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Mass transport modelling of total organic carbon in groundwater to determine the location of petroleum fuel pollutant sources in the area of Jlagran, Yogyakarta City, Indonesia

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Abstract. Hydrocarbon pollution in the Jlagran area's groundwater, Yogyakarta City, has been going on for more than 20 years. So far, the pollution source has been inferred from a leak in the diesel fuel storage tank from near Train Station. This study aims to prove the claim that the source of hydrocarbon pollutants comes from the location of the fuel storage tank or not. This research was conducted by collecting data on hydrogeological aspects and total organic carbon (TOC) concentration in groundwater, followed by modeling flow and mass transport using Visual Modflow MT3DMS. The modeling results show that the contamination plume distribution in groundwater at the recent time cannot be caused by only one point source, namely the fuel oil storage tank's location, but also may come from the train maintenance area. It is estimated on this area that the disposal of train maintenance waste of hydrocarbon as a result of poor practices for at least two decades has been developing a residual hydrocarbon zone in the unsaturated zone, and now potentially seeped into the aquifer and also contribute as a source of hydrocarbon pollutant to groundwater.

1. Introduction

In the year between 2000-2001, groundwater in the dug wells of residents around Jlagran and Jlagran Lor, Kapanewon Gedongtengen, Yogyakarta City, was contaminated by diesel fuel, and the contamination was at that time due to a leak in the fuel storage tank at the Train maintenance, Yogyakarta Station (see figure 1) [1]–[3]. The petroleum/hydrocarbon contamination in groundwater is a typical fuel tank leakage [4]–[6]. Diesel fuel is one type of organic carbon contaminant, which is composed of approximately 75% aliphatic hydrocarbons ($C_{10}H_{20}$ – $C_{15}H_{28}$), more or less 25% aromatic hydrocarbons (benzene, styrene), and a minor fraction of sulfur depending on crude oil source and cleaning quality [7]. The characteristics of the liquid phase organic carbon contaminants are divided into two, namely NAPL and plume. NAPL (nonaqueous-phase liquid) is a phase of organic carbon contaminants that forms its liquid phase. NAPL is divided into two types based on its density: LNAPL (light nonaqueous-phase liquid) and DNAPL (dense nonaqueous-phase liquid). LNAPL, such as fuel, has a lower density than water, so the movement of LNAPL is strongly influenced by the direction of groundwater flow [8]. On the other hand, plume is a phase of organic carbon contaminants that is dissolved in groundwater. Additional components in fuel (additive oxygenate ether) such as methyl



tertiary butyl ether (MTBE) or ethanol have a high level of solubility in water, so that some of the LNAPL phase can be dissolved. The extent of the plume coverage varies depending on the natural attenuation process. Natural attenuation is a variety of physical, chemical, or biological processes that occur naturally, reducing the mass, toxicity, mobility, volume, or concentration of contaminants in groundwater [9].

The spreading of hydrocarbon contamination plumes in the study area (see figure 1) has been studied by some researchers. It was found that the dimensions of hydrocarbon contaminant plumes are 350 m long and 270 m wide [10]. A similar study was conducted [11], and it seems that there was no significant change in the contaminant plume. The plume length was still around 338 m and 325 m wide, with the highest oil and fat concentration, reported to be 55 mg/l. Theoretically, the length of the plume condition, which tends to be constant, shows a balance between the attenuation process and the continuation of pollutant spilling. This condition certainly raises a question; if the pollutant source is a leak in a fuel storage tank where the source was stopped in the early 2000s, then the plume's levels and distribution should shrink over time. One simple way to simulate this may be done by performing numerical modeling of the mass transport, such as MT3DMS. The MT3DMS is a modular three-dimensional, multispecies solute transport model in groundwater flow systems and is intended to simulate changes in concentrations of soluble contaminants in groundwater flow systems taking into account advection, dispersion, molecular diffusion, and some essential chemical reactions, including non-linear absorption, and first-order radioactive decay or biodegradation [12]. Many researchers have carried out the application of MT3DMS for modeling hydrocarbon pollution in groundwater. MT3DMS was used to model and predict groundwater pollution due to leakage of petroleum pipes [13]. Xu et al. [14] and Colombo et al. [15] clearly states that Modflow / MT3DMS can simulate organic chemical contamination of PCE (perchloroethylene) in groundwater. On the other hand, Gao et al. [16] utilized MODFLOW / MT3DMS for modeling migration of organic pollutants in shallow groundwater conditions validated by electrical resistivity tomography results.

One of the manifestations of hydrocarbon pollution in groundwater is the increase in the level of Total Organic Carbon (TOC) concentration of groundwater [17], [18]. TOC is a parameter that describes the total concentration of organic carbon in groundwater. The average concentration of natural organic carbon in the groundwater system is only 0.7 mg/l [7]. Of course, a high TOC concentration will be associated with the presence of either natural or non-natural sources of hydrocarbons. Based on the above, in this study, the TOC level in groundwater is used as a species parameter in MODFLOW / MT3DMS to simulate whether the source of hydrocarbon pollutants in the study area is a point source or an area source.

2. Study Area

The research area is located in Gedongtengen District, Yogyakarta City, with a surface elevation ranging from 106-112 m above sea level (see figure 1). Geomorphologically, Yogyakarta is located at the foot of the volcanic landscape of Merapi Volcano. Yogyakarta City's regional stratigraphy comprises Tertiary-aged rock formations that form basement and Quaternary deposits [19]. In Tertiary rock formations, the regional geological structure in Yogyakarta is in the form of faults that form a graben morphostructure called the Yogyakarta graben and Quaternary deposits as filling material [19]. Based on the Yogyakarta sheet's geological map [20], the Quaternary deposits of Yogyakarta City are Quaternary sediments resulting from a fluvio-volcanic process known as the Young Merapi Sediment Formation. This formation is divided into the Sleman Formation and the Yogyakarta Formation [19]. In general, these two formations are composed of gravel, sand, silt, and clay deposits and form the primary aquifer in the Merapi Aquifer System [21].

There are four dominant types of lithology between the bedrock and Yogyakarta City's surface [22]. The lithology is fine sand, coarse sand, silt sand, and loamy sand, interpreted in a stratigraphic map (See figure 2). Groundwater in Yogyakarta City is part of the Merapi Aquifer System. In general, in Yogyakarta City, the groundwater level's depth is less than 20 m from the ground surface, with the regional groundwater flow direction from north to south. Local groundwater also flows out into rivers

that divide Yogyakarta city [23]. The Merapi Aquifer System's hydraulic conductivity is known to range from 9.26×10^{-6} m/s to 1.1×10^{-3} m/s, with storativity values ranging from 0.001 to 0.2 [24]. In Yogyakarta, Wijaya [11] states that the study area's permeability value ranges from 4.6×10^{-5} m/s to 8.2×10^{-4} m/s, and the average permeability value is 3.8×10^{-4} m/s. In contrast, the average aquifer porosity value in the study area is 35%. The groundwater recharge in Yogyakarta ranges from 400-600 mm/year [25]. Concerning the TOC level in groundwater in the Yogyakarta-Sleman area, Kaempfer [26] states that the initial environmental baseline conditions for TOC in groundwater in this area are 3.7 mg/l, meaning that values higher than this are categorized contaminated.

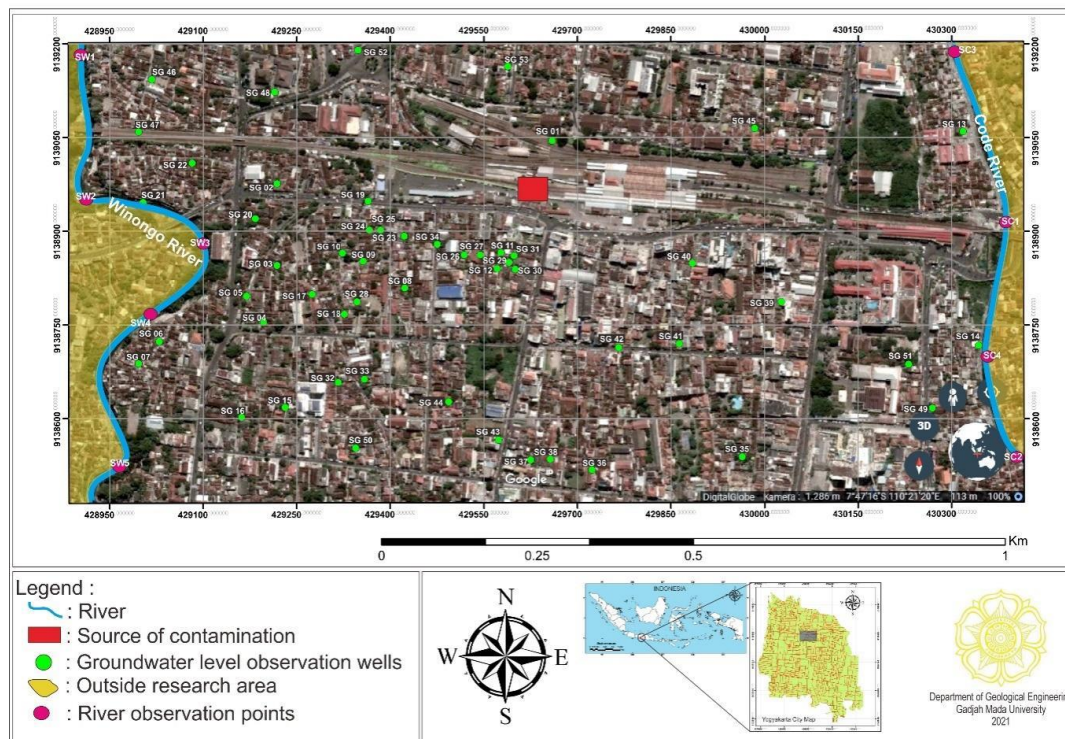


Figure 1. Study area in Yogyakarta City of Indonesia.

Based on the stratigraphic conditions shown in figure 2, in general, the aquifer unit of the study area can be divided into two main hydrostratigraphic layers; namely, the upper hydro-stratigraphic unit, which is composed of alternating layers of sandstones with loam-clay sand and lower hydrostratigraphic units composed of alternating clay sandstones with clay. The boundary between the two hydrostratigraphic layers is a layer of claystone that is assumed to be continuous. This limiting clay layer is considered as basement of the aquifer for upper hydrostratigraphic unit. It is located at a depth of 50-55 m from the ground surface. Groundwater recharge through rain enters directly into the upper hydrostratigraphic unit.

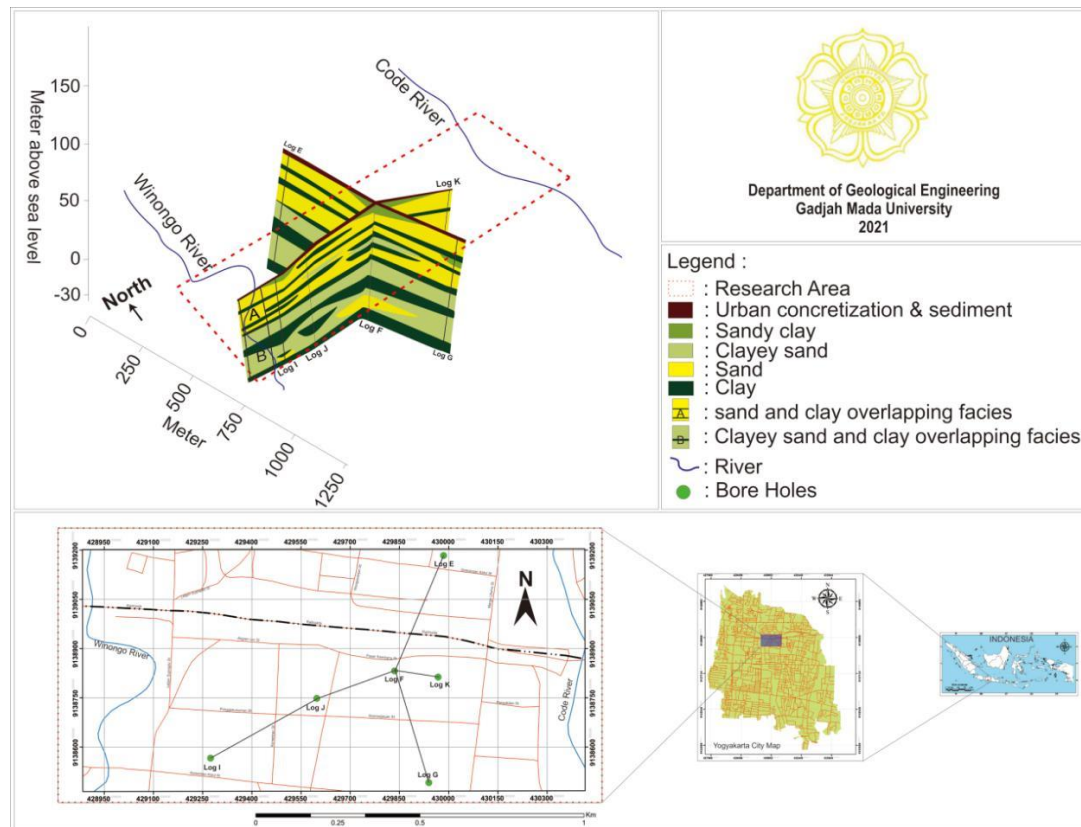


Figure 2. Fence diagram of subsurface conditions around the study area [21].

3. Methodology and Conceptual Model

3.1 Groundwater Sampling and Laboratory Works

This study aims to determine the level of TOC in groundwater as the basis for numerical modeling of groundwater pollution. In this study, TOC groundwater samples were taken and collected using dark glass bottles and stored in an icebox to keep groundwater samples associated with volatile pollutants in temperatures below room temperatures. Because the distance between the study area and the Get in Cicero laboratory is relatively close, about 6 km, groundwater samples can be analyzed immediately after being taken to the laboratory.

The tool used to analyze the TOC concentration of the groundwater sample in this study was the Vario TOC Analyzer. This tool provides measurement results in the form of TOC concentration in mg/l units. TOC standard solution (20 mg/l) is needed to calibrate the Vario TOC Analyzer tool's sensitivity, to get the accuracy of measuring TOC levels in groundwater samples. A TOC standard solution of 20 mg/l was used, obtained from a 500 mg/l dilution of the TOC standard solution that was made before analyzing groundwater samples. This 500 mg/l TOC standard solution is prepared by mixing 531.25 mg KHP (potassium hydrogen phthalate), 2206.1 mg Na_2CO_3 (sodium carbonate), 758.95 mg NaNO_3 (sodium nitrate), and 477.7 mg NH_4Cl (ammonium chloride) with ultrapure water as much as 500 ml. It is necessary to calibrate by analyzing the TOC level in the TOC standard solution (20 mg/l) that has been made. Suppose that reading the TOC level in the Vario TOC Analyzer tool against the TOC standard solution (20 mg/l) matches the TOC level (20 mg/l) in the TOC standard solution made. In that case, the Vario TOC Analyzer can be used to analyze groundwater samples that have been collected from the study area. The ultrapure water is also used to test the Vario TOC Analyzer's sensitivity to ensure that the instrument was sensitive to changes in TOC levels in the sample measurement. Ultrapure water has a TOC level of 0 mg/l. It is expected that the results of the Vario TOC Analyzer reading on the ultrapure water will show a TOC level of 0 mg/l. Suppose that reading on the results of the ultrapure water analysis is 0 mg/l. In that case, the Vario TOC analyzer

can be declared sensitive to changes in the TOC concentration in the samples can be analyzed being tested so that the collected groundwater sample. After the sensitivity test of the TOC standard solution (20 mg/l) and ultrapure water, shows the yield levels of the Vario TOC Analyzer according to the TOC levels in the standard solution (20 mg/l) and ultrapure water (0 mg/l), analyse of groundwater samples may conducted.

3.2 Numerical Model

In this study, numerical modeling of groundwater flow and mass transport was carried out only for the upper hydrostratigraphic unit using Visual Modflow and MT3DMS. The aquifer is assumed to be isotropic and homogeneous. Groundwater flow modeling was carried out at a steady-state, while mass transport was carried out transiently.

The research area with an area of 1.2 km² is discretized into 60 x 40 grid cells, where each grid cell's size is approximately 26.2 m x 19.6 m. Vertically, this model is divided into two layers, where layer 1 represents the upper hydrostratigraphic unit / unconfined aquifer and layer 2 represents the clay layer as the base of the unconfined aquifer. The hydraulic conductivity value in the hydrostratigraphic unit was applied at 3.8×10^{-4} m/s, while the limiting clay layer was 1×10^{-9} m/s. The first surface elevation layer is 120-113 masl to a depth of 49-50 masl. Furthermore, the lower level of the boundary between the shallow aquifer and the model's lower elevation limit is entered. The lower limit of this model's elevation is at an elevation of 50-55 masl, representing a continuous layer of clay.

The modeling boundary conditions applied to the model are river boundary, constant head boundary, specified flow boundary, and no-flow boundary. Input data from the river boundary were obtained from observations of the Winongo river in the western part of the study area and observations of the Code River in the eastern part of the study area. Data relating to the river boundary include river water level elevation, river sediment base elevation, river sediment thickness, and the value of the hydraulic conductivity of river sediments and river width. The river observation data are shown in Table 1. The model's constant head boundary conditions are placed on the model area's northern and southern boundaries. The constant head value was applied in the range 99-103 meters above sea level in the northern boundary. In the southern part of the model, the constant head boundary value was defined 95-100 meters above sea level. Groundwater level and groundwater flow patterns were obtained from shallow wells' elevation measurements in the study area (see Table 2 and figure 3). Recharge is applied as the specified flow boundary and has value of 500 mm/year. In contrast, the no-flow boundary was placed on the model's western and eastern boundaries as inactive cells (see figure 4).

Table 1. Observations of the Winongo and Code rivers.

Site	River stage (m)	River width (m)	The thickness of water (m)	The thickness of sediment (m)	River base elevation (m)	Type of sediment	Hydraulic conductivity of sediment*(m/s)
SW1	92	8.7	0.49	0.3	91.21	Medium sand	9×10^{-7}
SW2	90	10.8	0.19	0.11	89.7	Medium sand	9×10^{-7}
SW3	90	13.5	0.27	0.15	89.58	Medium sand	9×10^{-7}
SW4	90	10	0.94	0.25	88.81	Medium sand	9×10^{-7}
SW5	88	11.6	0.3	0.16	87.54	Medium-fine sand	2×10^{-7}
SC1	98	13	0.14	0.12	97.74	Medium-fine sand	2×10^{-7}
SC2	95	10.4	0.26	0.18	94.56	Medium-fine sand	2×10^{-7}
SC3	100	11.1	0.18	0.16	99.66	Medium-fine sand	2×10^{-7}
SC4	96	11.4	0.3	0.2	95.5	Medium sand	9×10^{-7}

SW: Winongo River, SC: Code River *K average value based on sediment grain size [27]

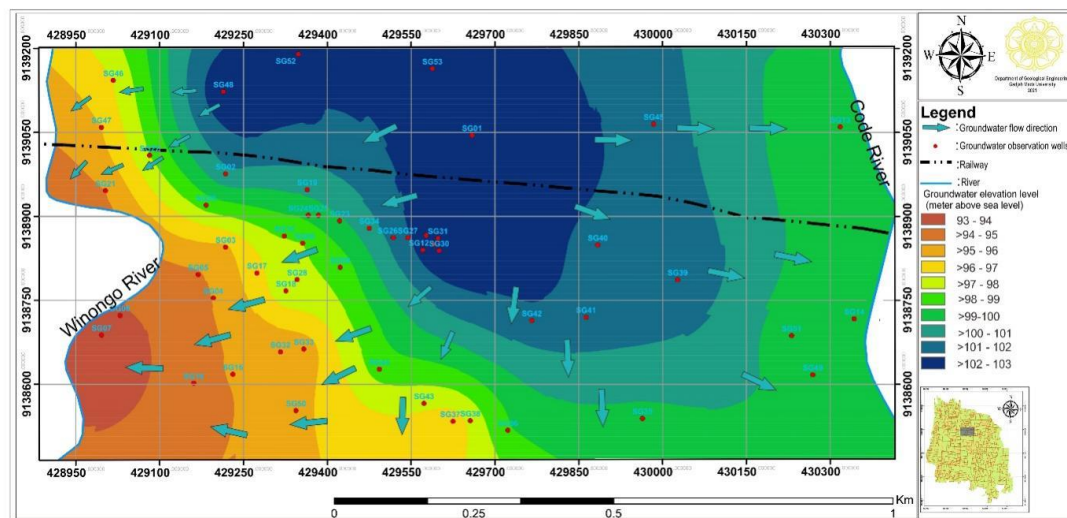


Figure 3. The contour of groundwater level and groundwater flow patterns measured in the study area.

Table 2. Observations of the depth and groundwater level in the study area.

Obs.Site	Elevation (masl)	Water table elevation (masl)	Obs.Site	Elevation (masl)	Water table elevation (masl)	Obs.Site	Elevation (masl)	Water table elevation (masl)
SG 01	115.8	102.8	SG 19	113.5	100.3	SG 37	109	96.35
SG 02	111	100.8	SG 20	107	98.45	SG 38	110	97.45
SG 03	110.5	95.8	SG 21	105	95	SG 39	114.5	102
SG 04	110	94.9	SG 22	112	98	SG 40	114	101.55
SG 05	106.9	94.9	SG 23	111	100	SG 41	114.5	101.6
SG 06	104	93.9	SG 24	111	97.3	SG 42	114	101.8
SG 07	106	93.3	SG 25	111	98.7	SG 43	113	101.8
SG 08	110	98.4	SG 26	114	103.1	SG 44	110.5	98.55
SG 09	110	98	SG 27	115	103.1	SG 45	114.5	101.5
SG 10	111	99.4	SG 28	111	97.5	SG 46	113	97
SG 11	114	102.9	SG 29	115	103.45	SG 47	111	96
SG 12	114	102	SG 30	114.95	103	SG 48	118	103
SG 13	101	99	SG 31	114	101.65	SG 49	114	100
SG 14	102.6	99.6	SG 32	108	95.2	SG 50	108	95.7
SG 15	110	95.1	SG 33	108	95.3	SG 51	114	99.4
SG 16	110	94.55	SG 34	112	100.6	SG 52	116.5	102.2
SG 17	109	95.85	SG 35	112	99.7	SG 53	115.5	102.2
SG 18	111	97.8	SG 36	111	98.9			

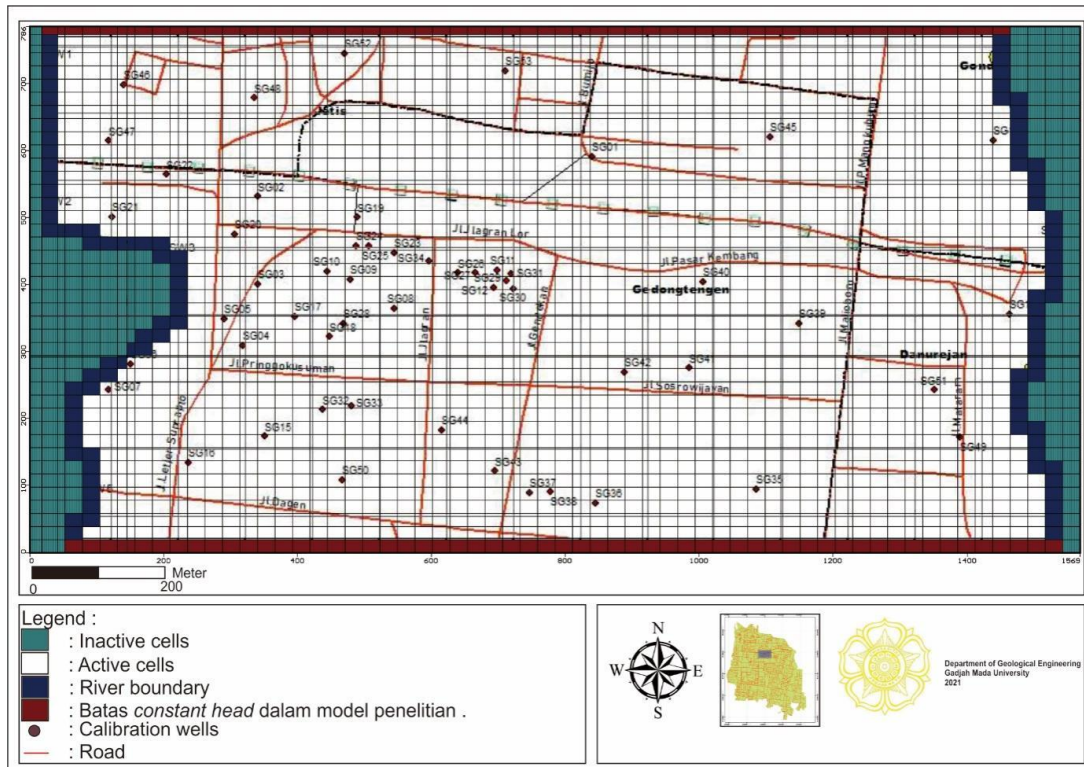


Figure 4. Boundary conditions applied to the groundwater flow model.

In the mass transport model, in addition to the input data above, data are required in the form of pollutant source points, species parameters, bulk density, dispersion, and initial concentration and particle tracking. It is known that organic pollutants undergo biodegradation, so the input data for species parameters in the form of decay value or first order of decay is required. Pollutants in the form of fuel have a half-life of decay ranging from 3-200 days with an average of 34 days [28] or converted to a decay rate around 0.02 /day. The movement of fuel pollutants in groundwater will experience sorption, which is called retardation and the influencing factor is the bulk density of aquifer material. The input bulk density in the model was 1.8 kg/cm^3 where the value is taken from the range of bulk density values for sand-sandstones between $1.6 - 2.2 \text{ kg/cm}^3$ [29]. The longitudinal dispersion coefficient value of materials similar to the aquifer material ranges from $1.31 \times 10^{-7} \text{ m}^2/\text{s}$ to $1.48 \times 10^{-5} \text{ m}^2/\text{s}$ so that the average longitudinal dispersion coefficient is $2.20 \times 10^{-6} \text{ m}^2/\text{s}$ [1]. The transverse dispersion value is assumed to be 1/10 of the longitudinal dispersion. The initial concentration of represented fuel polluting groundwater (TOC) in all model areas are considered to be 3.7 mg/l, according to the initial environmental baseline conditions of TOC of groundwater in the Yogyakarta-Sleman Groundwater Basin [26]. The initial concentration of pollutant sources is estimated to be in the range of 300 - 30000 mg/l, where the pollutant sources are in the form of fuel storage tank point and the entire train maintenance location [2]. The TOC level test was carried out using the Vario TOC Elementar tool at the GetIn-Cicero Laboratory. Data from physical observation and TOC levels in community dug wells are shown in Table 3. The TOC levels representing dissolved hydrocarbon at a depth of 1 m below the groundwater level as the LNAPL pollutants are still in their original form or their derivatives [30].

Groundwater flow model simulations were carried out in a steady-state assumption, and groundwater flow model calibrations were based on 53 groundwater level elevations obtained from field observations. The results of the calibrated model were used for transient modeling of MT3DMS mass transport in groundwater. Mass transport modeling was carried out to simulate the incidence of pollution occurring from 2000 to 2001. The time discretization was divided into 0-180 days when the leak occurred 180-8030 days when the fuel storage tank was cleaned and has been no longer used until

now. The mass transport model running was carried out in two cases. The first case was carried out when the pollutant source was determined to be the fuel storage area that leaked. Meanwhile, in the second case, the source of pollution was the train maintenance facility's entire area. The mass transport modeling calibration with TOC as its parameter was carried out only for the 2020 simulation results or 8030 days since the fuel storage tank leak occurred.

Table 3. Observation data and TOC levels in dug wells of residents in the study area.

No	Well Code	TOC (mg/l)	Description
1	SG 08	5.02	The surface is cloudy, smells like diesel
2	SG 09	5.35	Clear, no diesel smell
3	SG 10	6.28	Clear, no diesel smell
4	SG 11	25.49	Slightly cloudy, Very smelly diesel, there is some trash
5	SG 12	10.42	Cloudy, smelled a little diesel.
6	SG 19	5.89	Clear, no diesel smell
7	SG 23	9.35	Clear, a little smelling of diesel
8	SG 25	13.41	Slightly cloudy, smelled a bit diesel, not used
9	SG 26	18.10	The surface is LNAPL cake, thick & smells very badly of diesel fuel
10	SG 27	17.69	It smells of diesel fuel, is cloudy yellowish
11	SG 28	5.35	Clear, a little smelling of diesel
12	SG 29	9.42	Clear, the smell of diesel
13	SG 30	4.88	Clear, a little smelling of diesel
14	SG 31	5.97	Clear, a little smelling of diesel
15	SG 34	19.68	A little cloudy yellowish color smells of diesel fuel.

* Water samples for TOC were taken 1 m below the groundwater level

4. Results and Discussion

4.1 Groundwater flow model

The results of the calibrated steady groundwater modeling with the slightest error are shown in figure 5. The groundwater flow model calibration was performed by zoning the hydraulic conductivity parameters of layer 1 into zones with different hydraulic conductivity, as shown in figure 6. In contrast, in layer 2, the hydraulics conductivity was not changed. In the calibration process, it is known that changes in the recharge value of groundwater, either increasing or decreasing the value, cause a more significant error. Therefore the recharge value was not changed. The plotting diagram between the measured and calculated groundwater level elevation values from the calibrated groundwater flow model results is shown in figure 7. When compared between figure 3 and figure 5, it can be seen that there is a visual correspondence between these two figures, where the groundwater flow was generally divided into three flow directions, namely to the south, to the west as inflow into the Winongo River, and to the east as inflow into the Code River. The groundwater flow pattern towards the rivers shows that the two rivers are a gaining stream type. This gaining stream can be seen as seepages or springs coming out of the river wall. In several locations, the seepage/spring on the river's edge is used by the community as a water source. Based on the calibration diagram and the suitability of groundwater flow patterns with actual conditions, this calibrated groundwater flow model meets the requirements for input data in MT3DMS mass transport modeling. The result of groundwater flow modeling in this study is also in accordance to previous groundwater flow models carried out in Yogyakarta City [22], [23].

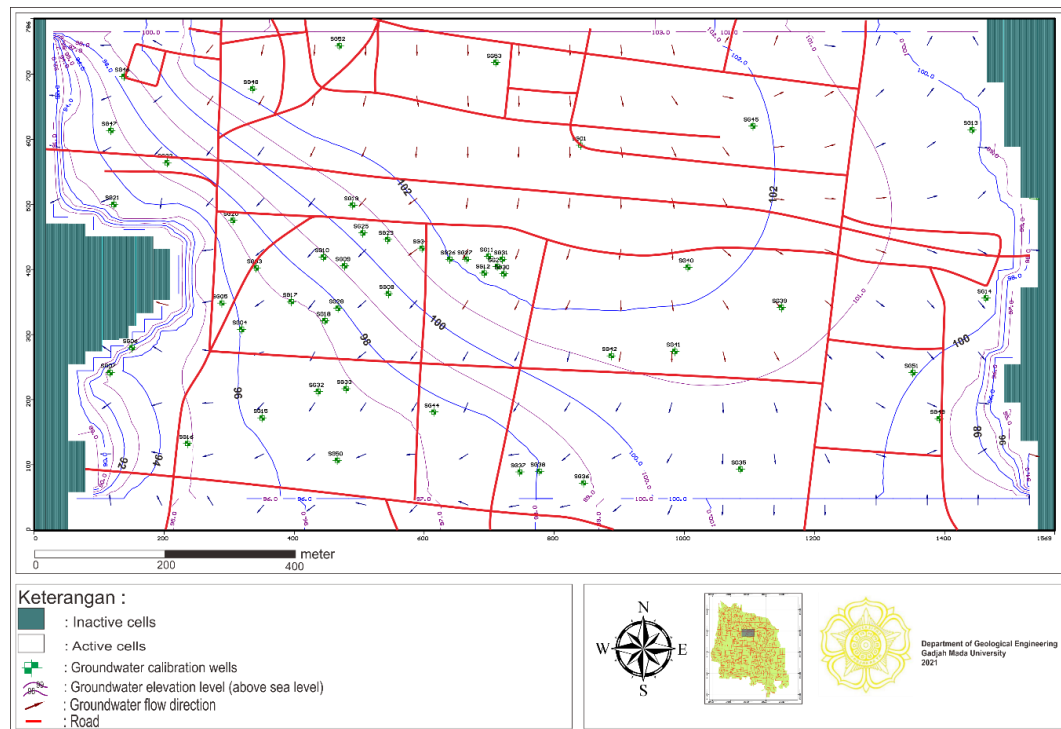


Figure 5. Calculated groundwater levels and flow patterns.

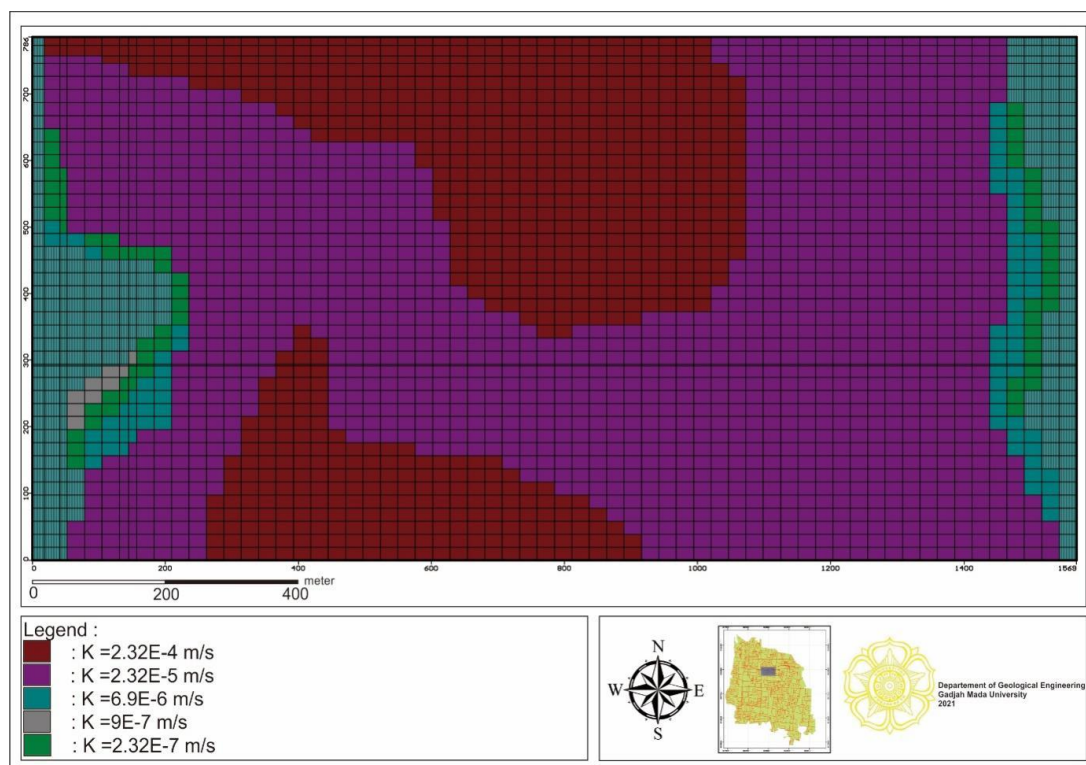


Figure 6. Zoning of hydraulic conductivity in the groundwater of flow model calibration process.

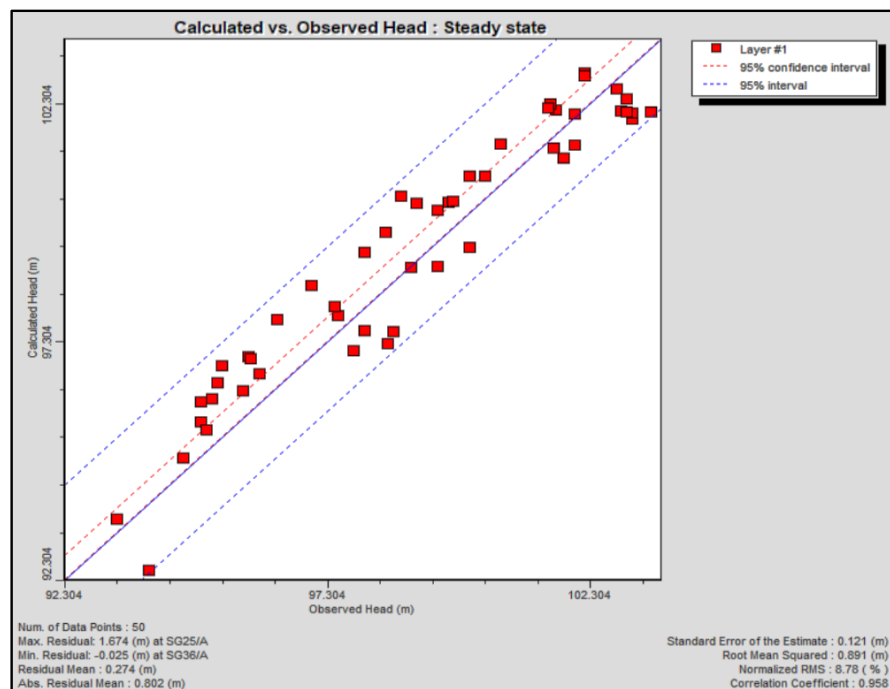


Figure 7. Calibration diagram of measured versus calculated groundwater levels.

4.2. Mass Transport Model of MT3DMS – Case 1

As explained in the methodology, the Case-1 mass transport model was carried out by entering a pollutant source in the area indicated as a fuel storage area of about 20 years ago (see figure 8) as a recharge concentration, with TOC concentration in groundwater is applied as 300 mg/l at a time interval of 0 - 180 days, but after 180 days to 20 years the pollutant source is not activated. The results of MT3DMS case 1 mass transport modeling are shown in figure 9. In figure 9, it can be seen that the pollution plume forms a plume that extends south-southwest about 200 m with a maximum plume width of approximately 70 m to the west-east. In this Case-1, it is clear that the plume of contamination in Case-1 does not affect several dug wells that are indicated to be contaminated, which are analyzed either directly or in the laboratory and have a distinctive fuel odor, turbidity and have high TOC levels such as SG08, SG09, SG10, SG23, SG28, SG29, SG30, SG31, and SG34 wells.

Despite, for the past 20 years, it has been believed and determined that the cause of groundwater fuel pollution in the study area has been only caused by leakage of subsurface fuel storage tank. The Case-1 mass transport modeling results indicate that the possible pollutant source as a point caused by a fuel storage tank leak is not quite right. The result of Case-1 was contrary to the point pollution source used by previous studies on fuel pollution in groundwater of the research area, as reported by Setyaningsih [10], Wijaya [11], and Rahman, et al. [31].

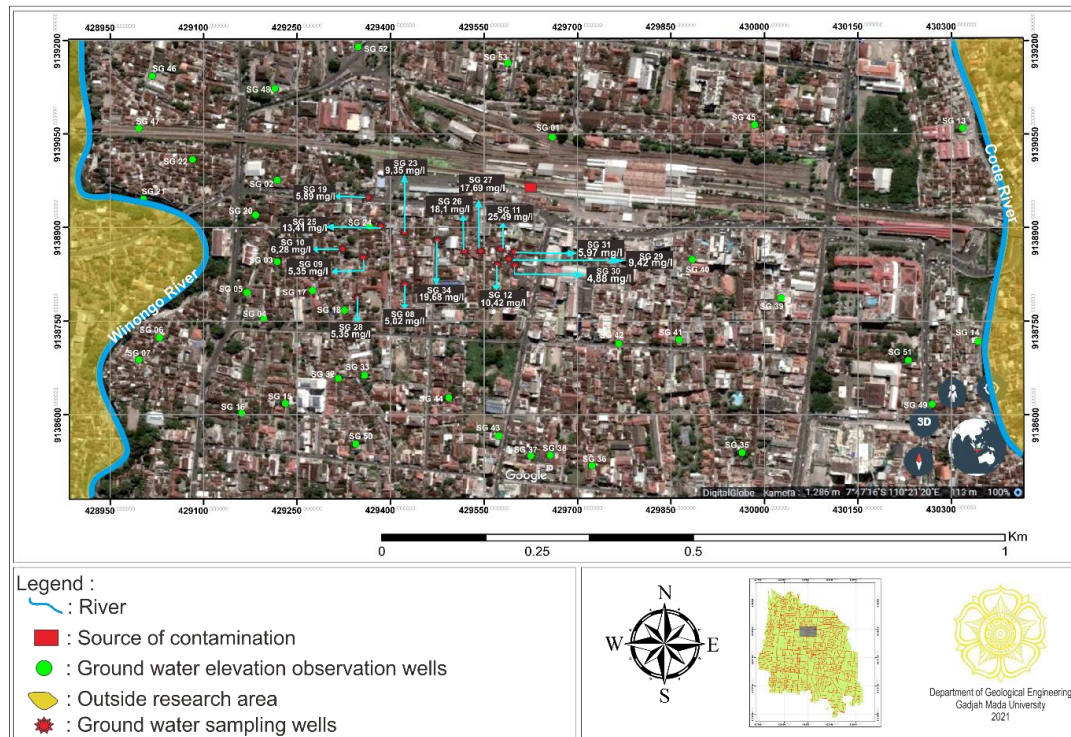


Figure 8. Estimated locations of Case-1 pollutant sources and TOC levels in observation wells.

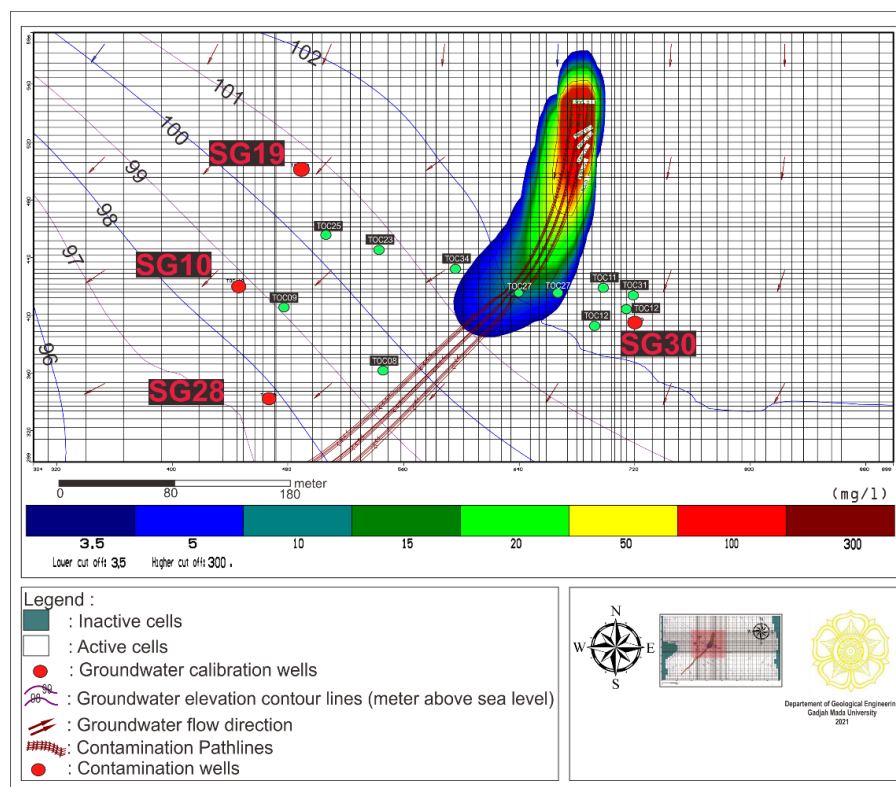


Figure 9. Modeling results of mass transport case-1.

4.3. Mass Transport Model of MT3DMS – Case 2

Based on the results of the Case-1 simulation, where the plume distribution does not match the current plume distribution, the pollutant source is thought not only from the tank leak (point source) but also from other sources. The best other probable source is the maintenance workshop area. The suspicion area was made possible by the existence of non environmentally practices in disposing of waste in the form of oil or fuel in the past 20 years. It can be seen in the results of research by Priambodo [2], which states that the distribution of TOC levels in the unsaturated zone in the train maintenance area are very high, some even exceeding 30000 mg/l levels and smells of fuel. Priambodo [2] also reports the closer to the water table, the TOC level in the unsaturated zone will decrease. In the Case-2 mass transport model, the facts above were used as the basis for allegations that the source of fuel pollutants has been the source area, as shown in figure 10.

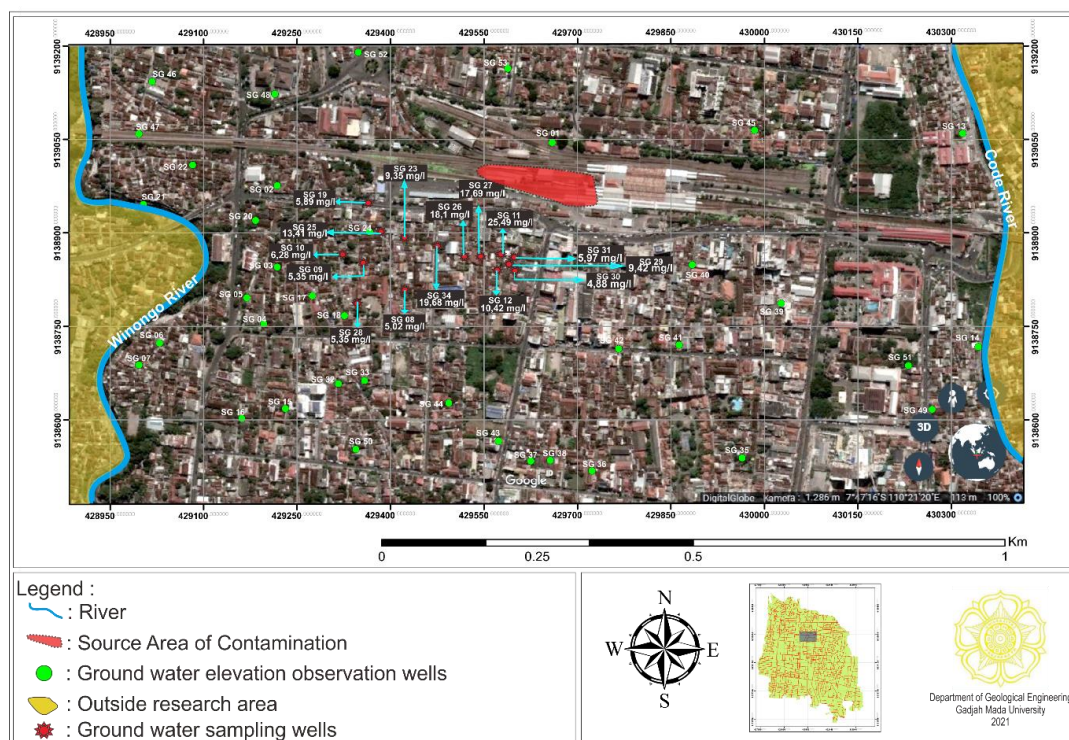


Figure 10. Estimated locations of case-2 pollutant sources.

The Case-2 mass transport model's simulation results by applying a broader pollutant source with the same concentration of 300 mg/l and the same time-division for pollution events can be seen in figure 11. Figure 11 shows that fuel pollution in groundwater is moving according to the direction of groundwater flow, where the plume moves to the south and southwest of the model area. The contamination plume is elliptical and has approximately 370 m and a maximum width of 270 m. For the calibration process, not all of the TOC sampling wells were used for calibration. Since the case of petrol contamination occurred until now, cleaning of community dug wells by pumping was carried out by PT. KAI (Indonesian Railways Company). However, the pumping time, pump discharge rate, and pumping duration to reduce pollutant levels in groundwater around the affected area are not recorded. Due to the pumping activity, the actual results of the pollutant level in most of observation wells cannot describe the actual situation. Based on the interview information obtained during field observation, only SG10, SG19, SG28, and SG30 were never been pumped so that only these four wells were used as a reference for calibrating the distribution of LNAPL pollutant plume concentrations in groundwater. The measured and calculated TOC data calibration at wells SG10,

SG19, SG28, and SG30 reveals good calibration results with a small error value and a correlation coefficient of up to 0.992 (see figure 12). The results of this Case-2 modeling prove that the source of the case of fuel pollution in groundwater in the study area does not only comes from the leakage of the fuel storage tank as a point source, but also from the entire train maintenance (area source) due to the possibility of poor waste management practices in the train maintenance in the past.

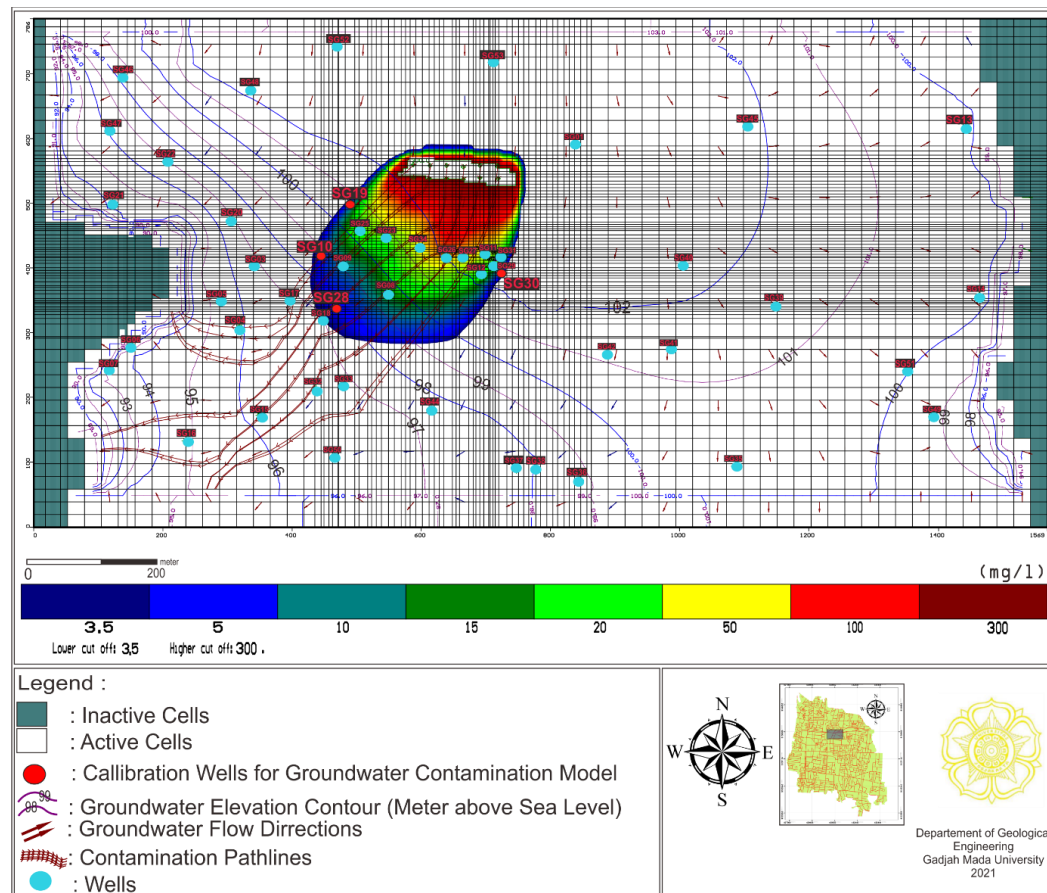


Figure 11. Mass transport modeling results of case-2.

The length and width of the pollution plume produced by the MT3DMS mass transport model are not much different from Setyaningsih [10] and Wijaya [11]. In theory, this indicates that the pollution plume has tended to be stable since 2010, which means a balance between the pollutant input (mass loading) and the pollutant attenuation process in groundwater. Concerning attenuation, in addition to natural aspects in the form of sorption and biodegradation, it may also be supported by the pumping activities of the dug wells of the affected population to clean LNAPL, which carried out so far by PT. KAI. According to PT. KAI, although the pumping is not regular, these activities have continued to be carried out since groundwater pollution occurred. Based on these findings, groundwater remediation from this fuel pollution must be carried out immediately, including remediation of the pollution plume and remediation actions for the presence of hydrocarbon residuals in the underground water-unsaturated zone of the train maintenance area.

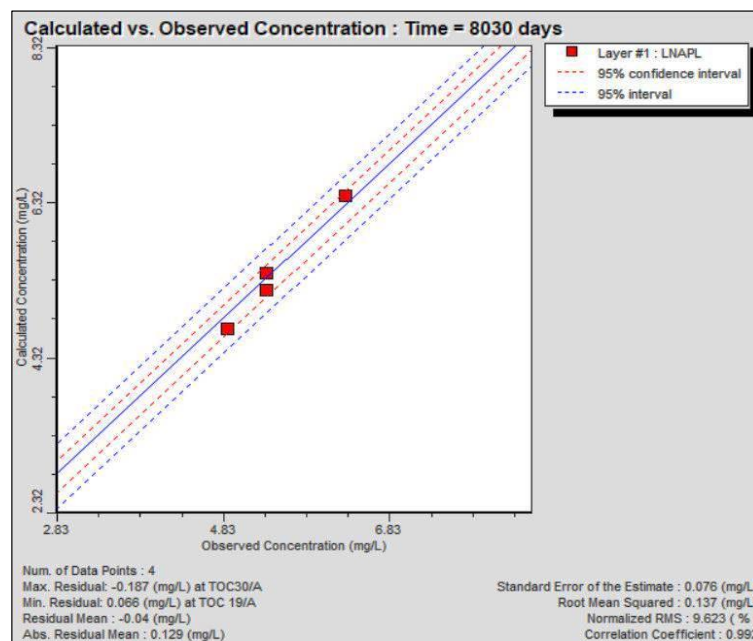


Figure 12. Calibration diagram of measured TOC concentration vs. calculated TOC concentration in the Case-2 mass transport model.

5. Conclusion

The study of mass transport modeling of fuel hydrocarbon pollution in groundwater of Jlagran, Kapanewon Gedongtengen, Yogyakarta City using TOC as the pollutant and the application of Visual Modflow / MT3DMS software can show the actual possible sources of hydrocarbon pollutant. It is already two decades that the source of pollution was believed to come from the fuel storage tank's leaks. However, the recent study proves that the train maintenance area is also the source of pollutants. In the mass transport model, the actual plume of pollution based on the TOC concentration in groundwater only matches if the pollutant source was determined as a whole area of the train maintenance area. Despite the negative findings, the modeling also contributed to non-continuous operational pumping to clean LNAPL in community dug wells carried out by the train company. Moreover, these pumping activities can reduce pollutant levels in dug wells. However, the pumping indeed has no significant effect on the spreading of the pollution plume. To accelerate the restoration of the groundwater environment in this area, active and passive remediation measures are required to reduce the length, width, and concentration of pollutants in the groundwater.

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