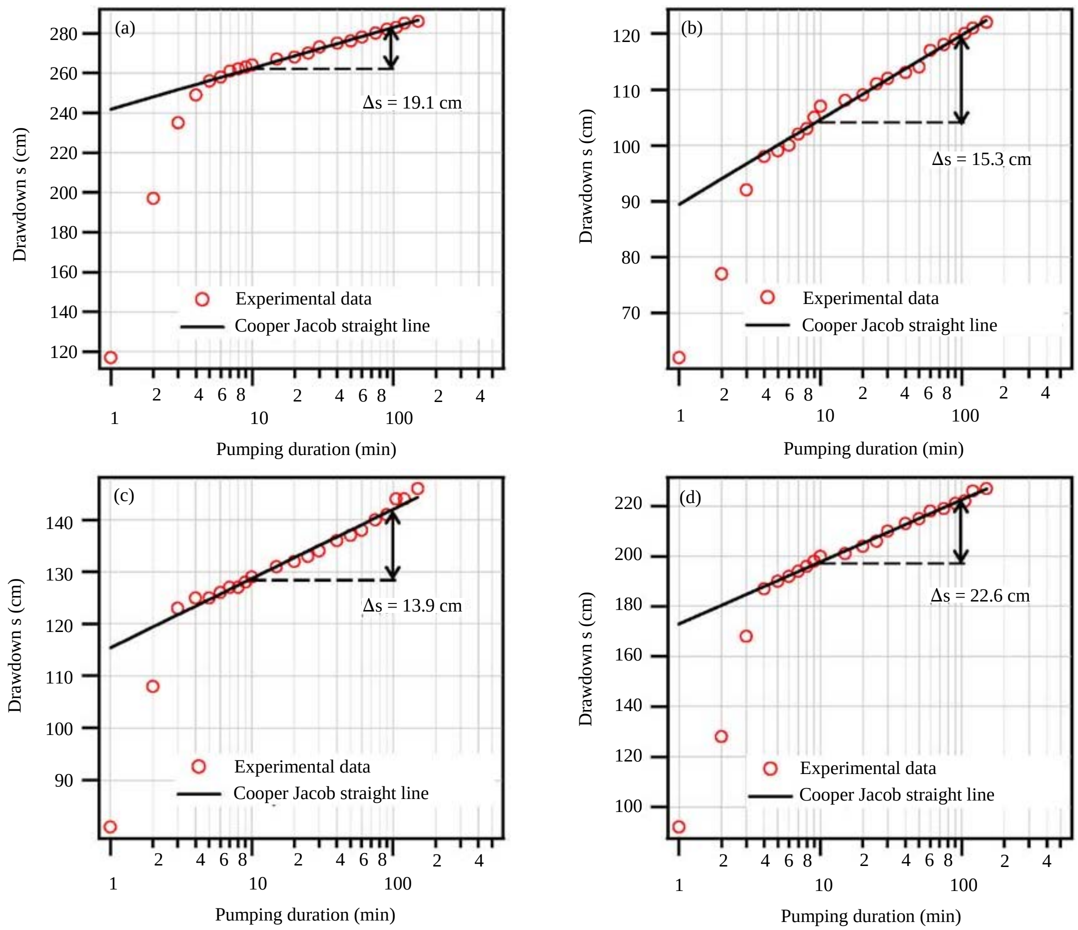

Fig. 1(a-d): Drawdown vs. pumping duration in the constant rate measurements

The transmissivity of the aquifer was determined by combining Eq. 2 with the values of Δs obtained from the drawdown-pumping duration plots. T was equal to 15.3 , 12.9, 10.4 and 9.2 m^2 day^{-1} for well A, B, C and D, respectively. The average value was 12.2. According to Table 1, this make the studied aquifer suitable for sustainably providing water to a small community. From the Central Bureau of Statistics and the Department of Mines and Energy of Pekanbaru, the thickness of the unconfined aquifer in Tampan District of Pekanbaru is about 7.3 m. Using Eq. 3, the average hydraulic conductivity K is found to be 1.7 m day^{-1}. From Table 2, this indicates that the lithology of the aquifer can be classified in the fine sand category and coarse soil class.

CONCLUSION

A method to establish appropriate conditions for the sustainable exploitation of the groundwater in an aquifer was presented. The method was based on constant rate pumping tests, drawdown measurements and Jacob Cooper time-drawdown analysis. It was applied on 4 test wells in Tampan district of Pekanbaru, Indonesia. The minimum and maximum of the drawdown over one log cycle of the pumping duration were 13.9 and 22.6 cm. From these values, the average hydraulic transmissivity of the aquifer was computed to be 12.24 m^2 day^{-1}. This indicated that the studied aquifer has the potential to sustainably provide water to a small sized community. The average conductivity is 1.68 m day^{-1}, which corresponds to fine sand lithology.

SIGNIFICANCE STATEMENT

This study describes a new method to determine sustainable limits to the exploitation of groundwater in aquifers. It is based on pumping tests and Cooper-Jacob analysis that permits deriving the hydraulic conductivity and transmissivity of the aquifer. From these parameters, the lithology of the aquifer and its potential for groundwater exploitation is determined. The proposed method provides a fast and low cost tool for the sustainable management of groundwater resources.

ACKNOWLEDGMENT

The author would like to thank University of Riau in data processing at the Physics Laboratory of the Earth Department of Physics Mathematics and Science Faculty University of Riau.

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