Conceptual Model of Heavy Metals Contaminant in Groundwater Flow of Sidoarjo Regency, East Java

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Abstract. Since the Lapindo mudflow incident in Sidoarjo Regency in 2006, it has caused groundwater pollution, which contains hazardous materials, especially metals. This study discusses a conceptual model of ground air flow contaminatedwith heavy metals. The conceptual model is the most essential and fundamental step in groundwater modelling. The conceptual model is a descriptive representation of the groundwater system that combines geological and hydrological conditions. To analyze this conceptual model requires good information about geology, hydrology, boundary conditions, and hydraulic parameters (hydraulic conductivity, porosity, specific yield, transmissivity). From the last ten years, hydrological data (rainfall, temperature), topographic maps, geological maps, and hydrogeological maps can be seen as theexisting hydrogeological conditions in the Sidoarjo area. Determining the boundary conditions of the research area is the Sidoarjo area; the interest area is the Lapindo Mudflow and the model area boundary, namely the northern boundary of theCAT (groundwater basin), is the city of Surabaya and Sidoarjo which has no flow boundary, the eastern boundary is the Madura strait, the southern boundary is the Porong River which is the flux boundary. Another boundary condition is the specified head boundary from the groundwater level in observation wells.

Keywords: Conceptual model, heavy metals, contaminated.

BACKGROUND

Heavy metal is a poison that often contaminates industrial and municipal waste (Demirbas, 2008) [1]. Heavy metals are produced from various industries, such as mining, plating, dyeing, electro-chemical metal processing, and battery storage, plus human activities (Kadirvelu K. *et al*., 2001) [2]. Disposal of wastewater without proper treatment causesresidues and accumulation of heavy metals in the environment (Vinodh R. *et al.*, 2011) [3].

According to (Antara 2009) [4], there were 200 farmers affected by the dumping of mud volcanoes into the river in Porong (district of Sidoarjo). The dumping can affect the vegetation and aquaculture because the mud contains several hazardous materials, such as hydrocarbon, sulphide, mercury, cadmium, chromium, arsenic and phenol (Antara, 2006; Mawardi, 2006;(Herawati & Niniek, 2007); Pohl, 2007; Mc Michael, 2009) [5-7]. There are many studies on the behaviour of heavy metals adsorbed by soil, but only a few soils were investigated in these studies. In addition, the simulation of real conditions when wastewater enters the ground is not comprehensive. This study aimed to determine the conceptual model of groundwater flow contaminated with heavy metals in the Sidoarjo area.

In making the conceptual model, a description of the boundary conditions is carried out to limit what parameters will be used in groundwater flow modelling (Cahyadi et al., 2017) [8]. Groundwater modelling is used to simulate and predict aquifer conditions and their changes. The benefit of this modelling is to present groundwater conditions, such as groundwater flow patterns, quantity, and quality of groundwater, at present and in the future. Groundwater modelling in the research area is strongly influenced by conditions: lithology/aquifer and geometry, hydraulic heads, hydrogeological boundaries, and model discretization (Devy, 2018) [9]. The modelling in this research uses Visual Modflow software.

METHOD

The data collection method is used to get a more in-depth explanation of the object of research, namely to find out the causal relationship of the research object. In this study, the object of research is heavy metals, which cause contamination in groundwater flow. Heavy metals contained in the Porong river include Cu (copper); Pb (lead); Cd (cadmium); Zn (zinc); Hg (mercury).

Based on Figure 1 below, we need both primary and secondary data for the study identification of the conceptual model. *Primary data* is data obtained by researchers directly or with direct measurements. At the same time, secondary data is data obtained by researchers from existing sources. The following is an explanation of the availability of data in this study:

Primary data collection such as:

- Observation of geological and hydrogeological conditions from geological and hydrogeological maps of the study area.
- Geoelectric survey at several points near the monitoring well (2019 research).
- Measurement of ground water level (MAT) through direct measurement and testing of hydraulic conductivity on monitoring wells (results of a 2009 drill log survey in Tambak Kalisogo village, 9.2 km from the Lapindo mud source with a MAT of 1.35 – 1.40 m), data source from P2AT (Groundwater Development Project Agency)
- Sampling and laboratory testing for groundwater quality at the Groundwater Laboratory of Water Resources Engineering, Universitas Brawijaya.

Secondary data collection such as:

- Regional hydrogeological map on a scale of 250,000 sheets of Kediri
- Regional geological map with a scale of 100,000 sheets of Malang
- Sub regional groundwater basin (sub - CAT) map of Mojokerto, Sidoarjo
- Monthly rainfall at Porong rain station 1997 – 2019
- Climatological data of Sidoarjo Regency

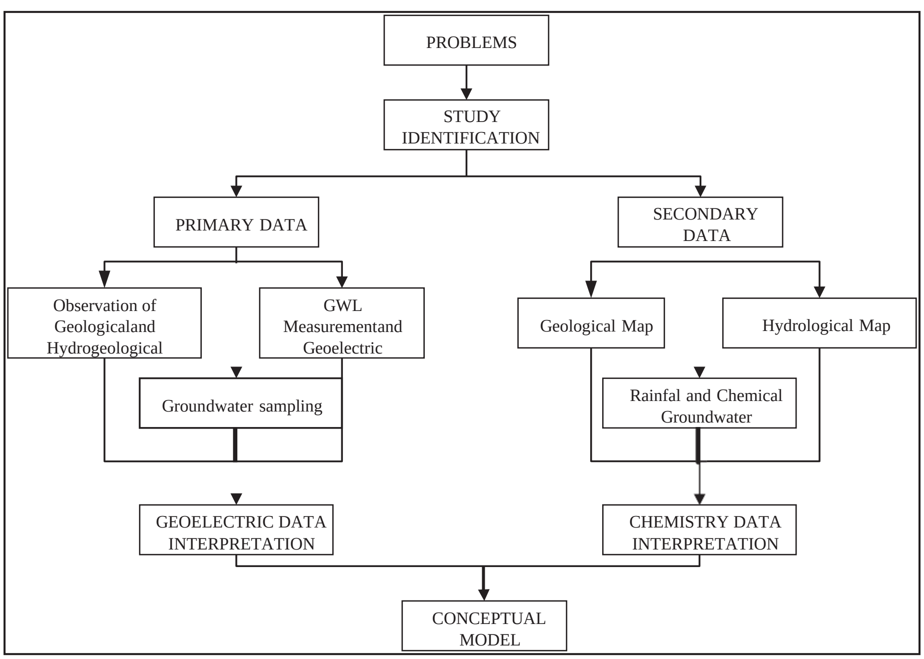

FIGURE. 1. Flow Chart Research

The conceptual model is the most essential and fundamental step in groundwater modelling. The conceptual model is a descriptive representation of a groundwater system that combines geological and hydrological conditions. (Baalousha, 2008) [10]. Building a conceptual model requires good information about geology, hydrology, boundary conditions, and hydraulic parameters. A good conceptual model should describe reality in a simple way that satisfies the modelling objectives and management requirements (Bear & Verruijt, 1990) [11]. This should summarize our understanding of water flow or contaminant transport in terms of groundwater quality modelling. The main data (inputs) that the conceptual model must enter are:

1) Aquifer geometry and model domain

All mathematical models for groundwater flow are based on the principle of water balance. Combining the water balance equation and Darcy's law produces the equation for groundwater flow.

The general equation that uses a three-dimensional combination of the waterbalance equation and Darcy's lawis given by: (Namitha *et al.,* 2019) [12].

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \quad (1)$$

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) \pm W = S_z \frac{\partial h}{\partial t} \quad (2)$$

With:

K_x, K_y, K_z : hydraulic conductivity values along the x, y and z coordinate axes, h: potention metric aquifer surface,

W : volumetric flux per unit volume (representing the source and/or standing water), if W < 0.0flowing out of the groundwater system, and W > 0.0 for flow in the groundwater system),

Sz : aquifer specific storage,

t : the time it takes for the groundwater level to change.

2) Boundary conditions (Konig L *et al.,* 2009) [13]

Identification of boundary conditions is the first step in the conceptual model. Solving groundwater flow equations (partial differential equations) requires identification of boundary conditions to give a good solution. Improper identification of boundary conditions affects the solution and can result in completely incorrect output. Boundary conditions can be classified into three main types:

a. Defined groundwater table (also called Dirichlet or type I boundary). This canbe expressed in mathematical form as: h(x, y, z, t) = constant.
b. Specific flow (also called Neumann limit or type II). In mathematical form it is: h(x, y, z, t) = constant
c. Flow dependent on the groundwater table (also called the Cauchy boundary ortype III). The mathematical form is: h (x, y, z, t) + a * h = constant (where "a"is a constant).

In groundwater problems, boundary conditions are not only a mathematical constraint, but also represent sources of contaminants and mixes in the system (Harbaugh *et al.,* 2004) [14] The selection of boundary conditions is very important for the development of an accurate model (Franke *et al.,* 1987) [15].

For simplification, the 1-dimensional case of Equation 2 solving h using the Finite Different Method (FDM) results in:

$$\frac{\partial^2 h}{\partial x^2} = \frac{\partial}{\partial x}\left(\frac{\partial h}{\partial x}\right) = \frac{1}{\Delta x}\left[\frac{h_{i+1}-h_i}{\Delta x} - \frac{h_i-h_{i-1}}{\Delta x}\right] = \frac{h_{i-1}-2h_i+h_{1+1}}{(\Delta x)^2} \quad (3)$$

3) Parameters of the aquifer system in the study area such as the distribution of k values (hydraulic conductivity), soil porosity, storativity, aquifer thickness, groundwater recharge, amount of evapotranspiration and runoff, contaminant concentration, dispersibility, andothers.
4) Interpretation of geoelectrical data, drill logs and MAT measurements, manufacture of groundwater flownets, interpretation of groundwater chemical data and physical modeling of aquifers.

RESULTS AND DISCUSSION

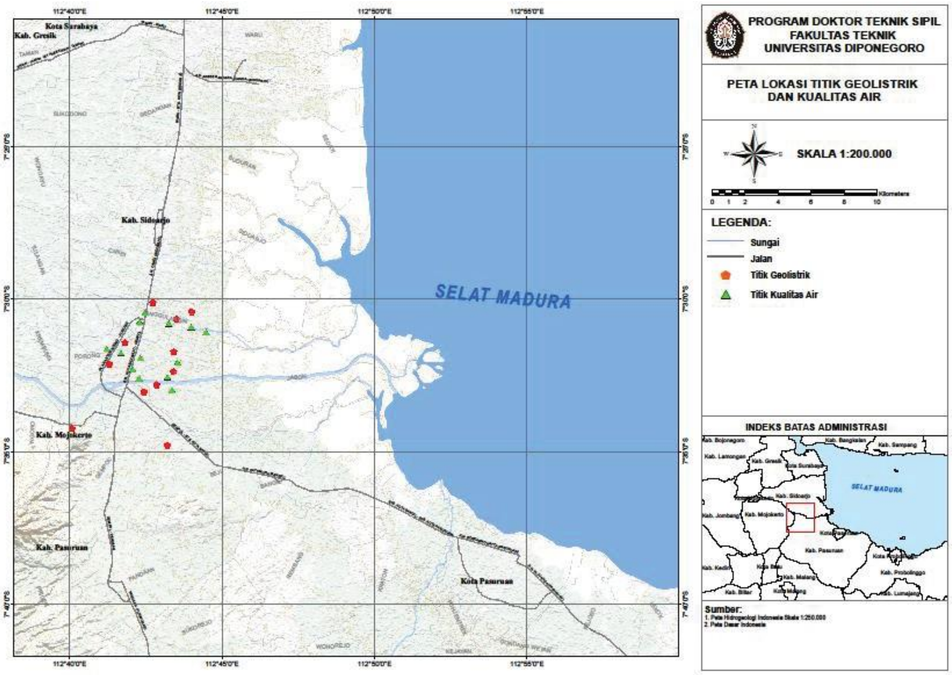

FIGURE 2. Study Location

This research was conducted around the Porong River, Sidoarjo Regency. The Porong River is a tributary of the Brantas River which originates in the City of Mojokerto (New Lengkong Dam), flows eastward and empties into the Madura Strait.

The selection of the sampling location limits refers to 2 (two) previous research results in the Porong river area (Lapindo mud), namely:

a) The first study (Purwaningsih *et al.*, 2013) [16] showed that the direction of pollutant flow originating in the middle of the embankment moved eastward about 2 km and westward about 1 km.
b) The second study (Yasintasari *et al.*, 2019) [17] for well water sampling was carried out in the rainy season in January 2019 with a distance from the Lapindo mud source around 1.8 km – 3.8 km.

Model Muse is a graphical user interface (GUI) for the U.S. Geological Survey (USGS) for groundwater modelling software models, was modified to support Modflow 6. (Langevin *et al.*, 2017) [18]. All the various versions of Modflow are three-dimensional finite-difference or finite volume (MODFLOW 6) groundwater models. They simulates steady and nonsteady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined.

In model selection there are: (**FIGURE 3.**)

1. Models MODFLOW 6 (Langevin and others, 2017, Provost and others, 2017, Hughes and others, 2017) [18],
2. MODFLOW-2005 (Harbaugh, 2005) [14],
3. MODFLOW-NWT (Niswonger and others, 2011), MODFLOW-NWT provides an alternate method for solving problems involving drying and rewetting nonlinearities of the unconfined groundwater-flow equation.
4. MODFLOW-OWHM (Hanson and others, 2014), MODFLOW-OWHM, combines features of MODFLOW-2005, MODFLOW-NWT, and MODFLOW-LGR and also adds methods for water management in a water allocation context.
5. MODFLOW-CFP (Shoemaker and others, 2007), MODFLOW-CFP adds methods for simulating conduit flow,
6. MODFLOW-LGR (Mehl and Hill, 2005, 2007, 2010), MODFLOW-LGR adds local grid refinement to MODFLOW.
7. SUTRA (Voss and Provost, 2002), WellFootprint (Winston and Goode, 2017), SUTRA uses the finite element

method in three dimensions to simulate groundwater flow and transport of either heat or solutes.

8. PHAST version 1 (Parkhurst and others, 2004). PHAST simulates multi-component, reactive solute transport in three-dimensional saturated groundwater flow systems.

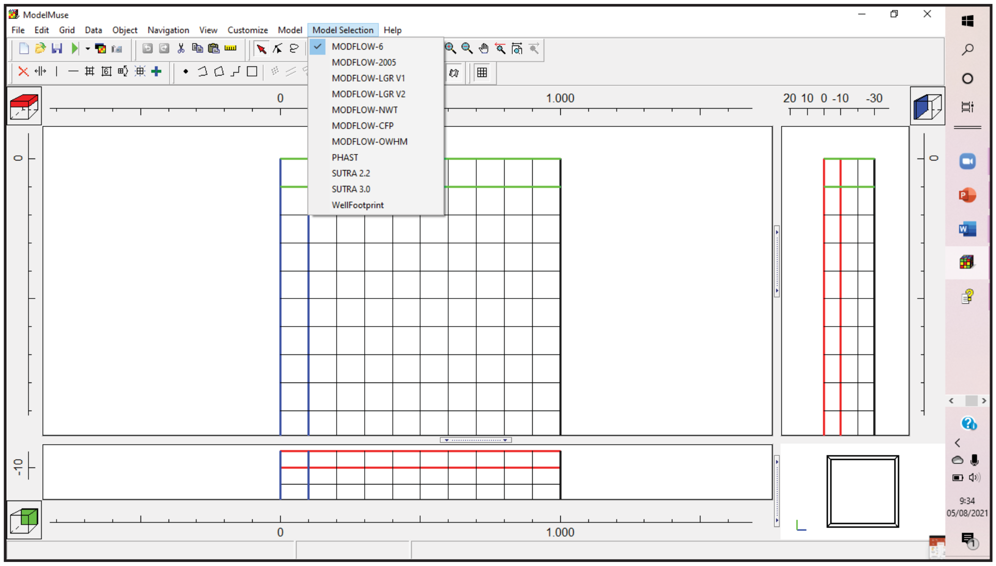

FIGURE 3. Overview Modflow 6 on Model Muse 4 Program

Modflow package and data sets
Boundary:

- DRN Package
- RCH Package
- EVT PackageAquifer properties:
- Model Top
- Upper Aquifer Bottom
- Middle Aquifer Bottom
- Lower Aquifer Bottom

Hydrology:

- Kx Variable Horizontal Hydraulic Conductivity
- Ky
- Kz
- Modflow Initial Head
- Modflow Specified Head

To determine the boundaries of the research area (balance area) as shown in Figure 2 and Figure 3 apart from the two previous studies (2013 and 2019), it is also based on the location of the Porong river (Dam Kalidawir; Kali Balonggati; Kali Rowogedek) which may be contaminated from the Lapindo mud, the location of several factories which is located close to the Lapindo mud source. So that 12 points were taken for sampling in the monitoring well (well observation). The distance from the Lapindo mud source is about 3-5 km and ten geoelectric points spread over the model area (study area) based on the identification survey last March 2021.

TABLE 1. Location of Geoelectrical Data and Monitoring Well Water Quality Data

No	Geoelectric	Monitoring Well
1	Ketapang	Ketapang
2	Gempolsari	Gempolsari/Tengah
3	Glagah Arum	Kalidawir
4	Besuki	Penatar Sewu
5	Kontrol Utara	Pusat Semburan Lumpur
6	Kontrol Sumur Bor	Glagah Arum
7	Pabrik	Kontrol Utara
8	Kontrol Barat Arteri	Kontrol Barat
9	Kontrol Selatan	Arteri Porong
10	Kontrol Watu Kosek	Porong
11		Selatan
12		Kontrol Selatan

Source : Survey,2021

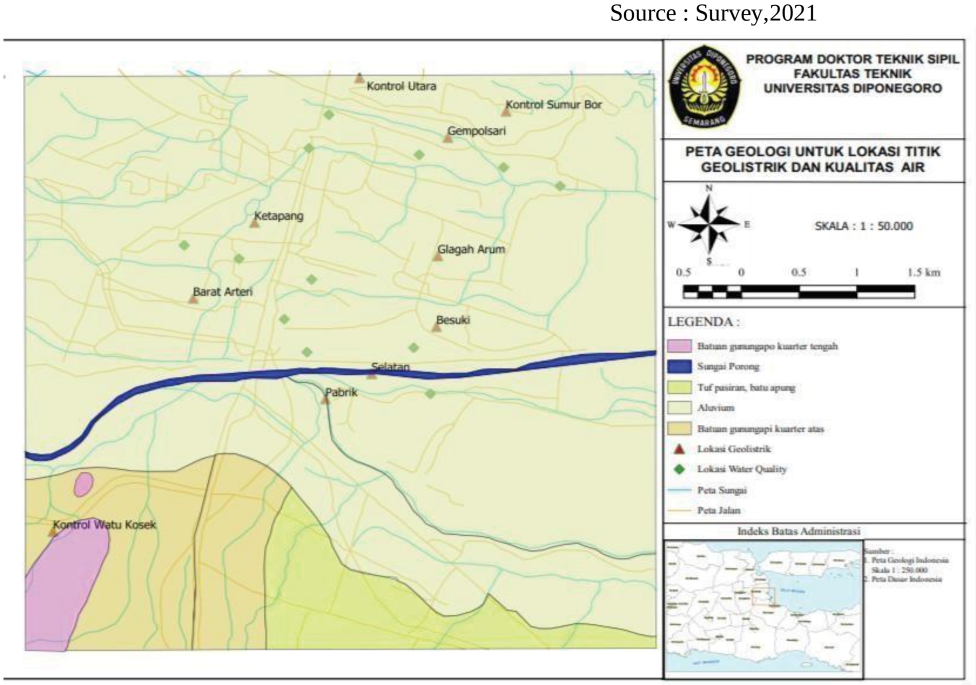

FIGURE 4. The Boundary Condition of The Research Area based on Geology Map by QGIS Program

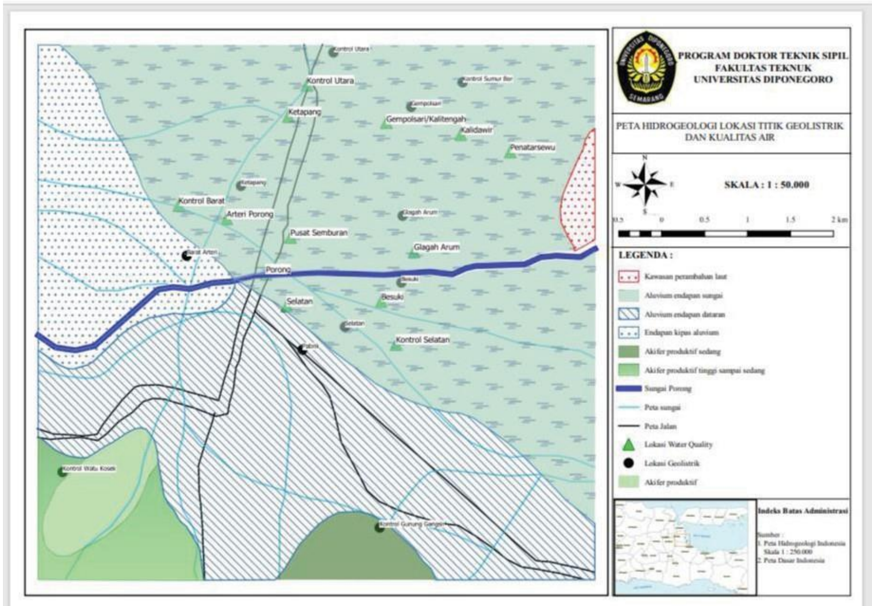

FIGURE 5. The Boundary Condition of The Research Area based on Hydrogeology Map by QGIS Program

To determine the value of hydraulic conductivity (K) there are various methods developed and selected depending on the availability of data. Among these methods, the most common is the pumping test. There are several methods that can be used to analyze pumping test data, namely Theis curve method, Coper and Jacob method, Chow method and Theis Recovery method. In this study only discusses the Theis curve method.

Theis, who developed the formula for unsteady flow, in which he introduced the time factor and storage coefficient. Theis notes that if from a well entering a confined and extensive aquifer, it is pumped at a constant rate, the effect of the discharge expands with time. The magnitude of the reduction in groundwater level multiplied by the coefficient of storage, then added up for the entire area of influence, will be equal to the discharge. Because the water must be obtained from the reduction of storage in the aquifer, then the groundwater level will continue to decrease as long as the aquifer is working effectively indefinitely. Therefore, theoretically there is no steady state. But the magnitude of the reduction in ground water level will continue to decline if the area of influence enlarges (Bisri, 2012) [19].

In using the Theis method, the assumptions used are: (Bisri, 2012) [19]

1) The flow to the well is an unsteady flow.
2) The type of aquifer is mainly for confined aquifers.
3) The diameter of the well is small, so the content in the well can be neglected.
4) The aquifer is considered to extend indefinitely in the horizontal plane, lies at the bottom of a layer that is impermeable to water and has a uniform thickness.
5) The aquifer is homogeneous, isotropic in the area affected by pumping.
6) The loss of compressive height caused by the vertical flow component in the aquifer is neglected.
7) The water flowing in the aquifer is a laminar flow (condition for the application of Darcy's law)
8) The release of water occurs immediately, this is due to the elasticity of water and the compaction of the aquifer material (material that is not compressible), as the basis of the law of continuity.
9) The water level on the piezometer and the free water level before pumping are almost horizontal.
10) Pumping is carried out with proper discharge.
11) The pumped well fully penetrates the aquifer.

The equation for groundwater subsidence and storage coefficient according to Theis is (Bisri, 2012) [19]

$$S = \frac{Q}{4\pi T} W(U) \qquad \text{or} \qquad T = \frac{Q}{4\pi S} W(U) \tag{4}$$

$$U = \frac{r^2 S'}{4Tt} W(U) \qquad or \qquad S' = \frac{Q4T'}{r^2/t} U \tag{5}$$

where :

S = Pisometer drop at a distance r (m) from the pumped well
Q = Fixed flow of pumped well (m^3/s)
T = Transmissivity of aquifer (m2/sec)
S' = Coefficient of containment (dimensionless)
T = Time since pumping started (seconds)
= radius of the observer well measured against the pumped well (m)

$$W(U) = - 0{,}5772 - \text{In } U + U - \frac{U^2}{2.2!} + \frac{U^3}{3.3!} + \frac{U^4}{4.4!} + \ldots \qquad (6)$$

W(U) = Exponential integral, or also known as U well function or Theis well function.

The value of W(U) can be obtained by using the normal type curve which is created by plotting the value of W(U) Vs U, or the reverse type curve which can be created by plotting the value of W(U) Vs l/U, on a log-log graph with W (U) as the vertical axis.

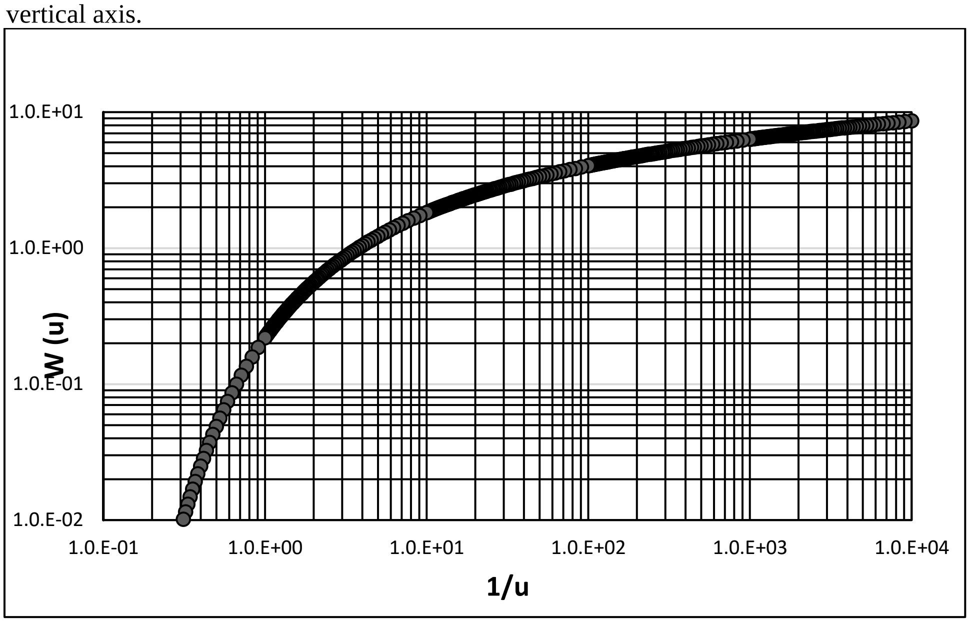

FIGURE 6. Graph of Relationship Between 1/U and W(U)

From the results of the field survey, the pumping test location is located at a location point north of the Porong River, with one production well and two observation wells. The coordinates can be tabled as in Table 1 below.

TABLE 2. Location of Pumping Test

No	Location	Coordinate
1	Production well	S : 7° 32’ 32,85” E : 112° 44’ 46,45”
2	Observation well 1	S : 7° 32’ 33” E : 112° 44’ 46”
3	Observation well 2	S : 7° 32’ 33” E : 112° 44’ 47”

Source : Survey,2021

The stages of analysis of Theis curve method are as follows :

- Determine the two intersection points and call them A and B. After that get the components $\left(\frac{t}{r^2}\right)_{A_A}, \left(\frac{t}{r^2}\right)_{B_A}, \left(\frac{1}{u}\right)_{A_A}, \left(\frac{1}{u}\right)_{B_{AA}}, W(u)_A, W(u)_B, s_A, s_B$
- From the picture below, the following components are obtained :

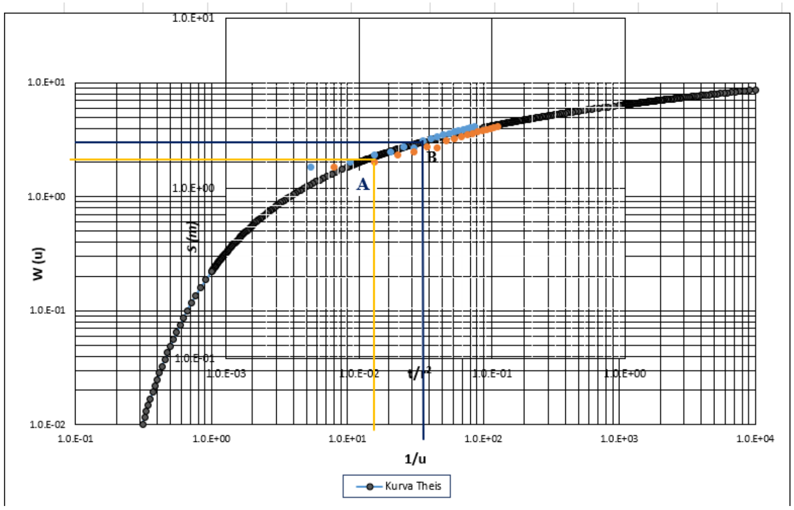

FIGURE 7. Superposition Graph of Experiment Theis

$\left(\frac{t}{r^2}\right)_{A_A} = 0{,}96$ $\left(\frac{t}{r^2}\right)_{B_A} = 0{,}5$

$\left(\frac{1}{u}\right)_{A_A} = 16$ $\left(\frac{1}{u}\right)_{B_A} = 36$

W $(u)_A$ = 1,2 W $(u)_A$ = 2,2

S_A = 1,65 m S_A = 2,5 m

- Determine the value of the transmissivity (T) and the storativity (S) with discharge of pumping is 88,364 m^3/day (1,023 liter/sec) :
  T_A = 5,117 m^2/day T_B = 6,191 m^2/day
  S_A= 8,528.10^{-4} S_B= 5,374.10^{-4}
- Get the hydraulic conductivity value with aquifer thickness (b) :

$K_A = \frac{T_A}{b_A} = 4{,}56.10^{-6}\ m/\sec$ $K_B = \frac{T_B}{b_B} = 5{,}512.10^{-6}\ m/\sec$

So the hydraulic conductivity average ($\overline{K}$) is 5,033.10^{-6} m/sec.

CONCLUSION

1. Based on data from the Meteorology and Geophysics Agency for the city of Sidoarjo in June 2021, the temperature was 32ºC, humidity was 82%, air pressure was 1008 hPa, wind speed was 8 km/hr, the probability of rain was 30% and K = 5,033.10^{-6} m/sec.
2. Determining the boundary conditions of the research area is the Sidoarjo area; the interest area is the Lapindo Mudflow and the model area boundary namely the northern boundary of the CAT (groundwater basin) is the city of Surabaya and Sidoarjo which has no flow boundary, the eastern boundary is the Madura strait, the southern boundary is the Porong River which is the flux boundary.
3. The results of the water quality test sampled from the Lapindo mud source in early March 2021, that are: Fe = 0,084 ppm; Zn = 0,32 ppm; Cd = 0 ppm; Pb = 0,0833 ppm; Hg = 0 ppm; Al = 0,804 ppm; Mg = 87,82 ppm; Cr^{6+} = 0,048 ppm; Cu = 0,0895 ppm and Ar < 0,0005 mg/L.

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