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Risk Analysis of the Groundwater Pollution in Sidoarjo Regency Based on Groundwater Quality Test and Vulnerability Mapping

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Abstract— *Mining and oil and gas industry were prevalent recently. However, the impact of the mining and oil and gas industry can affect the environment. One of the effects is the decrease in water quality. Another example of misconduct in the oil and gas industry is Lapindo mudflow. This mudflow has been flown out since 27 May 2006. This accident damaged infrastructure around the area and the mudflow already sink 600 ha of land and residential areas. This problem continues today, and nobody knows where it comes to an end. In this study, our outcome is to know the safety of the water resources around the mudflow area. The objective of this study is to know the distribution pattern of the pollutant and health risk analysis of the people around the mudflow area.*

To know the health risk of the Lapindo mudflow, vulnerability map has been made based on the DRASTIC Index method. Also, Pollution Index method was needed to assess the risk analysis accurately. Besides that, in this study, simulation of the pollutant transport across the surrounding area has been simulated by using advection theory in Hydrus-1D.

The potential of groundwater vulnerability was calculated using DRASTIC Index method. The result of the calculation was conformable with the outcome of the water quality test using Pollution Index method. The result of the DRASTIC index showed that the level of groundwater vulnerability is medium. Then, the result of water quality test revealed that the water from water wells is to meet quality standards and moderately polluted. The assessment of health risk analysis showed that the water is not detrimental to health. On the other hand, the simulation result for Fe, Al, and Mn have a similar speed to reach DK1 water wells, which is 1760,6 meter from the center of the mudflow. All three pollutants take ± 8 years to reach DK1 water wells. The conclusion of this study is the water wells, which is used by local people, was not detrimental to health, and Hydrus-1D was able to simulate the distribution of pollutants in the affected area.

Keywords— *Groundwater vulnerability test, pollution index, risk analysis, Hydrus-1D, advection.*

I. INTRODUCTION

The rapid growth rate of industrial estates in Indonesia not only has a positive impact in terms of the economy but also has a negative impact, especially environmental pollution, as is the case in Sidoarjo regency.

Groundwater pollution originating from human activities is a slow process, and the result is dangerous, which has a negative impact. The pollution process is not visible, has a complicated process, and have a long-term effect [1]. The mining and petroleum industry is one of the industries which is rapidly growing today. However, one of the consequences of mining and oil industry activities can affect the surrounding environment, one of which is a decrease in water quality [1]. One example of oil industry activity that has an impact on the environment is the mudflow in the Sidoarjo area due to oil drilling activities. Fitrianto, in his research, stated that the mudflow that began on May 27, 2006, destroyed various types of infrastructure and submerged at least 600 ha of land and settlements [2]. The Indonesian Supreme Audit Agency (BPK) estimates that the losses covered reached 32 billion rupiahs.

To reveal the risks of the mudflow, the mapping of a vulnerability map based on groundwater vulnerability test using the DRASTIC method, and the Pollution Index is also needed to provide the appropriate risk analysis. Sidibe revealed that vulnerability maps could be used as an essential tool to protect groundwater resources [1]. Because if groundwater is contaminated, it will be difficult to fix the contaminated area [3][4]. The DRASTIC method is one of the most popular methods used to assess groundwater vulnerability [5][6].

In addition to the DRASTIC method, the Pollution Index method was used in this study. The Pollution Index method is a method used to determine the level of pollution relative to permitted water quality parameters. This method has been widely used to assess water quality conditions and other related issues [7][8]. Therefore, knowing the extent of the distribution of pollutants in an area is vital to do to minimize the risks. Determination of the distribution of pollutants can be done through monitoring the concentration of pollutants by taking water samples in specific locations that depend on the interval of distance and time of water sampling, as well as using numerical models.

The output of this study is to provide an overview of the distribution of pollutants in the Sidoarjo mudflow region along with the risk analysis that will occur in the future based on groundwater vulnerability test, which will also be supported by groundwater quality data at the research site.

II. EXPERIMENTAL

In this section, the research method will be divided into 4 different parts, which are vulnerability mapping using the DRASTIC method, pollution index, health risk analysis of the groundwater, and pollutant transport simulation using Hydrus-1D. Each of the parts has a correlation to other parts supporting the result of this research.

This research was done in Sidoarjo regency, Jawa Timur, Indonesia. The vulnerability mapping and groundwater quality

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test was conducted in an area that covers Kecamatan Porong and Kecamatan Tanggulangin, as shown in Fig. 1.

Fig. 1. The map shows the boundaries of the research area.

A. Vulnerability Mapping using DRASTIC Method

The vulnerability mapping was done by using the DRASTIC method. The DRASTIC method is an indexing system developed by the U.S. Environmental Protection Agency (US-EPA) in 1980 to map the vulnerability of aquifer affected by contaminant [9]. This system used a rating to a specific area with the same vulnerability level. Afterward, the correct action can be done to prevent further contamination [10].

The DRASTIC method is an acronym of depth to watertable, recharge, aquifer media, soil media, topography (slope), the impact of the vadose zone media, and conductivity (hydraulic) of the aquifer. The equation of DRASTIC index is as follows:

Dr*Dw+Rr*Rw+Ar*Aw+Sr*Sw+Tr*Tw+Ir*Iw+Cr*Cw= DRASTIC Index (1)

Where,

Dr : Depth to watertable rating
Dw : Depth to watertable weight
Rr : Recharge rating
Rw : Recharge weight
Ar : Aquifer media rating
Aw : Aquifer media weight
Sr : Soil media rating
Tr : Topography rating
Tw : Topography weight
Ir : Impact of the vadose zone media rating
Iw : Impact of the vadose zone media weight
Cr : Conductivity (hydraulic) of the aquifer rating
Cw : Conductivity (hydraulic) of the aquifer weight
Sw : Soil media weight

The pollution level criteria are shown in Table 1. The criteria were divided into 4 different criteria, which can be seen in Table 1.

TABLE 1. The pollution level criteria based on the DRASTIC index [11].

Vulnerability level	DRASTIC Index	Notes
Low	1-100	Can only be polluted by continue discharge of a contaminant
Medium	101-140	Can be polluted by continue discharge of a contaminant
High	141-180	Can be polluted by all kind of contaminant, except the one that has high absorption ability and easily altered by multiple scenarios.
Very high	>180	Can be polluted by all kind of contaminant in a short time and any scenarios.

The depth to watertable data was obtained by surveying the research area. Then, the aquifer media, soil media, the impact of the vadose zone, and conductivity (hydraulic of the aquifer) results were obtained by analyzing the geoelectric data which is processed using IP2WIN program. Recharge data were collected from the facilities owned by Badan Meteorologi, Klimatologi, dan Geofisika (BMKG) around the research area. Lastly, the topography data were processed using ArcMap 10 program using data from national Digital Elevation Model (DEM).

B. Pollution Index

Pollution index was used in this research to assess the water quality in the actual condition. This method was proposed by Sumimoto and Nemerow from Texas University in 1970. Pollution index used to determine the level of pollution relative to the regulations. The equation (2) shows the calculation to obtain the pollution index.

$$IP_j = \sqrt{\frac{(c_i/L_{ij})^2_M + (c_i/L_{ij})^2_R}{2}} \qquad (2)$$

The pollution index criteria are shown in Table 2. The criteria are divided into 4 different criteria based on Lampiran II Kepmen LH No. 11 2003 (Indonesia Regulations).

TABLE 2. The pollution index criteria [8].

PI_j	Notes
$0 \leq PI_j \leq 1{,}0$	Meet the quality standard
$1{,}0 < PI_j \leq 5{,}0$	Mildly polluted
$5{,}0 \leq PI_j \leq 10$	Moderately polluted
$PI_j > 10$	Heavily polluted

The groundwater quality results are obtained from the laboratory test in Brawijaya University. Water quality checker Horiba U50 was used to analyze the pH, dissolved oxygen, conductivity, salinity, total dissolved solids, seawater specific gravity, and temperature. The concentrations of pollutant were analyzed using Atomic Absorption Spectroscopy.

C. Health Risk Analysis of the Groundwater

The health risk assessment was calculated based on the estimate daily intake (EDI) of the pollutant, which is consumed. The calculation was based on the US

Environmental Protection Agency and Shah [12][13]. The calculation of the estimate daily intake is as follows:

$$EDI = C \; x \; IR \; x \; ED \; x \; \frac{EF}{BW} \; x \; AT \qquad (3)$$

Where,
C : concentration of metals in water (□g/L)
IR : water intake rate(2L/hari)
ED : exposure duration (diasumsikan 67 tahun)
EF : exposure frequency (365 hari/tahun)
BW : body weight (72 kg)
AT : average lifetime (24,455 hari)

Then, to know the level of risk, the target hazard quotients (THQs) as calculated as shown in equation (4).

$$THQs = \frac{EDI}{RfD} \qquad (4)$$

Where,
EDI : estimate daily intake
RfD : reference dose of a particular metal.

The RfD value for Fe, Mn, and Al are 300, 140, and 0.0004 μg/kg-day, respectively [14][15]. If THQs<1 it is indicating that there is no health risk, but if THQs > 1 it indicates that there is health risk [16].

D. Pollutant Transport Simulation using Hydrus-1D

In this research, the simulation of the pollutant distribution was simulated by using Hydrus-1D. Hydrus-1D can solve the advection-dispersion equation based on the Richards partial differential equations which illustrate the flow of water in saturated porous media. The equation of 1-dimension advection pollutant transport for the semi-infinite boundary is as follows [17]:

$$C(x,t) = \frac{S_o}{Q} h\left(t - \frac{x}{u}\right) \exp\left(-k\frac{x}{u}\right) \qquad (5)$$

Where,
C : concentration of solute water (mg/L)
So : emission rate(g/s)
H : La Place equation
t : elapsed time (day)
Q : water flux (cm/day)
K : degradation rate
x : distance in direction (cm)
u : fluid velocity (cm/h)

The parameter which used as an input in this research are shown in Table 3.

TABLE 3. Input parameter for Hydrus-1D [8].

Parameter	Value	Unit
Saturated hydraulic conductivity	24,96	Ks (cm day^{-1})
Residual soil water content	0,078	θr
Saturated soil water content	0,43	θs
Parameter α in soil water retention	0,036	l/cm
Parameter n in soil water retention	1,56	
Bulk density	1,25	Bd (g cm^{-3})
Solution	Mn 5.3 x 10^{-5} Al 1.28 x 10^{-5} Fe 1.52 x 10^{-4}	C (mol L^{-1})

The soil type used in this simulation is loam. The loam soil parameter used in this research taken from the Hydrus-1D database. The simulation boundary conditions in this simulation used constant pressure head for upper boundary conditions and lower boundary conditions to simulate the horizontal distribution of the pollutant. All of the pressure head in the simulation was set to 0 to eliminate the pressure head effect.

III. Results and Discussion

The location of Sidoarjo mudflow is administratively located in Balongnongo, Renokonengo, Porong, located at approximately 12 km south of Sidoarjo Regency with a mud storage area of around 640 hectares. The topography of the research location is in the delta plain with a height between 0 and 25 m. Based on the hydrogeological map, the research locations in Tanggulangin, Porong, and Jabon are included in the high productive aquifer group with wide distribution.

The area boundary used for the study area is the perimeter boundary drawn from the midpoint of the Sidoarjo mudflow embankment for 1.5 km. Within a radius of 1.5 km, it covers 3 sub-districts located in Sidoarjo, namely Tanggulangin, Porong, and Jabon. The research area is shown in Fig. 2. As shown in Fig. 2, there are 5 points which showed the code for geoelectric test position and well position. G1 to G5 are the position of the geoelectric test and DK1, DG2, DK3, DP4, and DB5 are the well which water sample is taken.

Some of the data are obtained to calculate the DRASTIC index. The data are soil type, annual rainfall, and topography. The soil type was interpreted using geoelectric results. Based on the data obtained from the field, the resistivity values resulting from processing and interpreting resistivity data at 5 measurement points using the IP2WIN program, a description of the subsurface layer is obtained. The results showed that soil media is uniform from a depth of 0-6 m, which is loam. Below that is a mixture of loam and mud.

The annual rainfall in the research is obtained from the Porong Station. After collecting rainfall data for 20 years, it can be determined that the annual rainfall value in the Porong Rain Station is 34266.5 mm with an annual average rainfall of 1713,325 mm.

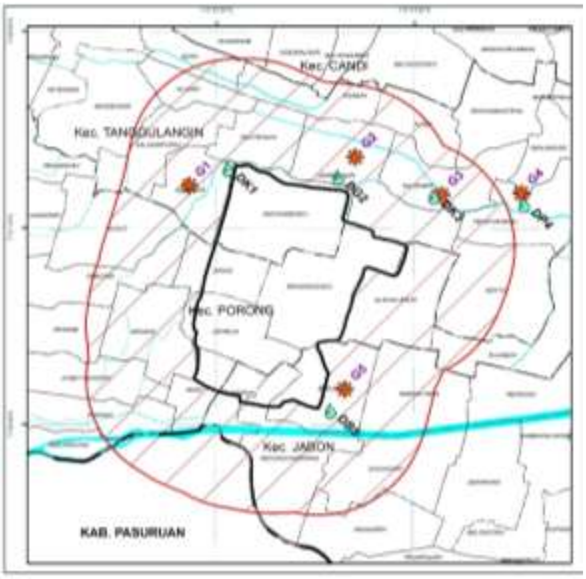

Fig. 2. Map of the research area, including the geoelectric test position and well position.

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The drastic method scoring is shown in Table 4 to Table 11. The table revealed the scoring results of depth to watertable, recharge, aquifer media, soil media, topography, the impact of the vadose zone, hydraulic conductivity, and DRASTIC Index.

TABLE 4. Depth to watertable score for DRASTIC index.

Area	Depth (meter)	Rating (Dr)	Weight (Dw)	Score (DwDr)
1	1	10	5	50
2	1,5	9	5	45
3	2	9	5	45
4	2	9	5	45
5	1,5	9	5	45

TABLE 5. Recharge score for DRASTIC index.

Area	Rainfall (mm)	Rating (Rr)	Weight (Rw)	Score (RwRr)
1	1713,325	6	4	24
2	1713,325	6	4	24
3	1713,325	6	4	24
4	1713,325	6	4	24
5	1713,325	6	4	24

TABLE 6. Aquifer media score for DRASTIC index.

Area	Aquifer media type	Rating (Ar)	Weight (Aw)	Score (AwAr)
1	Sedimentary/Metamorphic	4	3	12
2	Sedimentary/Metamorphic	4	3	12
3	Sedimentary/Metamorphic	4	3	12
4	Sedimentary/Metamorphic	4	3	12
5	Sedimentary/Metamorphic	4	3	12

TABLE 7. Soil score for DRASTIC index.

Area	Soil media	Rating (Sr)	Weight (Sw)	Score (SwSr)
1	Mud-loam	3	2	6
2	Mud-loam	3	2	6
3	Mud-loam	3	2	6
4	Mud-loam	3	2	6
5	Mud-loam	3	2	6

TABLE 8. Topography score for DRASTIC index.

Area	Slope (%)	Rating (Tr)	Weight (Tw)	Score (TwTr)
1	1,538	10	1	10
2	0,991	10	1	10
3	0,819	10	1	10
4	0	10	1	10
5	0,540	10	1	10

TABLE 9. Impact of vadose zone score for DRASTIC index.

Area	Aquifer media	Rating (Ir)	Weight (Iw)	Score (IwIr)
1	Silt/loam	1	5	5
2	Silt/loam	1	5	5
3	Silt/loam	1	5	5
4	Silt/loam	1	5	5
5	Silt/loam	1	5	5

TABLE 10. Hydraulic conductivity score for DRASTIC index.

Area	Hydraulic Conductivity (m/day)	Rating (Cr)	Weight (Dw)	Score (DwDr)
1	0,0002	1	3	3
2	0,0002	1	3	3
3	0,0002	1	3	3
4	0,0002	1	3	3
5	0,0002	1	3	3

TABLE 11. DRASTIC index score in the research area.

Area	Subdistrict	Village	Code	DRASTIC Index
1	Tanggulangin	Ketapang	DK1	110
2	Tanggulangin	Gempolsari	DG2	110
3	Tanggulangin	Kalidawir	DK3	105
4	Tanggulangin	Penatarsewu	DP4	105
5	Jabon	Besuki	DB5	110

The final step of the analysis of the DRASTIC method is making a zoning map of the seven parameters described above. The vulnerability map is shown in Fig. 3.

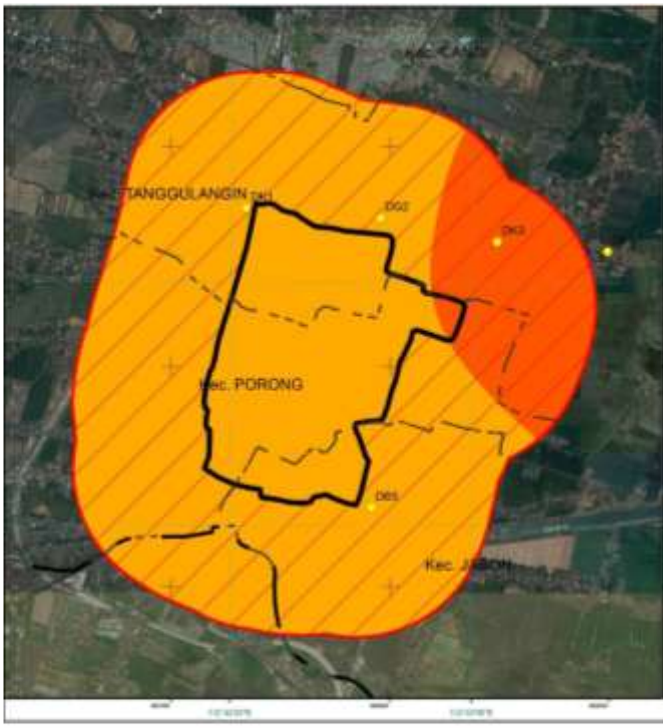

Fig. 3. Vulnerability map based on a DRASTIC index. (Yellow: 105, Orange: 110)

From the results of the DRASTIC index, it is revealed that the level of vulnerability of groundwater is in the medium category of pollution in the Sidoarjo mudflow area (Score 105-110). As shown in Table 11, the entire study area has a medium level of vulnerability. The high level of vulnerability of groundwater to pollution is caused by the depth factor of groundwater, which is relatively closer to the surface, which allows water to absorb the pollutant more quickly.

The results of the water quality pollution index are shown in Table 12 and Table 13. Based on the results of the pollution index of the well in the research area, it was divided into 2 results, meet the quality standards based on PP No. 82 Tahun 2001 Kelas 1 and moderately polluted based on Permenkes No. 492 Tahun 2010 about quality of drinking water.

These results show a reasonably good relationship between the level of vulnerability and the results of water quality tests, given the results of groundwater vulnerability with a moderate level of DRASTIC Index. Then it can be concluded that the results of the calculation of water quality using the Pollution Index support the results of the calculation of groundwater vulnerability using the DRASTIC method.

TABLE 12. Pollution index based on PP No. 82/2001 Kelas 1.

Area	Parameter	Standard	Ci	Ci/Ljx	Ci/Ljx
DK1	Temp.	-	29,10	-	
	DO	6	3,36	0,560	
	TSS	50	0	0	
DG2	Temp.	-	29,95	-	
	DO	6	2,49	0,415	
	TSS	50	0	0	
DK3	Temp.	-	30,84	-	
	DO	6	3,38	0,563	
	TSS	50	0	0	
DP4	Temp.	-	31,88	-	
	DO	6	5,11	0,852	
	TSS	50	0	0	
DB5	Temp.	-	29,71	-	
	DO	6	2,89	0,482	
	TSS	50	0	0	
				(Ci/Lix)R	0,287
				(Ci/Lix)M	0,852
				IPx	0,876

TABLE 13. Pollution index based on Permenkes No. 492 Tahun 2010.

Area	Parameter	Standard	Ci	Ci/Ljx	Ci/Ljx
DK1	pH	6,5-8,5	6,72	0,78	0,78
	TDS	500	1810	3,620	3,794
	Mn	0,4	1,524	3,810	3,810
	Fe	0,3	0,044	0,147	0,147
	Al	0,2	0,290	1,45	1,807
DG2	pH	6,5-8,5	7,26	0,24	0,24
	TDS	500	1570	3,14	3,485
	Mn	0,4	1,952	4,880	4,880
	Fe	0,3	0,056	0,187	0,187
	Al	0,2	0,247	1,235	1,458
DK3	pH	6,5-8,5	7,08	0,42	0,420
	TDS	500	1270	2,54	3,024
	Mn	0,4	1,190	2,975	2,975
	Fe	0,3	0,033	0,110	0,110
	Al	0,2	0,221	1,105	1,217
DP4	pH	6,5-8,5	7,2	0,3	0,300
	TDS	500	7780	15,560	6,960
	Mn	0,4	0,714	1,785	1,785
	Fe	0,3	0,009	0,030	0,030
	Al	0,2	0,178	0,890	0,747
DB5	pH	6,5-8,5	7,16	0,34	0,340
	TDS	500	826	1,652	2,090
	Mn	0,4	0,8570	2,1425	2,143
	Fe	0,3	0,0190	0,063	0,063
	Al	0,2	0,1290	0,645	0,048
				(Ci/Lix)R	1,714
				(Ci/Lix)M	6,960
				PIx	5,068

The total water consumption of residents located in the research area in two sub-districts, Jabon, and Tanggulangin Subdistricts, was obtained from interviews as shown in Table 14 as well as the concentration of selected pollutants from the well in the research area.

TABLE 14. Total water consumption of residents the concentration of the selected pollutant from the well located in the research area.

Area	Water need/people/day	Concentration (ppm)		
		Fe	Al	Mn
DK1	1,20	0,044	0,29	1,524
DG2	1,25	0,056	0,247	1,952
DK3	0,83	0,033	0,221	1,19
DP4	3,33	0,009	0,178	0,714
DB5	0,30	0,019	0,129	0,857

Based on the results of health risk analysis for the three selected metal parameters Mn, Al, and Fe, all three metals showed the same results which have THQs < 1, as shown in Table 15. It means that the metal content in the well is not indicated to be detrimental to health. If the THQs > 1, a health risk may occur if continuous exposure of Fe metal might lead to several diseases, including cirrhosis and heart failure. Al metal exposure that occurs continuously in large quantities can cause degenerative neurological diseases such as Alzheimer's, and exposure to Mn metal is feared to cause interference with iron absorption in the body. So it can be concluded that the condition of the well which is still being used, is in a condition that meets the quality standards and moderate pollution in terms of water quality determination and is not indicated to be detrimental to health even though it has been exposed for approximately 13 years.

TABLE 15. Calculation of health risk analysis based on THQs results.

Area	THQs Mn	THQs Al	THQs Fe
DK1	0,0010357	0,0388776	0,0005238
DG2	0,0009189	0,0518707	0,0006944
DK3	0,0005481	0,0210813	0,0002728
DP4	0,0017659	0,0505952	0,0002976
DB5	0,0001152	0,0054656	0,0000565

The simulation of the transport pollutant was done by using Hydrus-1D. In this research, the water flow is simulated using the advection to simulate the pollutant movement in the horizontal direction. The simulation was done by simulating node 1 to 6, which represent the area of the research area. The illustration of the nodes is shown in Fig. 4.

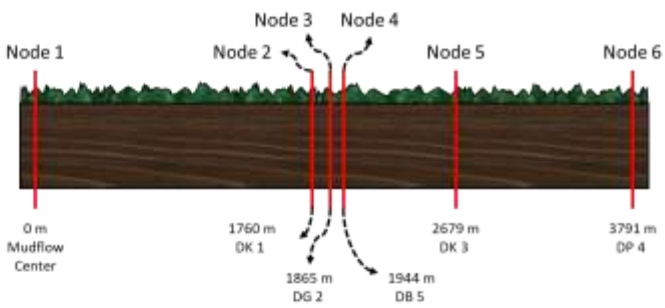

Fig. 4. Illustration of the node position is the Hydrus-1D.

Fig. 5, 6, and 7 are showing the simulation results of Mn, Al, and Fe, respectively. All three pollutants, which are Mn, Fe, and Al, show the same pattern. Based on the graph, it can be seen that the concentration is fluctuated in the center of Sidoarjo mudflow (node 1) and began to stabilize. Then the pollutants slowly move and reach node 2 in the 7th year, which is a DK1 well, which is 1760 meters away. At node 3 and node 4, which is relatively close to node 5, the time for the pollutants to arrive at this node is almost at the same time, which are at 7.5 and 8 years, respectively. Then the concentration will increase and decrease in the following years. Node 5, which is a DK3 well, located 2679 meters from the center of Sidoarjo mud, the pollutant will arrive in 11th year. Lastly, pollutant reaches node 6, which is 3791 meters in the 16th year and continues to increase its concentration to and slowly decrease. Also, at each node, the farther the node from the center of Sidoarjo mud, the maximum concentration of will slowly decrease. This is probably due to the broader coverage of nodes that are farther away from the center of the Sidoarjo mudflow, resulting in a smaller concentration of the pollutant when compared to the Sidoarjo mudflow center.

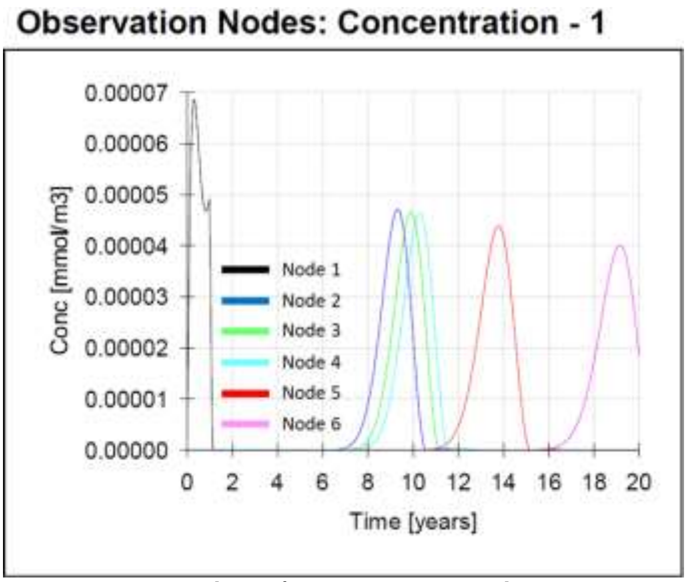

Fig. 5. Simulation of Mn movement using Hydrus-1D

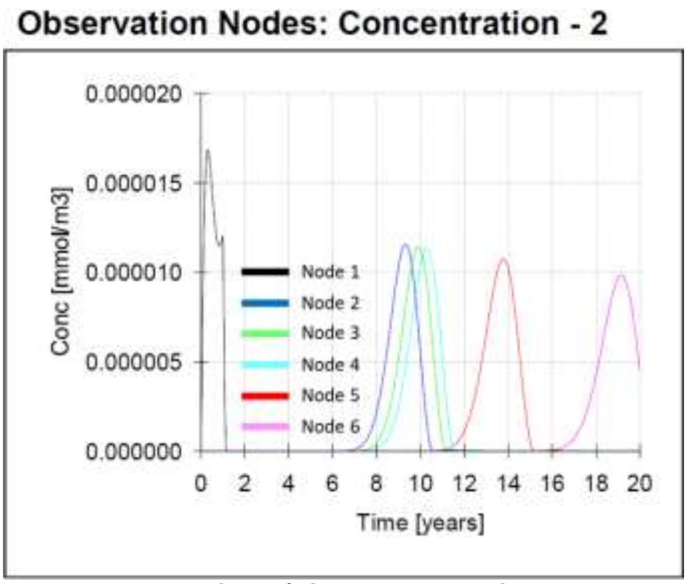

Fig. 6. Simulation of Al movement using Hydrus-1D

Based on all results, it can be concluded that the simulation results of HYDRUS-1D, pollution index, and DRASTIC are related to each other. As an example of calculation can be seen in the simulation results of HYDRUS-1D in the 13th year, the concentration results for node 5 or DK3 wells were obtained for Mn (concentration 1) metal at 1.3735 ppm, Al (concentration 2) 0.2023 ppm, and the concentration of Fe (concentration 31) 6.98 ppm. If the value is calculated using the pollution index, the value based on PP No. 82 of 2001 will meet the quality standards so that they are considered to be following the results of HYDRUS-1D. Then, for Permenkes No. 492 In 2010, the results were moderately polluted, so the results of HYDRUS-1D were considered not following IP results, this was due to the very high concentration of Fe in the simulation results compared to the analysis of the well. For conformity with the DRASTIC method, the vulnerability value for DK3 wells is more susceptible than the other wells. This indicates that the value is consistent with the pollution index value, where the pollution index is also consistent with the HYDRUS simulation results shows that the three results of this analysis are related to each other.

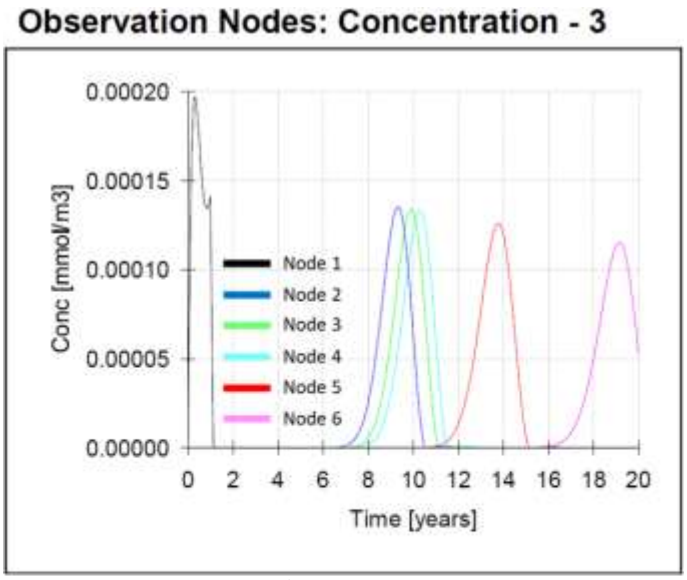

Fig. 7. Simulation of Fe movement using Hydrus-1D

IV. CONCLUSION

Based on the results of vulnerability test using DRASTIC method, pollution index, pollutant transport simulation using Hydrus-1D and calculation of health risk analysis of groundwater in Sidoarjo regency, the following conclusions are achieved:

1. Based on the DRASTIC method, the level of vulnerability around the Sidoarjo regency is medium (score: 105-110).
2. Groundwater quality test showed that the groundwater quality is to meet the quality standards and moderately polluted based on PP No. 82 Tahun 2001 Kelas 1 and Permenkes No. 492 Tahun 2010 (Indonesia Regulations), respectively.
3. Vulnerability test based on the DRASTIC method showed a consistent result with groundwater quality test using the pollution index.
4. Pollutant transport simulation using Hydrus-1D revealed that the pollutants, which are Mn, Fe, and Al, require 8 years to reach the DK1 well, which is 1760.6 m away from the center of Sidoarjo Mudflow. Also, the simulation showed a deviation between groundwater quality test and simulation. This phenomenon can be happening because of a complex soil type in the vadose zone, dilution process by rain, sampling process in the wet season, and minimum parameter input in Hydrus-1D.

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