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PERFORMANCE OF AERMOD MODELLING OF HYDROGEN SULFIDE (H_2S) CONCENTRATION FROM GEOTHERMAL POWER PLANTS IN ULUBELU, INDONESIA, AND HELLISHEIDI-NESJAVELLIR, ICELAND

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ABSTRACT

The performance of the AERMOD model was evaluated in five cases to improve the global H_2S air quality policy. The study cases simulated geothermal emission from Ulubelu power plants in Indonesia, and Hellisheidi and Nesjavellir power plants in Iceland and made comparison with observed H_2S data. AERMOD assessed the maximum concentrations of 1-hour (odour standard), 8-hour (occupational health standard), 24-hour and annual time averages (public health standard). Overall, AERMOD performed better for a long-term period than a short-term period and where the observation data sample points were up to 3 km from the sources. When evaluating the level of H_2S concentration based on season, it is expected to be higher during winter and autumn than other seasons for Hellisheidi and Nesjavellir. In contrast, for the Ulubelu case, the predicted H_2S concentration during the dry season was forecasted higher than during the wet season. Weather conditions and weather station distance to the sources affect the results of model simulations.

1. INTRODUCTION

Geothermal energy is heat utilized from natural heat sources in the earth. The common usage of high-temperature steam is transforming it into electricity, while for low-temperature resources it is direct use for space heating. Geothermal power is considered clean energy, compared to fossil fuel, because no combustion of fuel takes place during its production, thus being a sustainable source of renewable energy and vital in combating climate change. Global energy policy aims for two-thirds of energy coming from renewable energy by 2040 to tackle GHG emission (IAE, 2018). The geothermal power in the world is expected to grow to 32 GW by 2030 (GEA, 2016). In Indonesia, through their energy policy, the government is planning to boost geothermal power portion from 1,698.5 MW as stated of 2017 to 7,242 MW by 2025 (MEMR, 2017). In Iceland, the electricity consumption is projected to increase by 2.8% every year until 2020, and at a steady rate of 2% by 2030 (MIT Energy, 2017). The GEA (2016) reported, as of 2015, Iceland planned to develop about 575 MW from geothermal resources.

The sulphur gas associated with geothermal exploration and utilization is expected to increase air pollution (Kristmannsdóttir et al., 2000). In order to manage geothermal emissions in the current and future conditions, air modelling is required by decision makers to determine the consequences of geothermal development.

There are many methods for forecasting air pollution, here AERMOD was used for the model simulations. This software is recommended by the US Environmental Protection Agency for a regulatory purpose (US EPA, 2005). In order to make decisions about establishing and reviewing regulation policy, and mitigation action from model simulations, knowing the accuracy of model prediction is necessary. For instance, making a decision based on an underestimation of a model would lead to unhealthy air pollution for the population living around the geothermal field, and even further away from the emission source. On the other hand, if a model prediction is overestimated, it results in excessively high costs of H_2S abatement for the power plant stakeholders.

This study, therefore, assessed the H_2S pollution from geothermal power plants at Ulubelu in Indonesia, and Nesjavellir and Hellisheidi in Iceland using the software AERMOD. The first aim was to evaluate the performance of the AERMOD software in predicting H_2S emissions based on observation data from Ulubelu, and H_2S measurements in Reykjavik city. Secondly, the study predicted the H_2S concentration expected in the residential area in Reykjavik and Ulubelu villages nearby geothermal site and compared the predicted H_2S level with the Icelandic H_2S legislation, Indonesia H_2S legislation, and the WHO air quality guidelines.

2. BACKGROUND

Gas emission of H_2S is one of the main environmental concern resulting from geothermal utilization (Ármannsson and Kristmannsdóttir, 1992). H_2S is a flammable, hazardous, colourless gas with a characteristic odour of rotten eggs at low concentrations ranging from 0.69 to 417 $\mu g/m^3$ (ATSDR, 2014). H_2S is slightly heavier than air, and at high levels of concentration (>560 mg/m^3), the gas is toxic, predominantly affecting the respiratory system in the human body. As such, H_2S has been classified among asphyxiate gasses (Chou, 2003).

In determining the accuracy of AERMOD model simulation, Zou et al. (2010) analysed the performance of AERMOD for various averaging periods. The 1-hour, 3-hour, 24-hour, and monthly, annual exposure times were studied to simulate the impact of an SO_2 pollutant. The results of the model for short-term exposures (1-hour and 3-hour) did not perform as well as for long-term exposures; AERMOD simulated better for a monthly averaging period or longer-term periods. Another evaluation study by Putranto (2016) modelled the H_2S and NH_3 distribution from the Kamojang geothermal power plants. The results showed the AERMOD performed quite well in determining the levels of H_2S rather than NH_3. The correlation of the predicted concentrations between the observed values and the model values for H_2S and NH_3 were 0.89 and 0.51, respectively. Furthermore, the study highlighted that weather conditions influenced the outcome of simulation of H_2S concentrations, with the wet season values 76.26 $\mu g/m^3$, compared to lower H_2S concentrations during the dry season, 38.18 $\mu g/m^3$.

3. DESCRIPTION OF WORK

3.1 Power plant descriptions

Pertamina Geothermal Energy (PGE) supplies geothermal steam to Ulubelu power plant (Unit-1 is 55 MW) run by Indonesia Power (IP – subsidiary electricity state-owned company in Indonesia) since September 2012, followed by the 2nd unit (55 MW) on October 24th. 2012. The power plant for Unit-3 (55 MW) is operated by PGE since 2016, while power plant Unit-4 (55 MW) commercial operation began in March, 2017 (Pertamina Geothermal Energy, 2015). Ulubelu geothermal area is located in Ulubelu Regency, Lampung Province. The nearest Ulubelu villages are located as close as 6 km from the power plants.

The Reykjavík Energy operates the Hellisheidi and Nesjavellir power plants. The Nesjavellir power plant generates electricity with an installed capacity of 120 MWe; two turbines were installed in 1998 (2x30 MWe installed capacity). The third and fourth turbines (2x30 MWe) were added in 2001 and

2005, respectively. Nesjavellir power plant supplies 290 MWth for district heating in Reykjavik since 2005. The Hellisheidi power plant produces 303 MWe, and 133 MWth. It was commissioned in five stages during 2006-2011. The first and second turbines (2x45 MWe) went into operation in 2006. The third low-temperature power plant (33 MWe) started production in 2007. Two other geothermal power plants (each 2x45 MWe) were added in 2008 and 2011. The hot water production started in 2010 with a 133 MWth (Gunnarsson et al., 2013). The direction and distance to inhabited areas in Hveragerdi town and Reykjavik city from the power plants are S58°E /±10 km and N40-90°W / ±35km, respectively.

3.2 Air dispersion modelling software and model performance

Various methods were carried out for the model simulation and the evaluated model performance. In this study, to analyse the model performance, the Taylor diagram was used to assess the level accuracy of the model by comparing the predicted concentration and the observed H_2S monitoring. Three statistics parameters describe the performance: correlation coefficient (R), standard deviations (SD), and the root mean square error (RMSE) (Taylor, 2001). The results are important, since they can aid to evaluate the model performance in regulating and reviewing air quality guidelines, such as the scenario of predicting H_2S concentration based on a 1-hour (odour nuisance), 8-hour (occupational health), 24-hour and annual average (public health). Table 1 summarises descriptions of the model performance and the main simulation

TABLE 1: Input data in the software AERMOD and H_2S observation data

A. Ulubelu
1. Model performance: the input values for the Taylor diagram of test case A.1 were simulated by AERMOD with 8-hour and 24-hour averages; the input values for the model performance of A.2 based on model run for 24-hour average only. The input values were normalised to compare the different data sets of A.1 and A.2. The sampling data were taken 28–31 August 2017. The sampling points were up to 3 km from the source in Mekarsari, Ngarip and Karang rejo villages. It should be noted that observed data of UBL cases were limited.
2. Main simulation: flat and elevated option, rural, 1-year of Ulubelu and Lampung met. stations (August 2016-August 2017), H_2S flow rate units 1 and 2 (21.05 g/s) and Unit 3 and 4 (16.57 and 21.35 g/s), no background H_2S concentration input, highlighted on the dry season as indicated by higher concentrations.
B. Hellisheidi and Nesjavellir
1. Model performance: H_2S observation data obtained from the Grensásvegur, Hvaleyrarholt, and Nordlingaholt stations, 35 km from the source, on 1st March 2017 and 9th November 2015 (B.1 and B.2) and yearly period of 2012-2016 (B.3)
2. Main simulation: flat, urban, 5-years met data of Straumsvík, Reykjavík, and Hellisheidi stations (2012-Sept. 2017), the H_2S flow of Hellisheidi (540 g/s) and Nesjavellir (358 g/s), emphasis was on winter season and time averages of 24-hour and annual, the background concentration was not considered for the model simulation.

4. RESULTS

Five test cases were studied for analysing the performance of AERMOD. The results from the models were compared to the H_2S observation data. Other model simulations were examined to evaluate the results with the WHO air quality guideline and H_2S legislation on public and occupational health. Table 2 provides a summary of the model performance for Ulubelu (UBL cases; Table 2.A.1 and A.2), Hellisheidi, and Nesjavellir (HEL-NES cases; Table 2.B.1 to B.3).

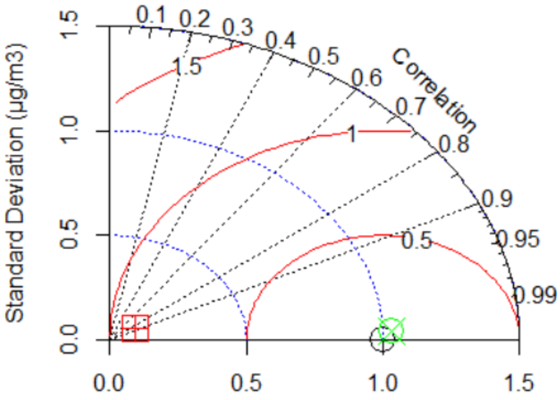

FIGURE 1: Model performance of Ulubelu cases

Figure 1 provides the Taylor diagram showing the

TABLE 2: Summary of model performances from the emission of Ulubelu, Hellisheidi and Nesjavellir power plants

Test cases	**Results of the models (µg/m³)**			
	R	**SD modelled**	**SD Observed**	**RMSE**
A. Ulubelu				
A.1. 8-hour and 24-hour averages	UBL 0.85	UBL 0.11*	10.91*	UBL 0.79*
A.2. 24-hour averages	UBL 0.99	UBL 1.03*	0.81*	UBL 0.044*
B. Hellisheidi and Nesjavellir				
B.1. 1-hour averages	RYKJ 0.28, STRM 0.44, HELS -0.47	RYKJ 5.05, STRM 7.39, HELS 6.44	29.57	RYKJ 28.37, STRM 27, HELS 30.52,
B.2. 24-hour averages	RYKJ 0.52, STRM 0.52, HELS -0.10	RYKJ 1.75, STRM 1.73, HELS 0.56	23.74	RYKJ 20.89, STRM 20.90, HELS 21.73
B.3. Annual averages	RYKJ 0.52, STRM 0.52, HELS 0.59	RYKJ 0.51, STRM 0.51, HELS 0.22	1.73	RYKJ 1.45, STRM 1.45, HELS 1.52

RYKJ = Reykjavik Metrological Station, STRM = Straumsvík Metrological Station,
HELS = Hellisheidi Metrological Station, UBL = Ulubelu Metrological Station, *normalised data

the model performance of A.1 (red square plus), A.2 (green circle cross), and observation values (circle). Table 2 shows that the model worked better for A.2 than A.1. The results of the model were good when the values of correlation were high, and the RMSE values were low (i.e. low error) (Harrison, 2014). In other words, the A.2 test case (green circle cross) fitted the observation data better as it was closer to the observed point (circle) (Figure 1). The correlations for the UBL case (A.1 0.85 and A.2 0.99) were classified very strong (0.8-1.0) (Evans, 1996), and the RMSE value of A.2 (0.044) was a lower error than A.1 (0.79). Furthermore, the SD of A.2 (1.03) was closer with the observed value (0.81).

Other test cases, B.1 to B.3, were assessed for HEL-NES. The results of the model for 1-hour, 24-hour and annual average periods were compared to the H_2S observation stations located in Reykjavik. Figure 2 plots test cases B.1 (green star), B.2 (red solid circle), B.3 (triangle), and the observation data (circle) simulated with STRM, HELS, RYKJ data.

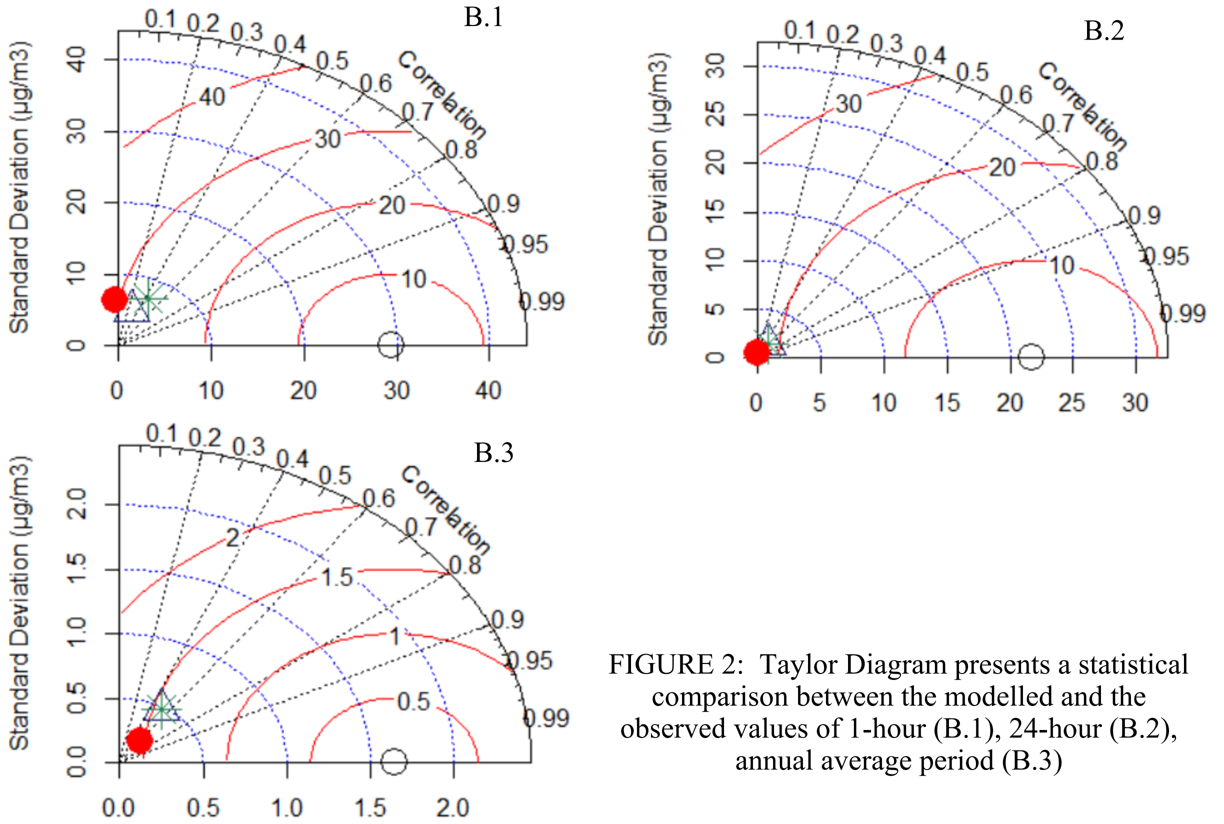

FIGURE 2: Taylor Diagram presents a statistical comparison between the modelled and the observed values of 1-hour (B.1), 24-hour (B.2), annual average period (B.3)

Unlike the UBL cases, the test cases of NES-HEL indicated that AERMOD underestimated the predicted H_2S concentrations. Figure 2 shows that the test cases were not close to the observation point. Despite that, test cases B.2 and B.3 performed well compared to the performance of B.1 (Table 2).

AERMOD recommends using site-specific meteorological data (US EPA, 2016). In the UBL case, the model worked well to predict the H_2S concentrations with distances up to 3 km. In contrast, for the NES-HEL case, the aim was to predict the H_2S concentration at receptors in Reykjavik city, simulated by site-specific meteorology (Hellisheidi weather station). As a result, the model accuracy did not perform well (R of 1-hr average -0.47, and R of 24-hr average -0.10) (Table 2.B.). On the other hand, when the model simulations were based on Reykjavik met station (35 km away from the emission sources), the model performance worked better (R of 1-hr average 0.28, and R of 24-hr average 0.52) (Table 2.B). This indicates that AERMOD does not work well to predict long-distance simulation when it uses site-specific meteorological data. The model simulation using STRM data showed similar performance of as with RYKJ. Both met stations are located in Reykjavik city.

The main goal for the simulation by AERMOD in the UBL cases and HEL-NES cases was to compare the predicted concentrations with the WHO air quality guidelines and the Icelandic H_2S legislation on public health. In this paper, only the highest predicted levels for the UBL cases (dry season), and HEL-NES cases (winter season) are shown. The model was aimed at residential areas and public facilities.

Figure 3 presents the model simulations of the UBL cases, which did not exceed the Indonesian occupational health limits (1400 $\mu g/m^3$ for 8-hour average) (Figure 3b), and the WHO air quality guidelines (150 $\mu g/m^3$ for 24-hour average) (Figure 3c). However, the predicted concentration at 2.7 km west of the emission sources, when compared with the Icelandic H_2S legislation, some locations

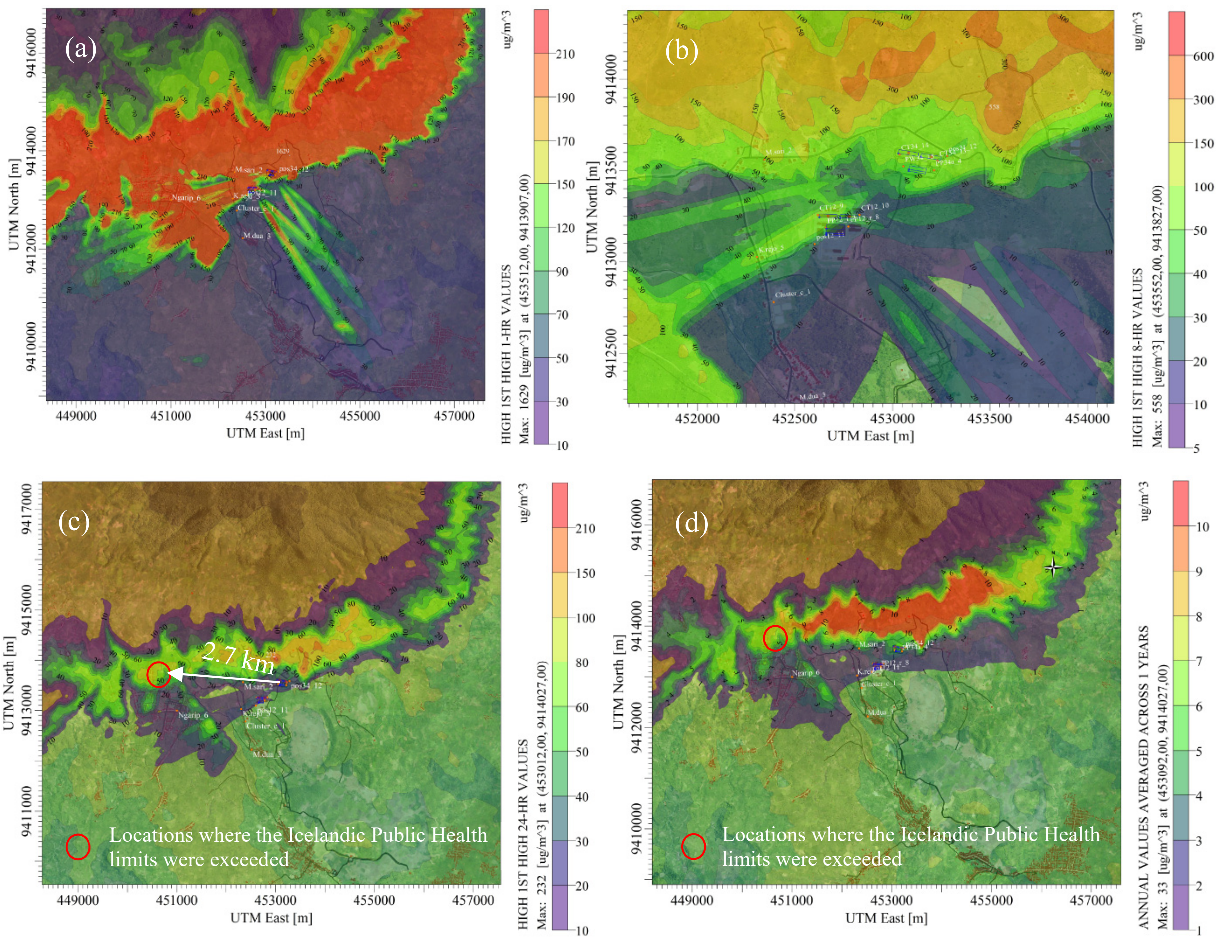

FIGURE 3 : The UBL case model simulation for a 1-hour (a), 8-hour (b), 24-hour (c) and annual average periods (d) during the dry season

(indicated with a red circle) exceeded the limits (50 µg/m^3 for 24-hour average and 5 µg/m^3 for annual average) (Figures 3c and 3d). Based on the previous discussion on model performance (Table 2), AERMOD did not perform well for modelling the odour nuisance (1-hour average); therefore, the time period of 1-hour was excluded in this evaluation. However, it is emphasized that special odour limits for geothermal fields have not been regulated in Indonesia and Iceland. For HEL-NES case, Figure 4 presents the model simulation using the Reykjavik met station (10-20 µg/m^3 for 24-hour average) (Figure 4a) and shows a higher predicted concentration for Reykjavik city than simulated for Hellisheidi met station (0-10 µg/m^3 for 24-hour average) (Figure 4b). In contrast, when using Hellisheidi met station it showed higher predicted levels near the emission sources (Figure 4b and 5b). However, the model simulation using the Reykjavik met station indicated that at the Waldorf School it is expected to exceed the annual limit of 5 µg/m^3. The school is located about 13 km north of the west side of the Hellisheidi power plant (red circle in Figure 5a). The different simulation results of the UBL, HEL, NES cases indicates that it is affected by weather conditions at each geothermal field.

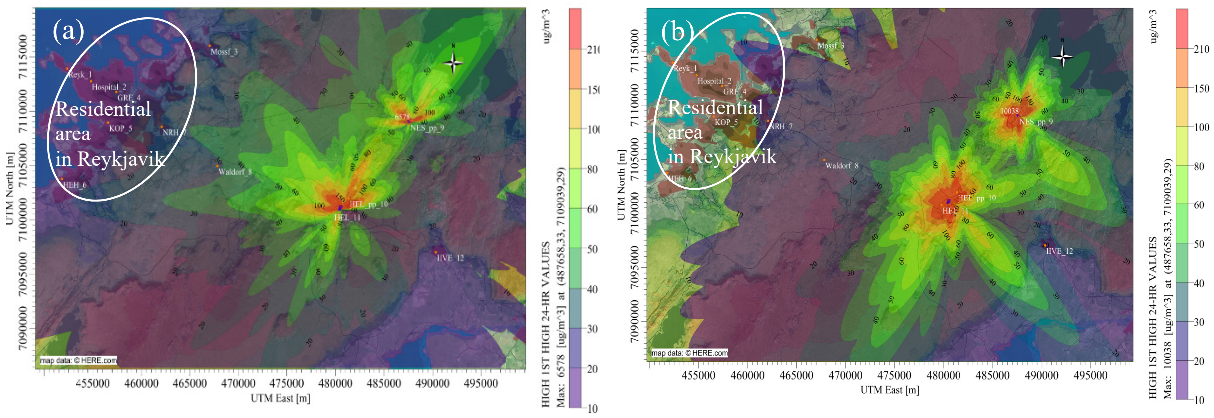

FIGURE 4 : The model for 24-hour simulated by Reykjavik met station (a) and Hellisheidi met station (b)

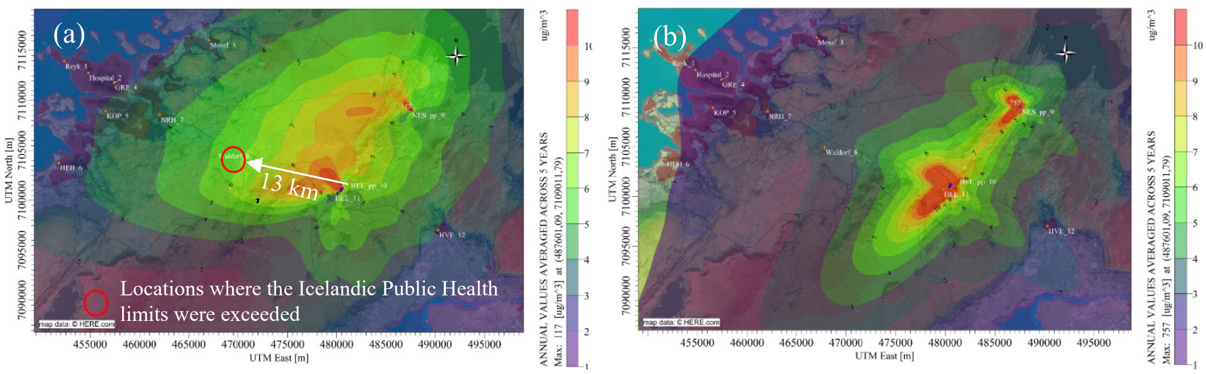

FIGURE 5: The model for annual averages simulated by Reykjavik met station (a) and Hellisheidi met station (b)

5. CONCLUSIONS AND RECOMMENDATIONS

Five cases of model performance and model simulations for emissions from the Ulubelu power plants (Indonesia), and Hellisheidi, and Nesjavellir power plants (Iceland) have been assessed. Looking at the model accuracy, which considers various average periods, the annual period worked well compared to the short-term period of 1-hour and 8-hour, and 24-hour averages. In this case, AERMOD tends to predict the H_2S concentration better for a long-term periods rather than short-term periods except for the 24-hour averages in the UBL case. The distance of the receptors and met stations, and also weather conditions affect the model simulation. Given the sample size, the study for UBL case is limited, ground monitoring of H_2S for short term periods (24-hour) and long-term periods (annual averages) are required to evaluate the impact of emission.

In this research, the results of model simulations indicate increasing level of H_2S concentration around the emission sources in both countries. In the UBL case, the closest residential area is located nearby the power plants (600 m). Neither Iceland nor Indonesia have legislation specifically for odour standard for geothermal fields. Furthermore, Indonesia has not developed a H_2S public health legislation. Looking at the energy policy, the geothermal power generation will grow significantly in the future, especially in Indonesia. Hence, the potential increase of H_2S levels must be considered, and mitigation of the H_2S impact on public health become compulsory. The approach can be done by integrating the policy of an Environmental Impact Assessment (Government project approval prior to the project commencement) together with H_2S air pollution guidelines, and with continued monitoring during operational activity. An evaluation of the methods is also recommended, which considers the performance of the model in the proposed H_2S air pollution guidelines. This paper is expected to act as a baseline study for replication, which combines the multi-disciplinary approach of *engineering,* i.e. environmental aspects of geothermal power plant construction and operation; *geoscience,* i.e. subsurface studies of reservoirs; and *social aspects,* i.e. public health studies.

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REFERENCES

ATSDR., 2014: *Public health statement: Hydrogen Sulfide.* Agency for Toxic Substances and Disease Registry, Atlanta.

Ármannsson, H., and Kristmannsdóttir, H., 1992: Geothermal environmental impact. *Geothermics*, *21-5/6*, 869–880.

Chou, C.H., 2003: *Hydrogen sulfide: human health aspects*. World Health Organization, Geneva, website: *apps.who.int//iris/handle/10665/42638*

Evans, J.D., 1996: S*traightforward statistics for the behavioral sciences*. Cole Publishing, Pacific Grove, CA.

GEA, 2016: *2016 Annual U.S. & global geothermal power production report.* Geothermal Energy Association, Washington, website : *geo-energy.org/reports/2016.*

Gunnarsson, I., Aradóttir, E.S., Sigfússon, B., Gunnlaugsson, E., and Júlíusson, B.M., 2013: Geothermal gas emission from Hellisheidi and Nesjavellir power plants, Iceland. *Geothermal Resource Council, Trans.*, *37*, 785–789.

Harrison, R.M., 2014: *Pollution; causes, effects and control* (5th ed.). RSC Publishing. Birmingham.

IAE, 2018: *World energy outlook 2017*. International Energy Agency, Paris, website:

www.iea.org/weo2017/.

Kristmannsdóttir, H., Sigurgeirsson, M., Ármannsson, H., Hjartarson, H., Ólafsson, M., 2000: Sulfur gas emissions from geothermal power plants in Iceland. *Geothermics*, *29*, 525–538.

MEMR, 2017: *Potensi Panas Bumi Indonesia Jilid 1 (in Bahasa).* Ministry of Energy and Mineral Resources of the Republic Indonesia, Jakarta, website: *ebtke.esdm.go.id/post/2017/.*

MIT Energy, 2017: *Electricity security of supply in Iceland; An assessment about how to achieve electricity security of supply by 2020 and 2030 in the most economical way*, MIT Energy, Cambridge, website: *www.os.is.*

Pertamina Geothermal Energy., 2015: *Annual integrated report.* PGE, Jakarta, website: *pge.pertamina.com/laporan-tahunan.aspx.*

Putranto, A.D., 2016: *H_2S and NH_3 dispersion analysis from geothermal power plants emission and its influence to ambient air quality (case study: PT. Pertamina Geothermal Energy Area Kamojang)*. Institut Teknologi Bandung (ITB), Bandung, 113 pp.

Taylor, K.E., 2001: Summarizing Multiple aspects of model performance in a single diagram. *Journal of Geophysical Research, 106-D.7,* 7183-7192.

US EPA, 2005: *Environmental revision to the guideline on air quality models: adoption of a preferred general purpose (flat and complex terrain)*. US Environmental Protection Agency, North Carolina, website: *www.federalregister.gov/*

US EPA, 2016: *AERMOD implementation guide*. US Environmental Protection Agency, North Carolina, website: *www3.epa.gov/ttn/scram/models/aermod/*

Zou, B., Zhan, F.B., Wilson, J.G., and Zeng, Y., 2010: Performance of AERMOD at different time scales. *Simulation Modelling Practice and Theory*, *5-18*, 612–623.