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Groundwater Inflow Prediction Using an Analytical Solution in the Gold Ore Exploration Tunnel of Underground Mine

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Abstract. Indonesia is a country rich in natural resources, especially gold resources. Gold mining in Indonesia is commonly using open pit and underground mining system. Although underground mining is not directly connected with weather and rainfall, that does not make an underground mining free of mine dewatering system's problem. The problems that may be occurred in the working front area of an underground mine are the high of the total head that has to be lifted by a pump, dimension of the mine channel and sump that small due to limited space of the tunnel, and flood. Flooding in a tunnel commonly caused by groundwater on the tunnel's surroundings. An accurate calculation of groundwater inflow into the tunnel is important to design the underground mine dewatering system. Measurement of actual groundwater inflow had been done to prove the accuracy of groundwater inflow's calculation using an analytical solution by El Tani method. This paper presents the alternative of the groundwaters seepage calculation those flows into the tunnel. The result of this research is the groundwater inflow can be predicted using an analytical solution accurately so that the design of the underground mine dewatering system can be held precisely.

Keywords: Mine Dewatering, Pump Network, Seepage, Total Head, Working Front Area.

INTRODUCTION

In Indonesia, the majority of underground gold mining sites are located inside the igneous rock with many fractures that can drain water. In various geological arrangements with low network fractures, groundwater streams occur commonly through breaks. At times a large portion of the stream occurs through one fracture or a fault plane, while in different cases the streams occur through a system of fractures. In either case, a comprehension is required of how groundwater courses through a solid harsh rock fractures [1].

A fractured rock conductivity is more unpredictable (level of heterogeneity and anisotropy) than the hydraulic conductivity of sedimentary rocks [2]. The hydrogeological states of solid rocks (metamorphic and igneous rock) in mine locations are regularly portrayed by a fractured condition under complex geographical settings comprising of a fault plane and fracture systems. The aquifer properties parameter is hydraulic conductivity (K), in-situ stress, rock lattice properties, fractures and opening, thickness, resistivity, predilection, interconnectivity, filling material, and ruggedness [3].

If at the mine sites there is an existence of aquifer, then the layer holds a large amount of water [4]. The mine can operate if the pumping network can drain the seepage groundwater during mining activities. [5]. Therefore, pumping networks are one of the most important aspects that must be considered from a mining system to increase efficiency and reduce pumping costs. [6].

The forecast of groundwater inflow into a passage is a significant issue in tunneling design. Groundwater inflow into a tunnel can prompt issues during development at that point the engineer needs to gauges the groundwater inflow for the design plan of the tunnel dewatering system. [7].

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The purpose of this research is to displays the prediction's alternatives of the groundwater inflow using three different range value of hydraulic conductivity and El Tani Method's equation and prove its accuracy so it can be used to predict the amount of groundwater inflow inside the tunnel.

SETTING

PT. Bumi Suksesindo is one of the mining companies located in Banyuwangi, East Java. This research was carried out at the Underground Decline Project, based on actual conditions that occur, mine water is one of the problems that are a concern because overflowing groundwater discharge causes development activities in the working face area to be disrupted. The tunnel is located beneath an open-pit mine that still operated at it is at 40 until 190 m depth below surface level. The tunnel is constructed declining with 8 degrees of the slope to reach the porfiri gold reserves that predicted located at 2000 m from the portal and 100 m below sea level. The portal can be seen in **FIGURE 1**. Like other areas in Indonesia, Banyuwangi and its surrounding tropical climate which is influenced by two seasons namely the dry season and the rainy season, the number of maximum daily rainfall rates in the period 1999 – 2017 is between 67 mm and 215 mm.

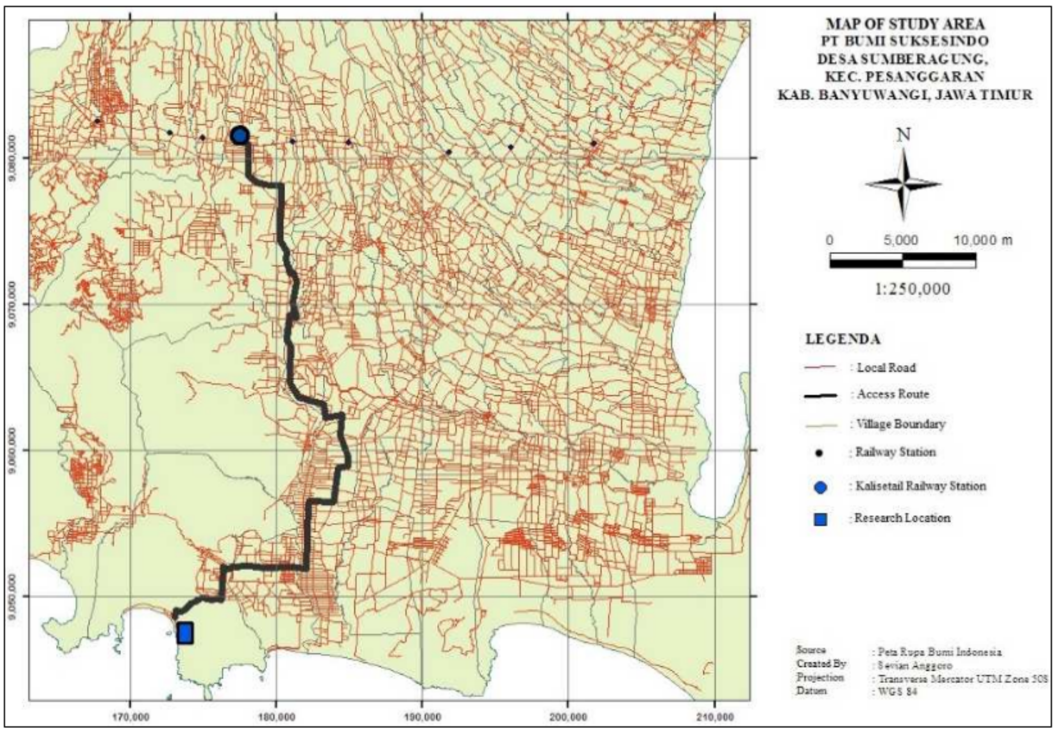

FIGURE 1. The Map of Study Location.

METHOD

The investigation was led by measuring the discharge of groundwater leakage directly at the examination site. Estimations are made using a tubular estimating instruments with measurements with a width (d) = 6 cm, radius (r) = 3 cm, height (h) = 20 cm. The volume of the compartment is 5.652 x 10^{-4} m^3. Groundwater leakage discharge is acquired from the time required for the cylinder to get full. Equation (1) is the groundwater discharge flow rate equation:

$$Q = v/t \quad (1)$$

explanation :
Q = Flow rate (m3/sec)
v = Volume (m3)

t = time (seconds)

Based on the result measurements of actual groundwater seepage release, the groundwater seepage stream that enters the tunnel is an average of 8.56 x 10^{-6} m^3/second at every groundwater seepage point.

Analytical Solutions of Groundwater Inflow in a Tunnel

Groundwater leakage discharge is the progression of water inside the earth's crust which pursues the essential standards of hydraulic through laminar pressure, including the stream movement at an extremely little speed. El Tani Method exhibited an analytical solution for determining the groundwater inflow (volume of water per unit tunnel length) into an unlined tunnel in the circumstance delineated in **FIGURE 3**, considering an elevation head periphery conditions at the tunnel boundary. Equation (2) [7] is the analytical solution:

$$Q = \frac{2\pi \text{ x } Kaq \text{ x } (A+H)}{\ln\left(\frac{h}{r}+\sqrt{\frac{h^2}{r^2}-1}\right)} \text{..........................(2)}$$

$$A = h(1-a^2)/(1+a^2)$$

$$a = \frac{1}{r}(h-\sqrt{h^2-r^2})$$

Equation Parameter:

Q = Groundwater inflow (m^3/sec)
K_{aq} = Hydraulic Conductivity (m/sec)
h = Depth of the tunnel center (m)
H = Groundwater Elevation (m)
r = Radius of the tunnel (m)

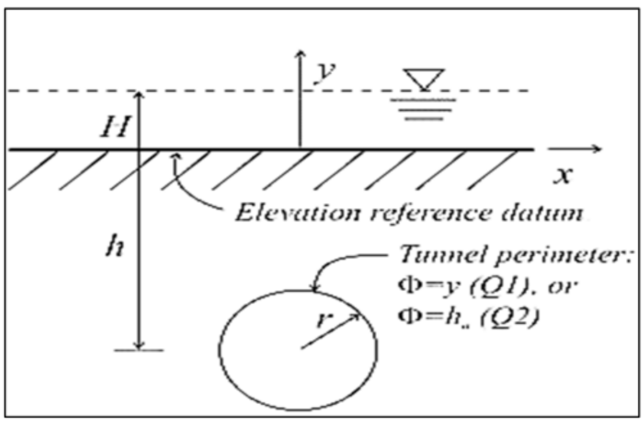

FIGURE 2. Spherical Tunnel in a Semi-Interminable Aquifer [8].

MATERIAL

Hydraulic Conductivity

Conductivity is the ability of a medium to deliver particles that pass through itself, in this case, the particles are water, while permeability is a measure of the easiness of a groundwater's flow through a porous medium [9]. A discontinuity such as rocks bedding, foliation, joint of rocks, cleavage, fracture, fissure, crack, or fault plane in rock masses takes a main role in the movement of groundwater flow and to form a fractured aquifer system. Fractured rock can be identified as an intact rock which is separated because of the discontinuity. Although the rock is impermeable, the existence of the discontinuity can increase the permeability's value of the entire rocks layer [10].

The hydraulic conductivity of fractured rocks can be seen in **TABLE 1**. Hydraulic conductivity is resolved not just by the attributes of minerals that form the aquifer yet additionally by different factors, for example, temperature, amount of air, particle synthesis in water [9]. The distribution of the hydraulic conductivity estimations by Schwartz (1990) [11], Cherry (1979) [12], and Bouwer (1978) [13] are displayed in **TABLES 1, 2, and 3**.

TABLE 1. Hydraulic Conductivity Based on Lithology [11]

Lithology	Porosity (percent)	Hydraulic Conductivity (cm/sec)	Compressibility (m^2/N or Pa^{-1})
Unconsolidated			
Gravel	25 – 40	$10^{-2} – 10^{2}$	$10^{-8} – 10^{-10}$
Sand	25 – 40	$10^{-4} – 1$	$10^{-7} – 10^{-9}$
Silt	35 – 50	$10^{-7} – 10^{-3}$	no data
Clay	40 – 70	$10^{-10} – 10^{-7}$	$10^{-6} – 10^{-8}$
Glacial Till	10 – 20	$10^{-10} – 10^{-4}$	$10^{-6} – 10^{-8}$
Indurated			
Fractured Basalt	5 – 50	$10^{-5} – 1$	$10^{-8} – 10^{-10}$
Karst Limestone	5 – 50	$10^{-4} – 10$	Not applicable
Sandstone	5 – 30	$10^{-8} – 10^{-4}$	$10^{-11} – 10^{-10}$
Limestone, Dolomite	0 – 20	$10^{-7} – 10^{-4}$	$< 10^{-10}$
Shale	0 – 10	$10^{-11} – 10^{-7}$	$10^{-7} – 10^{-8}$
Fractured Crystalline Rock	0 – 10	$10^{-7} – 10^{-2}$	$– 10^{-10}$
Dense Crystalline Rock	0 – 5	$10^{-12} – 10^{-8}$	$10^{-9} – 10^{-11}$

TABLE 2. Hydraulic Conductivity Classification [12]

Geological Classification		K (m/sec)
Unconsolidated Material	*Clay*	$10^{-8} – 10^{-2}$
	Fine Sand	1 – 5
	Medium Sand	5 – 2 x 10^{1}
	Coarse Sand	2 x 10^{1} – 10^{2}
	Gravel	$10^{2} – 10^{3}$
	Sand and Gravel Mixes	5 – 10^{2}
	Clay, Sand, Gravel Mixes (eg. Til)	$10^{-3} – 10^{-1}$
Rocks	*Sandstone*	$10^{-3} – 1$
	Carbonate rock with secondary porosity	$10^{-2} – 1$
	Shale	10^{-7}
	Dense solid rock	$< 10^{-5}$
	Fractured or weathered rock (core samples)	*Almost* 0 – 3 x 10^{2}
	Volcanic rock	*Almost* 0 – 10^{3}

Depth of the Center of Tunnel

The distance between the earth's surface and the tunnel is resolved to utilize a shape guide of the research region and a projection of the underground mine. The estimation of the vertical separation is measured starting from the earth contour level to the profundity of the underground mine. The depth of this tunnel influences the quantity of leakage of groundwater inflow that enters the underground mine. The cross-segment between the lower ground and the ground surface of the earth is displayed in **FIGURE 3**.

TABLE 3. Permeability and Hydraulic Conductivity Range [13]

Rocks	Unconsolidated Deposits	Hidraulic Conductivity K m/det	K cm/det	K gal/day/ft²	Permeability k Dar-cy	k cm²
	Gravel	1	10^{2}		10^{5}	10^{-3}
		10^{-1}	10	10^{6}	10^{4}	10^{-4}
Karst Lime Stone; Permeable Basalt	Sand	10^{-2}	1	10^{5}	10^{3}	10^{-5}
	Sandy silt	10^{-3}	10^{-1}	10^{4}	10^{2}	10^{-6}
Fractured Igneous Metamorphic Rock		10^{-4}	10^{-2}	10^{3}	10	10^{-7}
	Silt, loess	10^{-5}	10^{-3}	10^{2}	1	10^{-8}
Limestone & Dolomit; Batupasir (Sandstone)	Glacial Sill	10^{-6}	10^{-4}	10	10^{-1}	10^{-9}
		10^{-7}	10^{-5}	1	10^{-2}	10^{-10}
	Unweathered Marine clay	10^{-8}	10^{-6}	10^{-1}	10^{-3}	10^{-11}
		10^{-9}	10^{-7}	10^{-2}	10^{-4}	10^{-12}
Unfractured Igneous Metamorphic Rock; Shale		10^{-10}	10^{-8}	10^{-3}	10^{-5}	10^{-13}
		10^{-11}	10^{-9}	10^{-4}	10^{-6}	10^{-14}
		10^{-12}	10^{-10}	10^{-5}	10^{-7}	10^{-15}
		10^{-13}	10^{-11}	10^{-6}	10^{-8}	10^{-16}
		10^{-14}	10^{-12}	10^{-7}	10^{-9}	10^{-17}

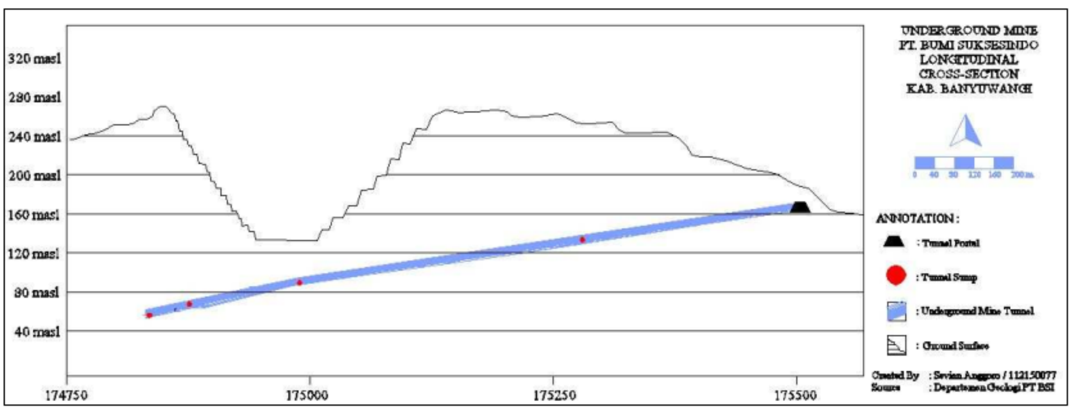

FIGURE 3. Cross-Sectional View of The Tunnel

Cross-sectional Radius of the Tunnel

The elements of underground mine that influence the release of the groundwater discharge is the estimations of cross-sectional radius. The radius of tunnel (appeared in **FIGURE 4**) affects determination of absolute drainage release and estimation of h-value. That h-value is profundity of center point of tunnel estimated from the earth surface.

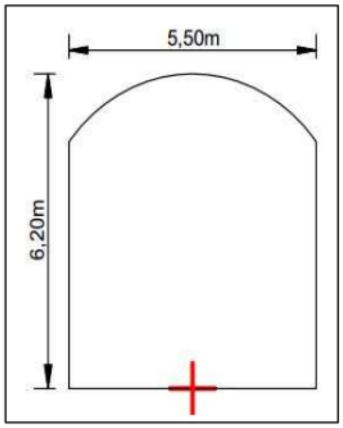

FIGURE 4. Tunnel's Dimension

Groundwater Elevation

Based on the topographical maps, the country rocks in Tujuh Bukit zone are a diorite and a volcanic breccia. Through investigation of geological cross-sectional maps, the presence of groundwater is assumed to potentially occurred in the diorite layer, because of its inconceivability to do the measurement of actual groundwater levels. The diorite layers on the guide are hued in pink, and it is portrayed as a fragmentary aquifer media that stores and streams groundwater through faults and rock fractures. The groundwater level is situated at the outskirt of diorite and volcanic breccia which its shading is brown as appeared in the transverse perspective on the geological map. In the beginning part of the underground mining tunnel, it doesn't expose to the dioritic so that there is no groundwater level in that small area, yet at the same time. The geological map of the research area is shown in **FIGURE 5**. The groundwater height can be found in **FIGURE 6**.

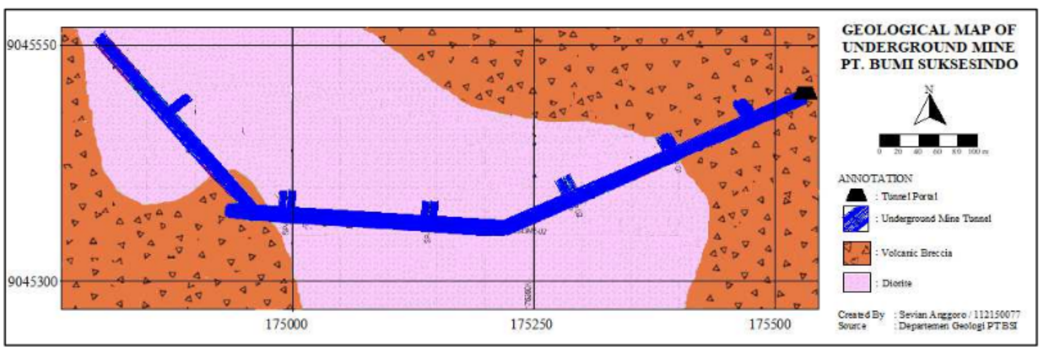

FIGURE 5. Geological Map at the Tunnel Boundary Conditions.

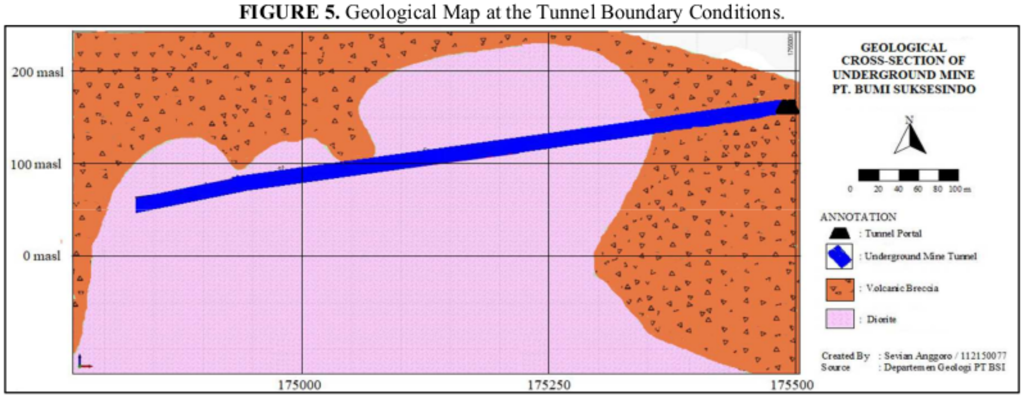

FIGURE 6. Transverse Perspective of The Geological Map

RESULT

Theoretical Groundwater Inflow

The Bouwer's range groundwater inflow alternative. This alternative uses hydraulic conductivity values according to Bouwer (1978) [13]. The rocks in the study area are classified as Fractured Rocks or Weathered Rocks so that the value of aquifer hydraulic conductivity is obtained in the range between 0 to 3.472 x 10^{-3} m / sec. The average seepage water inflows are 0 m^3 / sec and 0,75 m^3 / sec. The Schwartz's range groundwater inflow alternative. This alternative uses hydraulic conductivity values according to Schwartz (1990) [11]. The rocks in the study area are classified as Fractured Crystalline Rocks so that the value of aquifer hydraulic conductivity is obtained in the range between 10^{-4} m / sec to 10^{-9} m / sec. The average seepage water inflow is between 2.16 x 10^{-7} m^3 / sec to 0.021 m^3 / sec. The Cherry's range groundwater inflow alternative. This alternative uses hydraulic conductivity values according to Cherry (1979) [12]. The rocks in the study area are classified as Fractured Igneous Metamorphic Rocks so that the value of aquifer hydraulic conductivity is obtained in the range between 10^{-4} m / sec to 10^{-8} m / sec. The average seepage water inflow is between 2.16 x 10^{-6} m^3 / sec to 0.021 m^3 / sec. These alternatives are close to the value of seepage groundwater discharge, but based on some experiments the closest actual hydraulic conductivity value is K = 3.352 x 10^{-8} m / sec. The value of the hydraulic conductivity is in the range according to Cherry's Theory. Seepage water discharge is found at an average of 1.17 x 10^{-5} m^3 / sec at each point where seepage is located.

The water that enters the underground mine comes from seepage water that flows along the tunnel. Seepage water discharge is calculated using El Tani's method equation [14]. The location of the seepage of the groundwater located along the tunnel and the groundwater's inflow is listed in **TABLE 4**.

TABLE 4. Analytical Groundwater Seepage Flow rate.

Advance (m)	H-value (m)	h-value (m)	Flow rate (m^3/sec)
0	0	10.4	1.40019 x 10^{-6}
35	0	20.4	1.9329 x 10^{-6}
70	0	32.4	2.51949 x 10^{-6}
105	0	47.9	3.22624 x 10^{-6}
130	0	57.4	3.63989 x 10^{-6}
166	37.5	73.4	6.41435 x 10^{-6}
243	100	100.9	1.5986 x 10^{-5}
311	15	122.4	1.14454 x 10^{-5}
399	102.5	151.4	1.21658 x 10^{-5}
455	90	89.4	9.76409 x 10^{-6}
463	82.5	79.4	9.092 x 10^{-6}
471	75	71.4	8.4638 x 10^{-6}
479	2.5	61.9	3.97822 x 10^{-6}
484	5	52.4	3.73006 x 10^{-6}
492	5	44.4	3.39124 x 10^{-6}
516	27.5	38.4	4.63777 x 10^{-6}
588	30	38.4	4.80496 x 10^{-6}
604	25	50.4	4.88436 x 10^{-6}
610	25	50.4	4.88436 x 10^{-6}
618	25	61.4	5.2784 x 10^{-6}
626	22.5	72.4	5.5366 x 10^{-6}
632	15	83.4	5.53402 x 10^{-6}
639	30	93.4	6.70357 x 10^{-6}
647	40	15.4	7.64209 x 10^{-6}
654	42.5	116.4	8.14413 x 10^{-6}
661	52.5	127.4	9.00895 x 10^{-6}
669	55	138.4	9.4935 x 10^{-6}
676	57.5	149.4	9.97396 x 10^{-6}
684	57.5	160.4	1.03339 x 10^{-5}
691	60	172.4	1.08409 x 10^{-5}
697	62.5	182.4	1.12792 x 10^{-5}
733	65	219.4	1.25804 x 10^{-5}

continued

Advance (m)	H-value (m)	h-value (m)	Flow rate (m^3/sec)
748	62.5	191.4	1.15699 x 10^{-5}
752	62.5	181.4	1.12469 x 10^{-5}
878	62.5	198.4	1.17957 x 10^{-5}
		Average	1.17 x 10^{-5}

Actual Groundwater Inflow

The calculation of seepage groundwater discharge is done by direct measurement, then the results of these are being averaged. Based on the results of insitu measurements of actual groundwater seepage discharge, the seepage water discharge that enters the tunnel is an average of 8.56 x 10^{-6} m^3 / sec at each seepage point location. The following are the results of data's collected, listed in **TABLE 5**.

TABLE 5. Insitu Measured Groundwater Seepage Flow rates.

Advance (m)	Time (sec)	Flow rate (m^3/sec)
690	67.82	8.3333 x 10^{-6}
690	84.78	6.6666 x 10^{-6}
695	37.68	0.000015
695	37.68	0.000015
700	56.52	0.00001
700	66.49	0.0000085
705	45.22	0.0000125
705	67.82	8.8333 x 10^{-6}
710	67.82	8.3333 x 10^{-6}
710	67.82	8.3333 x 10^{-6}
715	66.49	0.0000085
715	65.98	8.5667 x 10^{-6}
720	66.11	0.00000855
720	38.53	1.467 x 10^{-5}
725	64.72	8.733 x 10^{-6}
725	57.28	9.867 x 10^{-6}
730	62.80	0.000009
730	66.49	0.0000085
735	64.84	8.7167 x 10^{-6}
735	63.74	8.867 x 10^{-6}
740	63.99	8.833 x 10^{-6}
740	65.21	8.667 x 10^{-6}
745	61.66	9.167 x 10^{-6}
745	141.30	0.000004
750	65.97	8.567 x 10^{-6}
750	102.76	0.0000055
755	108.01	5.233 x 10^{-6}
755	77.08	7.333 x 10^{-6}
760	75.36	0.0000075
760	84.78	6.667 x 10^{-6}
765	72.16	7.833 x 10^{-6}
765	42.95	1.316 x 10^{-5}
770	48.31	1.17 x 10^{-5}
770	56.52	0.00001
775	54.70	1.0333 x 10^{-5}
775	55.59	1.0167 x 10^{-5}
780	135.64	4.167 x 10^{-6}
780	99.74	5.667 x 10^{-6}
785	70.65	0.0000055
785	45.84	0.000008
790	77.08	1.233 x 10^{-5}
790	41.87	7.333 x 10^{-6}

continued

Advance (m)	Time (sec)	Flow rate (m^3/sec)
795	56.52	0.0000135
795	69.21	0.00001
800	125.60	8.167×10^{-6}
800	96.90	0.0000045
805	89.25	5.833×10^{-6}
805	100.04	6.333×10^{-6}
810	109.39	0.00000565
810	82.72	5.167×10^{-6}
815	170.39	6.833×10^{-6}
815	58.47	3.317×10^{-6}
820	52.19	9.667×10^{-6}
820	70.65	1.083×10^{-5}
	Average	8.56×10^{-6}

DISCUSSION

The number of location and the total flow rate of groundwater seepage that enters in every sump is recorded in **TABLE 6**. The layout of mine dewatering system inside the tunnel has appeared in **FIGURE 7** and the sump is displayed as a red dot. The portal of tunnel in the east and the work front area is in the east of the figure. The correlation coefficient between actual and analytical groundwater flow rate was acquired at 0.909 of 1.00 point. The chart of the relationship coefficient between analytical groundwater seepage and the actual measurement of leakage waters is shown in **FIGURE 8**. The leakage of water release, in principle, can't be equivalent to the groundwater seepage from the in-situ measurement results, because there is no information of hydraulic conductivity value in the area where the research has been done. This research approach depended on experimentation tests with the goal that the leakage groundwater's release is gotten approach reality. Overall, the analytical groundwater seepage is more prominent than the actual groundwater seepage, this is to organize the cynical guideline of the mine dewatering system if the flow rate of groundwater seepage has expanded. A comparison of flow rate among analytical groundwater seepage and genuine in-situ groundwater seepage at each point inside the tunnel has appeared in **FIGURE 9**.

TABLE 6. Comparison of Analytical and Actual Measure Groundwater Seepage

Location	Total of Seepage Point	Analytical (m^3/sec)	Actual (m^3/sec)
Work Front	1	1.179×10^{-5}	8.56×10^{-6}
Sump 4	3	4.718×10^{-5}	2.569×10^{-5}
Sump 3	15	1.143×10^{-4}	0.000128472
Sump 2	10	7.26×10^{-5}	8.564×10^{-5}
Sump 1	6	1.913×10^{-5}	5.138×10^{-5}

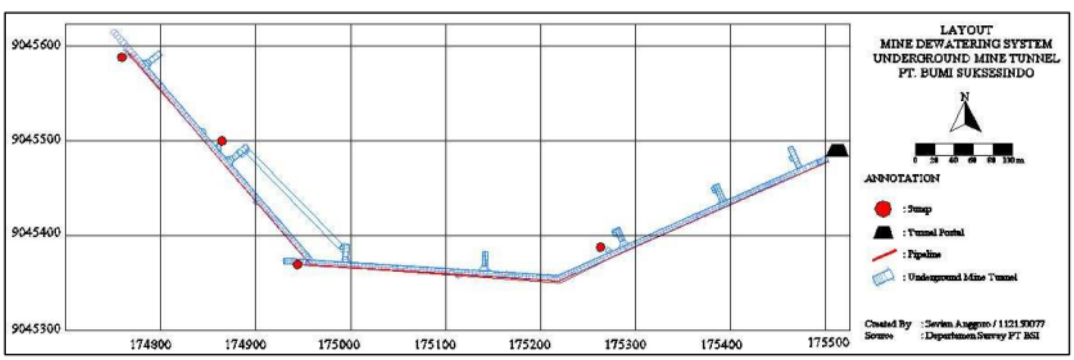

FIGURE 7. The layout of Mine Dewatering System in the Tunnel.

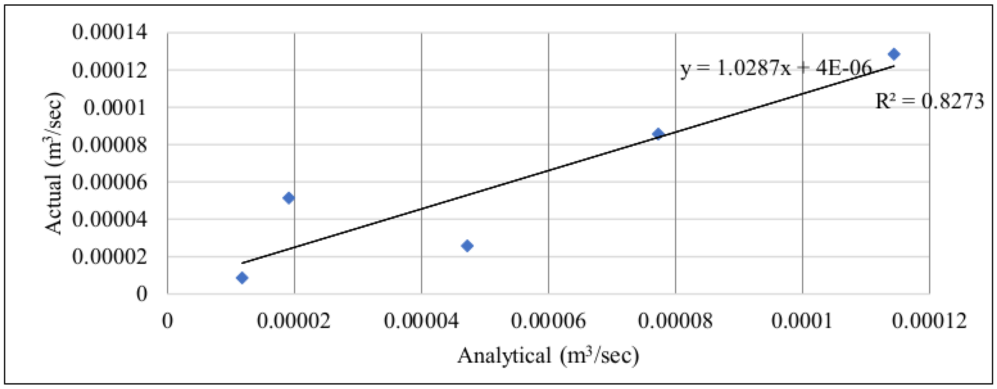

FIGURE 8. Chart of the Correlation Coefficient between Analytical and Actual Measured Groundwater Seepage that Flows into Every Sump.

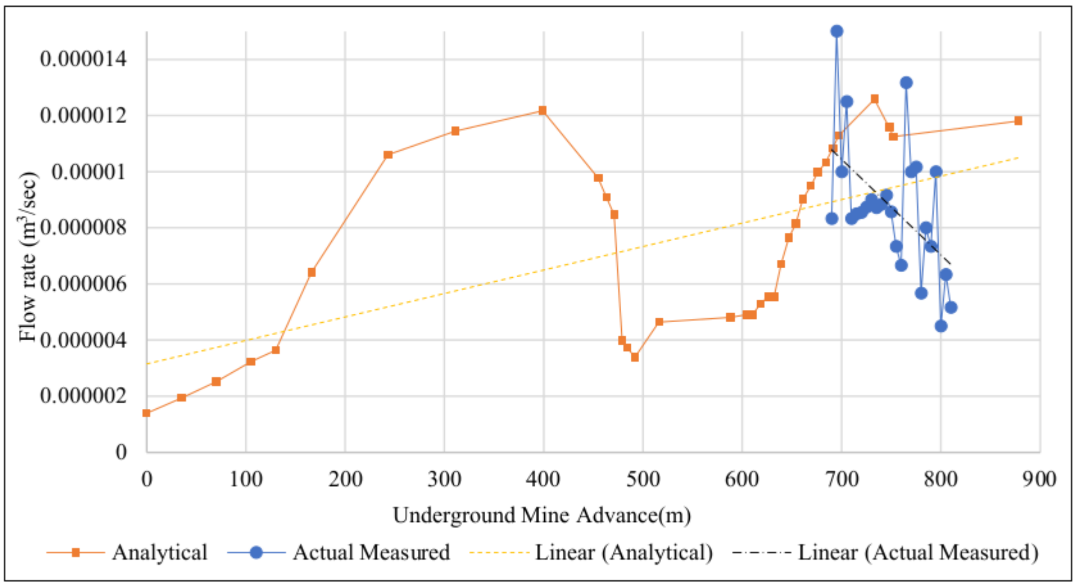

FIGURE 9. Comparison of the Analytical Groundwater Seepage and Actual Measured Groundwater Seepage at Each Location of The Tunnel Advance.

CONCLUSION

Groundwater seepage in gold exploration tunnel in the study area was determined dependent on the El Tani equation Method with a hydraulic conductivity value methodology as indicated by Cherry's order. Hydraulic conductivity of aquifer is acquired at 3.352 x 10^{-8} m/sec, with the average groundwater seepage flow rate is 1.17 x 10^{-5} m^3/sec at average on every leakage point location, while the real groundwater's discharge flow rate is 8.564 x 10^{-6} m^3/sec at average. At that point the correlation coefficient that obtained is 0.909 and the determination coefficient is 0.827.

Given the calculation that has been made, the aftereffects of analytical groundwater discharge flow rate are very near the genuine groundwater's inflow, as confirmed by the connection coefficient esteem that is near or equivalent to 1 and the coefficient of determination (r^2) is 0.8273. At that point, it tends to be reasoned that the El Tani Method condition to scientifically calculate the groundwater seepage inflow can be utilized to foresee the groundwater discharge inflow in the progress of the following mining advancement.

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