



GAUSSIAN MODELLING OF THE DISPERSION OF HYDROGEN SULPHIDE FROM HELLISHEIDI POWER PLANT, ICELAND

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ABSTRACT

Hydrogen sulphide is a colourless, toxic gas naturally present in geothermal fields. When released to the atmosphere it can be a nuisance at low concentrations, but toxic at higher concentrations when it becomes non-detectable by humans. The exploitation of natural geothermal fields for energy production, such as Hellisheidi in Iceland, increases hydrogen sulphide emissions to the atmosphere and can reduce the air quality of surrounding areas. Since Hellisheidi power plant opened in October 2006, hydrogen sulphide emissions have doubled in the area from 0.007 ppm to 0.014 ppm; this increase is thought to have affected air-quality in Reykjavík. Monitoring of hydrogen sulphide levels in Reykjavík showed episodes of increased concentrations before the opening of the power plant, and later registered up to 0.09 ppm on September 4, 2006, and up to 0.11 ppm on February 7, 2007. These increases coincided with the bleeding and testing of wells, low air temperatures, high wind-speed and a southeasterly wind direction in February. The Gaussian models of the plume of dispersion revealed that the concentrations emitted by the power plant in three different periods (October 2006, November 2006 and February 2007) were reduced to 1 ppm when dispersed, and only in special weather conditions or in connection with anomalies at the power plant, was the air quality in Reykjavík affected. Given plans to intensify power production at Hellisheidi, it is recommended that hydrogen sulphide levels are monitored closely in the region, as expansion of the plant could lead to emissions that might affect air-quality in Reykjavík and the surrounding regions.

1. INTRODUCTION

1.1 Geothermal utilization in Iceland

Iceland is located in a unique position over the Mid-Atlantic Ridge, allowing access to a vast supply of geothermal resources. Since the 1930s, when the first district heating system was started in Reykjavík (Thórhallsson, 1988), the country has been developing and exploiting its geothermal resources for energy and heating consumption. Iceland's renewable resources represent 74% of all its energy production, of which 18% is derived from hydro-electric power and 54% from geothermal sources (Björnsson, 2006).

In Iceland, increased utilization of geothermal resources has reduced the emissions of greenhouse gases (GHG), in comparison to emissions resulting from the use of fossil fuels. However, the exploitation of geothermal resources generates greater emissions of geothermal gases than are emitted naturally in geothermal fields before exploitation. When released into the atmosphere, these gases, mainly carbon dioxide and hydrogen sulphide, disperse and react with other elements. At high concentrations, hydrogen sulphide is a toxic gas, capable of varying degrees of damage to the eyes and respiratory system (WHO, 2003). Hydrogen sulphide can accumulate in low-lying areas such as cellars and basements, and it can be imperceptible at lethal concentrations (Hunt, 2001). Close to geothermal power plants, concentrated emissions of hydrogen sulphide are possible. Given that some power plants are located near populated regions, it is essential to monitor and control the levels of hydrogen-sulphide release.

1.2 Environmental impact and health effects of hydrogen sulphide emission

The World Health Organization (WHO, 2003) defines hydrogen sulphide (Appendix I) as a colourless, flammable, poisonous gas that smells like rotten eggs, and is soluble in water and organic solvents. It corrodes metals and can be formed under conditions of deficient oxygen, in the presence of organic material and sulphate. When dissolved, it is oxidised to sulphur or sulphate ion in the presence of oxygen or other oxidizing agents; it may also evaporate easily from water, depending on temperature and pH. Most atmospheric hydrogen sulphide has natural origins in decaying organic matter, sulphur springs and lakes, and is an air contaminant in geothermal regions such as Iceland. At industrial levels, it is emitted during the extraction of natural gas and oil, and energy generation in geothermal power plants and paper industries.

When hydrogen sulphide is discharged into the atmosphere, it is likely to remain there for less than one day (Hill, 1973) but it may persist for as long as 42 days during wintertime (Bottenheim and Strausz, 1980). Once in the atmosphere, the gas may partition to surface waters, groundwater, or moist soils and subsequently travel great distances. In addition, absorption of hydrogen sulphide from air into soils (Cihacek and Bremner, 1993) and plant foliage may occur (De Kok et al., 1988), retaining most of it in the form of elemental sulphur (Cihacek & Bremner, 1993). It may have significant effects on the climate in the vicinity of the power station, depending on the topography, rainfall, and wind patterns; under certain conditions there may be increased fog, cloud or rainfall (Hunt, 2001). Its impact on land use depends on the type of development, and the original use of the land.

In humans, hydrogen sulphide is unlikely to bio-concentrate in the food-chain because it is excreted through the urine, intestines and expired air (WHO, 2003). However, it can be a nuisance at very low concentrations of about 0.3 ppm; and as the concentration increases, it may irritate and injure the eyes (10 ppm), the membranes of the upper respiratory tracts (50-100 ppm), and lead to loss of smell (150 ppm). Because higher concentrations are not detectable, exposure could lead to death by asphyxia at levels exceeding 700 ppm (Webster, 1995).

1.3 Previous research

Because of its potentially hazardous effects on human beings, the surrounding environment, and electronic equipment, hydrogen sulphide is a great concern in geothermal industry. Therefore, energy companies are greatly interested in reducing emissions of hydrogen sulphide. This has promoted studies and research projects regarding its characteristics and concentrations when discharged into the atmosphere, risks of exposure, and impacts on human health and the environment.

Some of these studies have developed methods for studying hydrogen sulphide emissions and the dispersal of such gases. Scientific work on gas dispersion is extensive, dating back to the 1930s; this

research was stimulated by increased environmental control regulations. Many computer programs have been created to calculate the dispersal of air pollutants that have been called “air dispersion models”; these simulations are based on Gaussian modelling of a continuous, buoyant plume of air.

Air dispersion studies have taken place at numerous locations where hydrogen-sulphide emissions have been monitored and the resulting dispersion plume modelled; for instance: in the Imperial Valley in California (Gudiksen, 1979); in Cerro Prieto in Mexico (Gallegos-Ortega et al., 2000); and in Rotorua, New Zealand (Horwell et al., 2004). In Iceland, studies of hydrogen-sulphide dispersion have been made at Svartsengi (Kollikho, 1998), at Nesjavellir (Gíslason, 2000), and at Nesjavellir by Nyagah (2006). In June 2007, following the development of the Hellisheidi power-plant, Ólafsdóttir (2007) found a connection between emissions of hydrogen sulphide at Hellisheidi and periods of reduced air quality within Reykjavík, located 30 km southwest of the power plant.

1.4 Aims and objectives

The increased production of geothermal energy in the area surrounding Reykjavík due to the construction and development of the Hellisheidi power plant, contributes to the emission of hydrogen sulphide to the atmosphere (Ármannsson, 2002). Therefore, it is important to consider if geothermal emissions from the power plant affect the city of Reykjavík. Consequently, the goal of this project is to assess the air dispersion plume of hydrogen sulphide from the Hellisheidi power plant area (Figure 1), and to evaluate whether such plumes affect air quality in the Reykjavík area. The results of this study are based on a hydrogen sulphide dispersion model for the Hellisheidi power plant and the associated analysis of variations of hydrogen sulphide concentrations in the Hellisheidi area and Reykjavík area during the periods before and after the power plant began to operate.

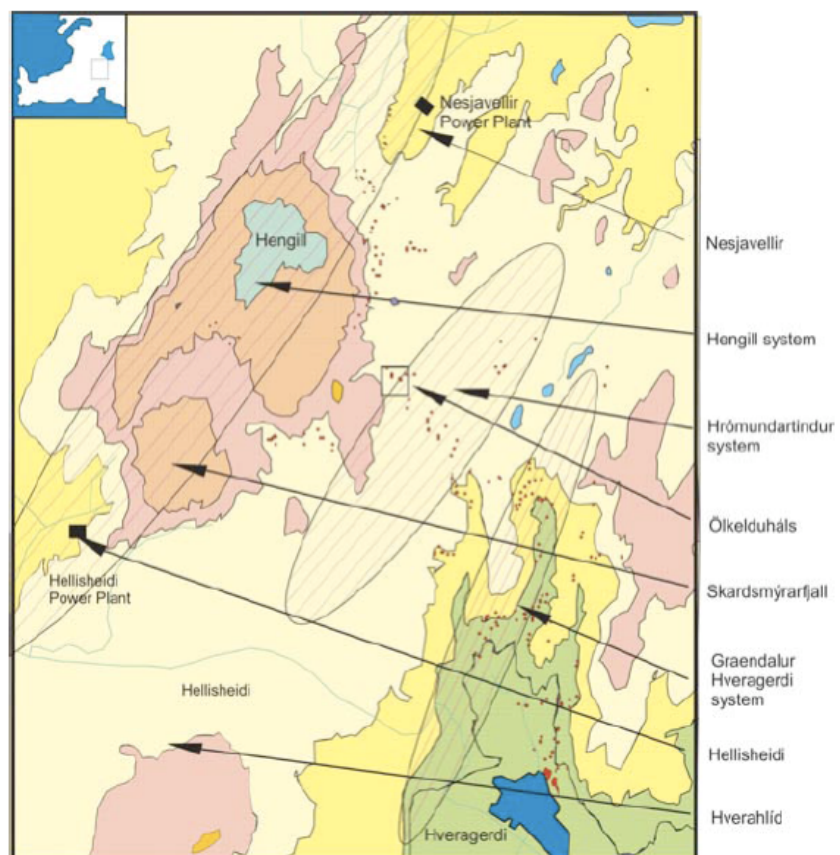


FIGURE 1: The Hengill geothermal area and its seven geothermal fields (Pendon, 2006)

The Hellisheidi geothermal area is one of seven geothermal fields within the region of the Hengill central volcano. The other six are: Nesjavellir, Hengladalur, Hverahlíð, Ölkelduháls, Graendalur

2. HELLISHEIDI GEOTHERMAL FIELD

2.1 Location and characteristics of the Hellisheidi geothermal field

The Hellisheidi geothermal area is one of seven geothermal fields within the region of the Hengill central volcano. The other six are: Nesjavellir, Hengladalur, Hverahlíð, Ölkelduháls, Graendalur

(Grensdalur) and Hveragerdi. The Hengill area lies on the plate boundary between the North American and European crustal plates. The mean, total spreading rate of these plates is 2 cm/year (Sigmundsson, 2006). Earthquakes are commonplace throughout the zone of active rifting, together with occasional volcanic eruptions. This rift zone is also highly permeable, and numerous fumaroles and hot springs are found on the surface (Björnsson et al., 2003).

The geothermal fields around Hengill's volcanic system have been studied extensively since 1947 (e.g. Björnsson et al., 2003, 2006; Pendon, 2006; Okedi, 2006). This region is considered one of the largest high-temperature geothermal fields in Iceland. Its geothermal activity is connected with three volcanic systems: The Graendalur Hveragerdi system, the Hrómundartindur system and the Hengill system (Figure 1).

The geothermal area of Reykjadalur and Hveragerdi (Figure 1) belongs to the oldest volcanic system the Graendalur-Hveragerdi system. North of the Graendalur area is a volcanic system named after Hrómundartindur, which last erupted about 10,000 years ago (Pendon, 2006). The geothermal field in Ölkelduháls is connected with this volcanic site. West of these volcanic systems lies the Hengill volcanic system, with volcanic fractures and faults stretching from southwest to northeast through Hellisheidi, Nesjavellir and Lake Thingvallavatn. The most promising geothermal areas are associated with this zone, Nesjavellir farthest to the north, and Hellisheidi on the southern side (Gunnlaugsson and Gíslason, 2003).

2.2 Hellisheidi geothermal power plant

The geothermal area of the Hellisheidi geothermal power plant is located between the mountains Stóra Skardsmýrarfjall and Stóra Reykjafell at a distance of 30 km southeast of Reykjavík city. The construction area is in the Hellisheidi heath and its vicinity south of Hengill volcano (Figure 2). The

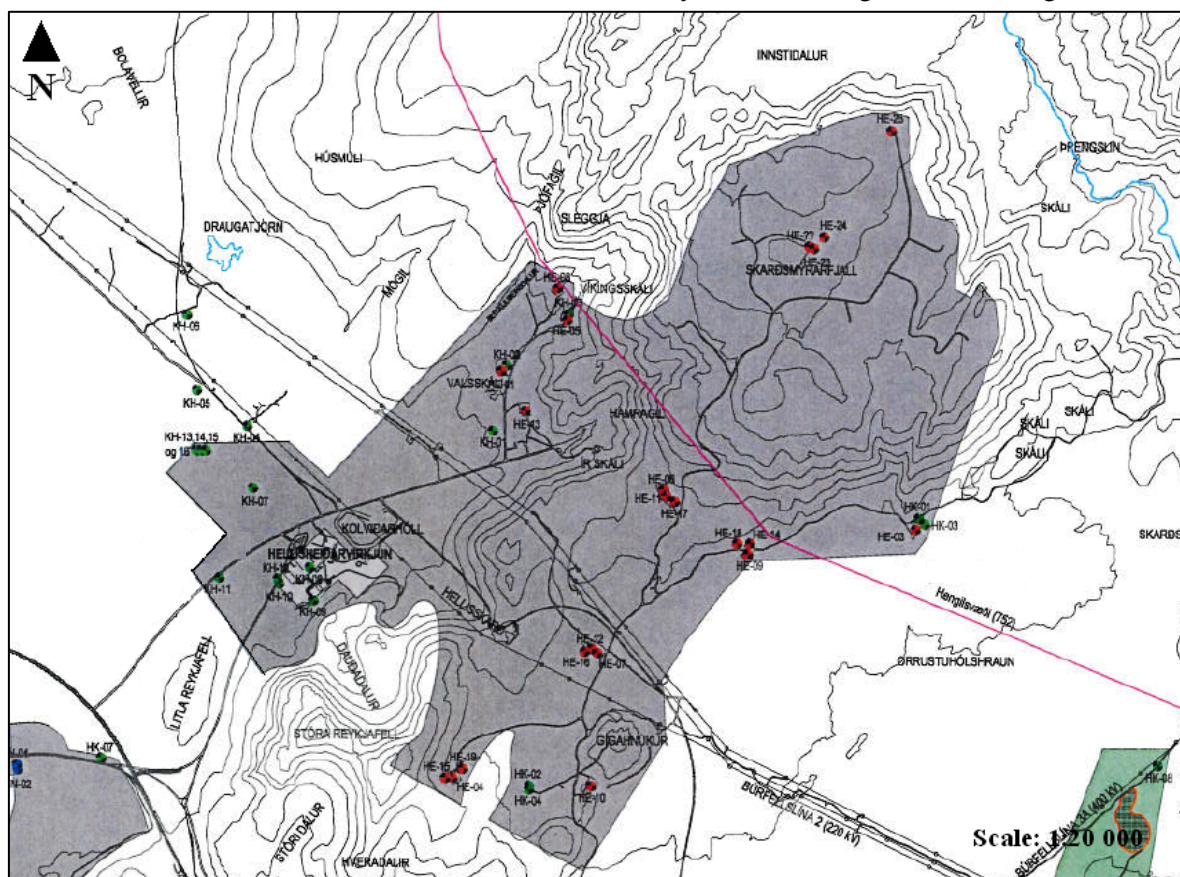


FIGURE 2: The Hellisheidi area (VGK, 2006)

area is divided into the upper geothermal area above Hellisskard pass and the lower area below the pass. A much larger area has, however, been included in research done to assess the environmental impact of the power plant. This is especially true for groundwater research, which covers the area from the south coast, west to Faxaflói bay, north to Esja Mountain and Thingvallavatn Lake and east to Ölfusá River (Reykjavík Energy, 2007).

Exploration studies indicate that there is a potential for 300 MW of electricity and 400 MW of thermal energy and with connections to the adjacent areas, the plant could be substantially enlarged (Reykjavík Energy, 2007). In 1985, a research borehole was made at the Kolvidarhóll hill (in the same area in which the plant is situated). In 1994, another borehole was drilled on Ölkelduháls ridge. Both boreholes offered some clues, but the evidence was not enough for basing a decision. In 2001, two boreholes were drilled in Hellisheidi heath and three more in 2002. The information from these holes provided the grounds for the power plant (Reykjavík Energy, 2007).

On 21 October 2006, electricity production started, with two steam turbines of 45 MW each generating a total of 90 MWe. Presently, further expansion plans are being implemented with the installation of a 30 MWe low-pressure turbine. In 2008, electricity production will start in two 40-45 MW turbine units with steam from Stóra-Skardsmýrarfjall Mountain. Lastly, in 2009, hot-water production will begin at the site.

2.3 Emissions of hydrogen sulphide

In geothermal power plants, hydrogen sulphide is released through the steam from geothermal groundwater during the process of electricity generation (Figure 3). In Hellisheidi power plant the velocity of steam release is 180 kg/s, of which 30% (54 kg/s) is hydrogen sulphide (Gestur Gíslason, personal communication). At Hellisheidi, power production is achieved via the extraction of geothermal groundwater from wells HE-11 and HE-17 at temperatures of 190°C. The groundwater goes through the pipelines into separation units and into the steam turbines, where steam is used to generate electricity. The water separated from the steam is reinjected and the steam that comes from the turbines is used in the heat exchanger and then cooled down in the cooling tower to be reinjected; other parts of the steam go through the condenser and into the cooling tower to continue the process (Figure 4).



FIGURE 3: Steam emissions from the Hellisheidi power plant

The steam, containing a mixture of vapour, carbon dioxide, hydrogen sulphide and other gaseous compounds, is released through the cooling tower, condenser gas removal, condensate, in geothermal water discharge, in steam stacks during shutdown, and during well testing and bleeding (Figure 4). Most of the hydrogen sulphide originally present in the total discharge from the well is concentrated into the vapour phase during steam separation (Webster, 1995).

Counting the two wells that are actually being exploited for electricity, there are 28 wells in total that have been drilled. Some of them are waiting to be used in the next development of the power plant.

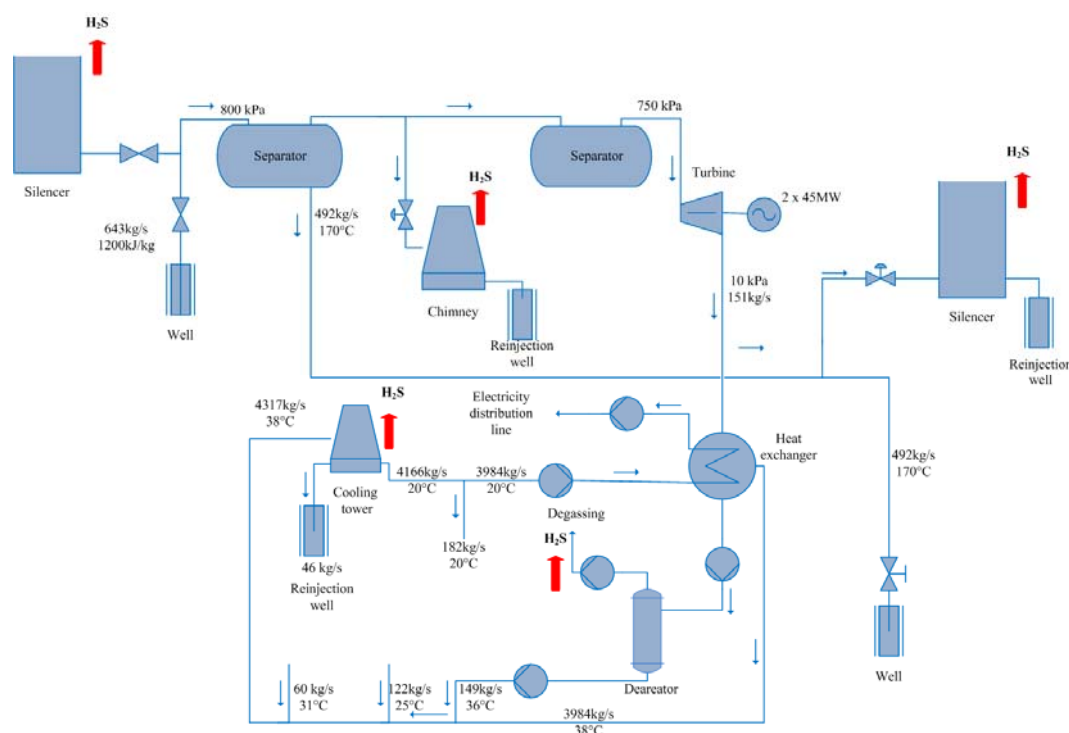


FIGURE 4: Process diagram of Hellisheidi electricity production (VGK, 2004)

3. METHODOLOGY

3.1 Methods for monitoring hydrogen sulphide levels around the Hellisheidi power plant and the Reykjavík area

3.1.1 Monitoring in the Hellisheidi area

The Hellisheidi area is monitored by Reykjavík Energy, which began measurements in 2001, and gradually increased the number of measuring points when the power plant began functioning. The existing 86 measuring points are monitored every two months over a period of two days. At each point, three samples are taken and the mean value is used. The monitoring is done when weather conditions are favourable, which reduces the constancy of measurements taken. Initially, locations were selected randomly, based mostly on accessibility, but latter sites were selected considering the wells and power-plant location (Figure 5).

The instrument used to monitor these points is a portable device called Jerome 631XE (Appendix II). The instrument offers an analysis range of 0.003 - 50 ppm for odour and corrosion control, safety, and leak detection. It utilises a patented gold film sensor that eliminates interferences from sulphur dioxide, carbon dioxide, carbon monoxide, and water vapours. An internal pump draws air into the device and any hydrogen sulphide present in the sample is absorbed by the sensor which registers a proportional change in its electrical resistance.

3.1.2 Monitoring in the Reykjavík area

Air quality in the Reykjavík area is monitored by the Environmental Department of Reykjavík City at its measuring station (Figure 5) located at Grensásvegur 15. That monitoring station takes constant measurements of NO, NO₂, NO_x, CH₄, NMHC, THC, CO, SO₂, O₃, benzene, toluene, xylene, PM10, PM2.5, and H₂S; which are directly uploaded to the internet at the website: www.loft.rvk.is.

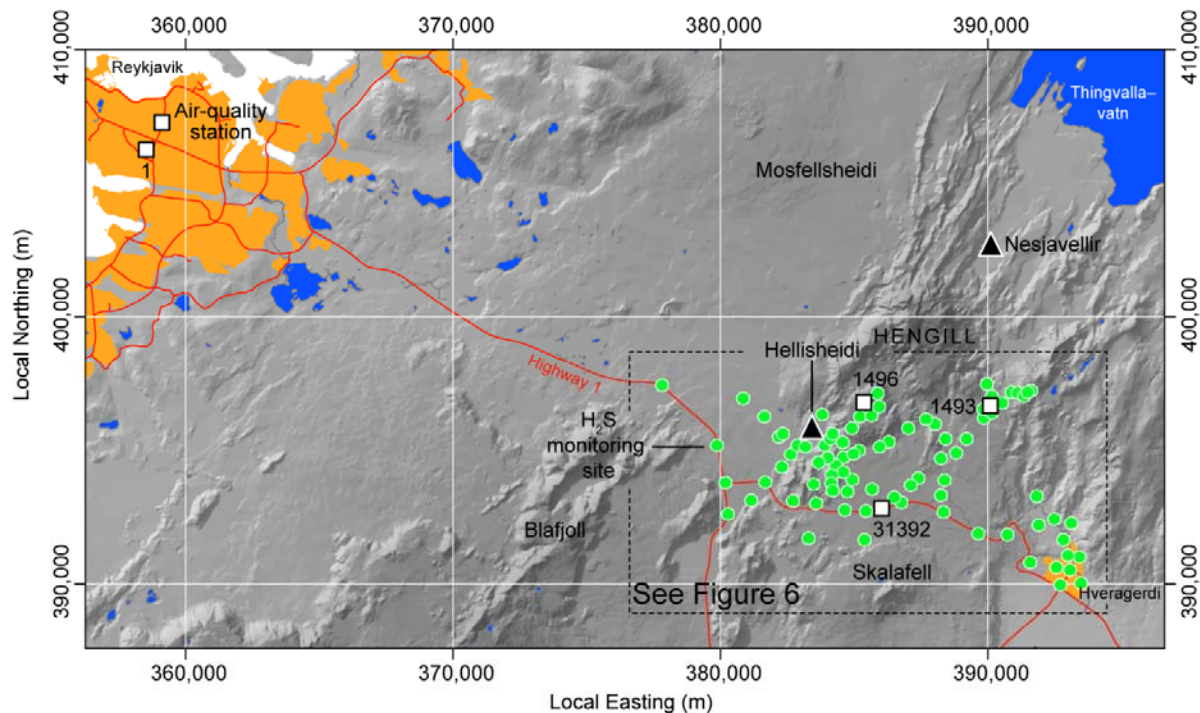


FIGURE 5: Map of monitoring stations for hydrogen sulphide in Hellisheidi and Reykjavík (see Figure 6 for an additional map of the monitoring sites)

The instrument used to measure hydrogen sulphide is an ambient monitor HORIBA APSA-360A (Appendix III), which measures hydrogen sulphide and sulphur dioxide in ppm units every 30 min. Measurements have been made since February 2006.

3.2 Data gathering and processing

The data collected from the monitoring stations was analyzed to select the most representative and relevant information necessary for the purpose of this study. Data was selected for the period before the power plant was built and started operation, and the period after it began functioning in October 2006. For the analysis of increased hydrogen sulphide concentration in the Hellisheidi area, data from Reykjavík Energy was used, covering the period monitored: from 9 July 2001 to 19 July 2006; 24 October 2006; 25 October 2006; 8 November 2006 and 7 February 2007. For the analysis of increased hydrogen sulphide concentration in the Reykjavík area, data from the monitoring station located in Grensásvegur 15 was used. The data was selected to cover the period prior to the opening of the power plant - from June to September 2006 - and the period after the power plant began functioning. Taking into consideration the dates used in the analysis for the Hellisheidi area and for the model, the relevant dates are October 24 and 25, 2006, to November 8, 2006 and February 7, 2007.

To determine whether there is a connection between concentrations measured at the monitoring stations on Hellisheidi and levels measured in Reykjavík, two methods of analysis were used:

- An air dispersion model to determine the dispersion plume of hydrogen sulphide from Hellisheidi power plant; and
- A comparative analysis of hydrogen sulphide concentrations measured in the Reykjavík area and Hellisheidi area.

The modelling software AERMOD View 5.6 was used to analyse the field data for Hellisheidi. Four specific periods were chosen, based on the availability of field data:

October 24, 2006,
November 8, 2006,

October 25, 2006,
February 7, 2007.

The meteorological data necessary to create the model were compiled for the identified periods, with a range of 3 days around the days studied.

The comparative analysis of hydrogen sulphide concentrations in Reykjavík and Hellisheidi area was based on data gathered in these two areas before the power plant began production and after start-up.

3.3 Delineation of study area

The study area was delineated taking into account the 86 monitoring stations located in the Hellisheidi area (Figure 6). This area covers 150 km². However, the dispersion model creates a specific area of study when processing the data provided. This maximum area is about 50 km² for each of the modelling runs.

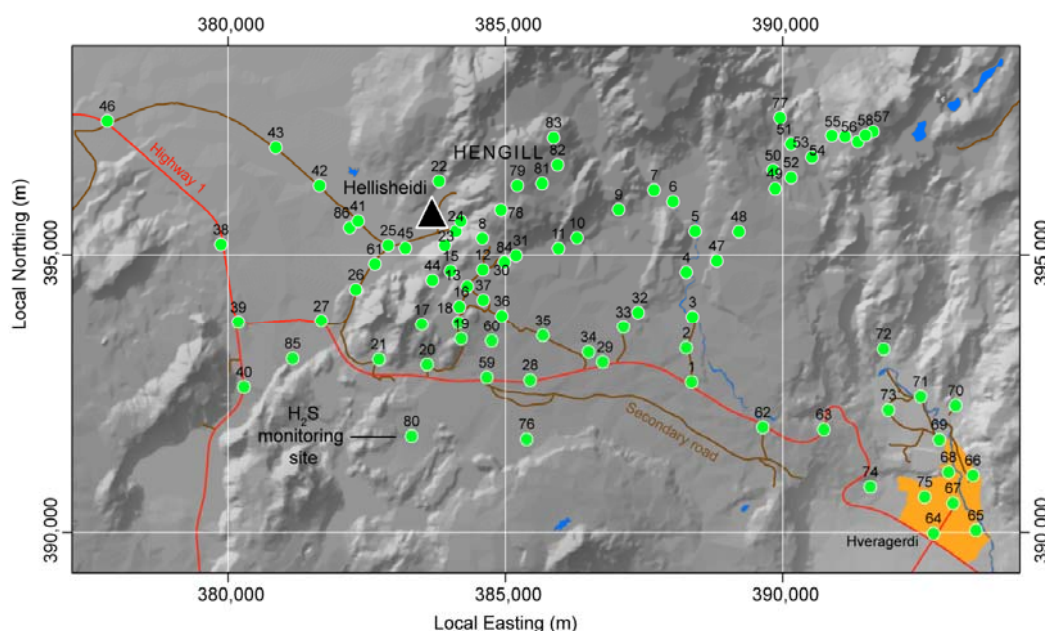


FIGURE 6: Study area for the hydrogen sulphide dispersion model from Hellisheidi power plant; monitoring sites are represented by the circular symbols

3.4 The air dispersion modelling software AERMOD View

AERMOD is a steady-state plume model, designed to run with a minimum of observed meteorological parameters and as a replacement for the ISC3 model. It requires only a single surface measurement of wind speed (measured between 7 z₀ and 100 m - where z₀ is the surface roughness height), wind direction, ambient temperature and observed cloud cover. If this last parameter is not available, two vertical measurements of temperature and a measurement of solar radiation can be used (Cimorelli et al., 2004). A full morning upper air sounding (RAWINSONDE) is required to calculate the convective mixing height throughout the day; however, a mixing height estimator can be used. In order to construct similarity profiles of the relevant planetary boundary layer (PBL) parameters, surface characteristics (surface roughness, Bowen ratio, and albedo) are also needed. If not available, the software includes a selection of surface characteristics with standard values for each season and annually.

The software consists of one main program (AERMOD) and two pre-processors (AERMET and AERMAP):

AERMET is the meteorological interface of AERMOD, used to calculate planetary boundary layer (PBL) parameters, such as: velocity (u), Monin-Obukhov length (L), convective velocity scale (w), temperature scale (θ), mixing height (z_i), and surface heat flux (H) (Cimorelli et al., 2004). These parameters are then passed to the interface where they are used to calculate vertical profiles of wind speed (u), lateral and vertical turbulent fluctuations (F_v , F_w), potential temperature gradient ($d\theta/dz$), and potential temperature.

AERMAP is the terrain pre-processor, used to calculate a representative terrain height scale (h_c). The terrain height scale is used to calculate the dividing streamline height. AERMAP is also used to create a receptor grid which includes: the receptor's location (x_r , y_r), its height above mean sea level (z_r), and the receptor specific terrain height scale (h_c).

AERMOD handles the pollutant plume of dispersion in both flat and complex terrain within the same modelling framework (Figure 7). In stable flows, a two-layer structure develops in which the lower layer remains horizontal while the upper layer tends to rise over the terrain.

The weighting between the two states of the plume depends on the relationship between H_c and the vertical concentration distribution at the receptor location. In the AERMOD approach, plume height, receptor elevation, and H_c will determine how much plume material resides in each plume state. During convective conditions the concentration at an elevated receptor is simply the average of the contributions from the two states (Figure 8). As plumes above H_c encounter terrain and are deflected vertically, there is also a tendency for plume material to approach the terrain surface and to spread out around the sides of the terrain.

Overall, AERMOD models a plume as a combination of two limiting cases: a horizontal plume (terrain impacting) and a terrain-following plume. Therefore, the total concentration, at a receptor, is bounded by the concentration predictions from these states. In flat terrain the two states are equivalent.

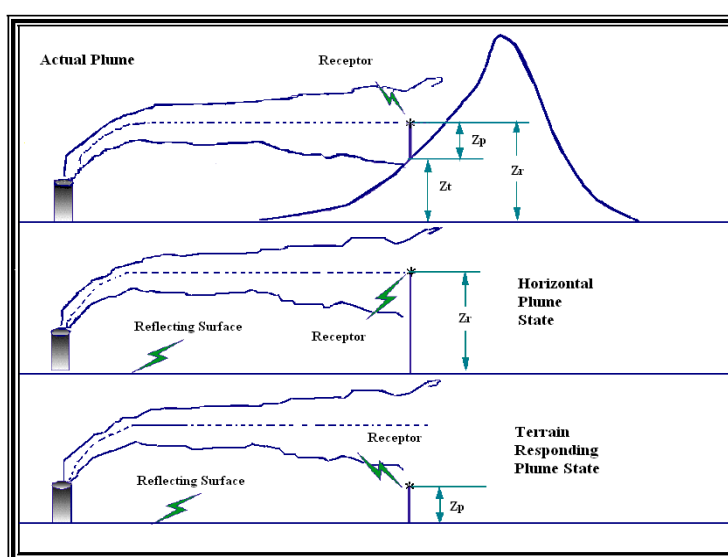


FIGURE 7: AERMOD two-state approach; total concentration predicted is the sum of the two extreme plume states (Cimorelli, 2004)

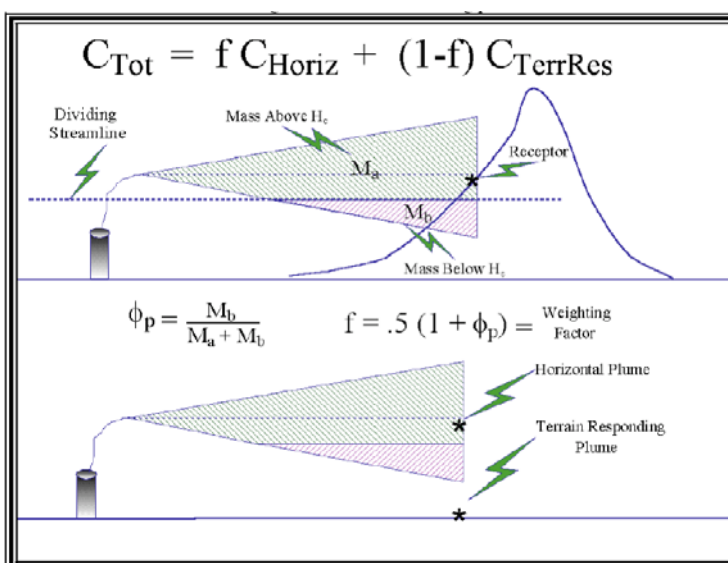


FIGURE 8: Treatment of Terrain in AERMOD; construction of the weighting factor used in calculating total concentrations (Cimorelli, 2004)

4. RESULTS

4.1 Comparative analysis on the concentrations measured in the monitoring stations of the Hellisheidi area

Based on the periods selected for the Hellisheidi area, comparisons can be made of the variations of hydrogen sulphide concentrations due to the presence of the geothermal power plant. In Figure 9, there is an increase in hydrogen sulphide emissions from the first period to the second period. This variation is present at 49 (57%) of the monitoring stations; however, only at 28 (32.5%) of them were emissions twice as high as the initial measurements.

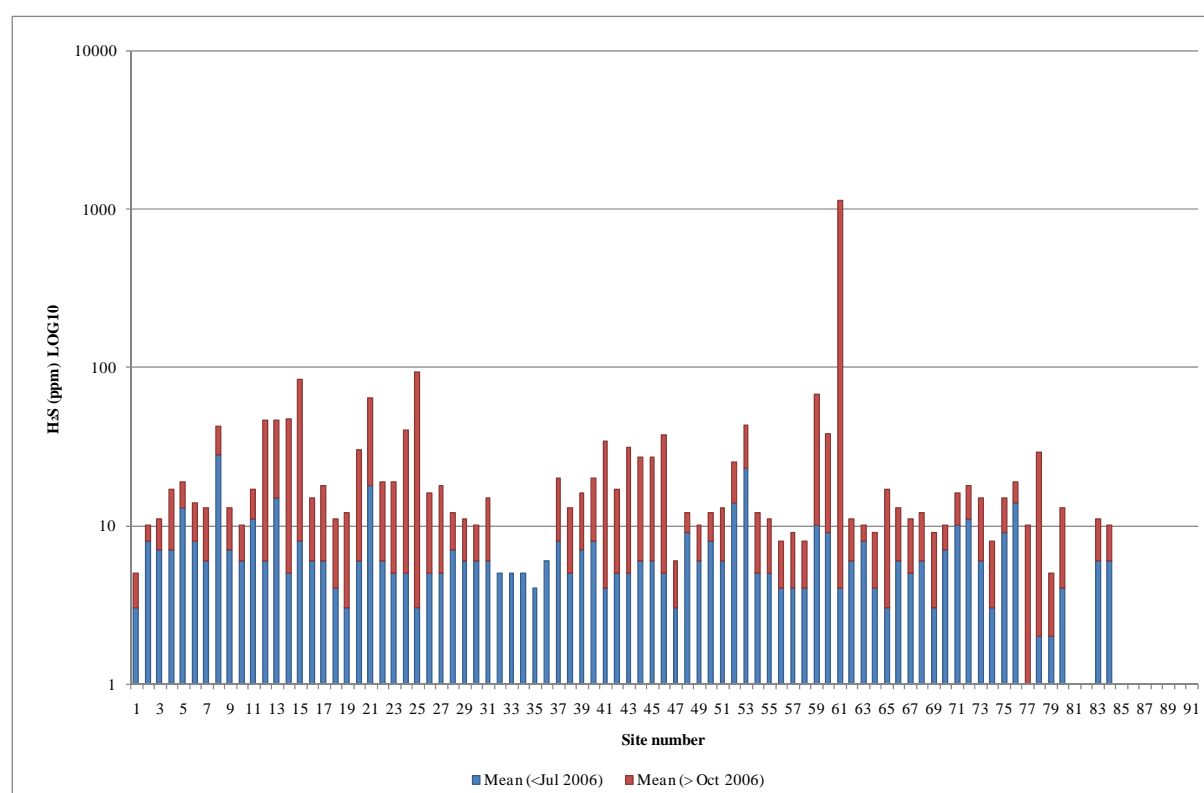


FIGURE 9: Logarithmic increase of hydrogen sulphide concentrations in the Hellisheidi area before and after the power plant was put into operation

It is important to mention that stations 12, 14, 15, 24, 25, 41, 43, 46, 59, 61, 77 and 78 (Figure 6) presented the highest increased variations in hydrogen sulphide concentrations ranging from 5 to 30 times higher than the measurements taken in the first period. The highest variation is found at station 61, located close to the power plant, with an increase of 283 times in comparison with emissions measured before the beginning of the power plant production at the end of October 2006. In concentrations, this means an increase from 0.004 ppm in the first period to 1.132 ppm in the second period.

There is some data missing from the first and the second periods, preventing a comparison between those sites. However, the missing data for both periods only represents 10.5% of the total data and a comparison can be made using data from the rest of the sites. One of the monitoring stations that does not have a comparative value from the first period is station 86, but it is worth mentioning as its readings represent the third highest value of the second period: 0.078 ppm.

Based on the mean for the first and second period, there is a general fourfold increase in the hydrogen sulphide concentrations in the area, from 0.007 to 0.028 ppm. These results are influenced

significantly by the high measurements obtained in station 61. With data omitted from station 61, the value is double the original emissions, obtaining a mean of 0.014 ppm.

The third period considered for this study is based on data gathered in February 2007. When comparing the hydrogen sulphide concentrations measured for the three periods (Figure 10), it demonstrates that there is still a rise in hydrogen sulphide emissions around the Hellisheidi area. There is an increase in the mean concentration from the first period to the third period in 34 (40%) of the 86 monitoring stations, up to 14 times. Concentrations measured in the second and third periods were five times higher in 3 (3.5%) of the 86 monitoring stations. These are stations 1, 22, and 26 which yielded increased levels of 5.5, 5.2 and 6.4, respectively.

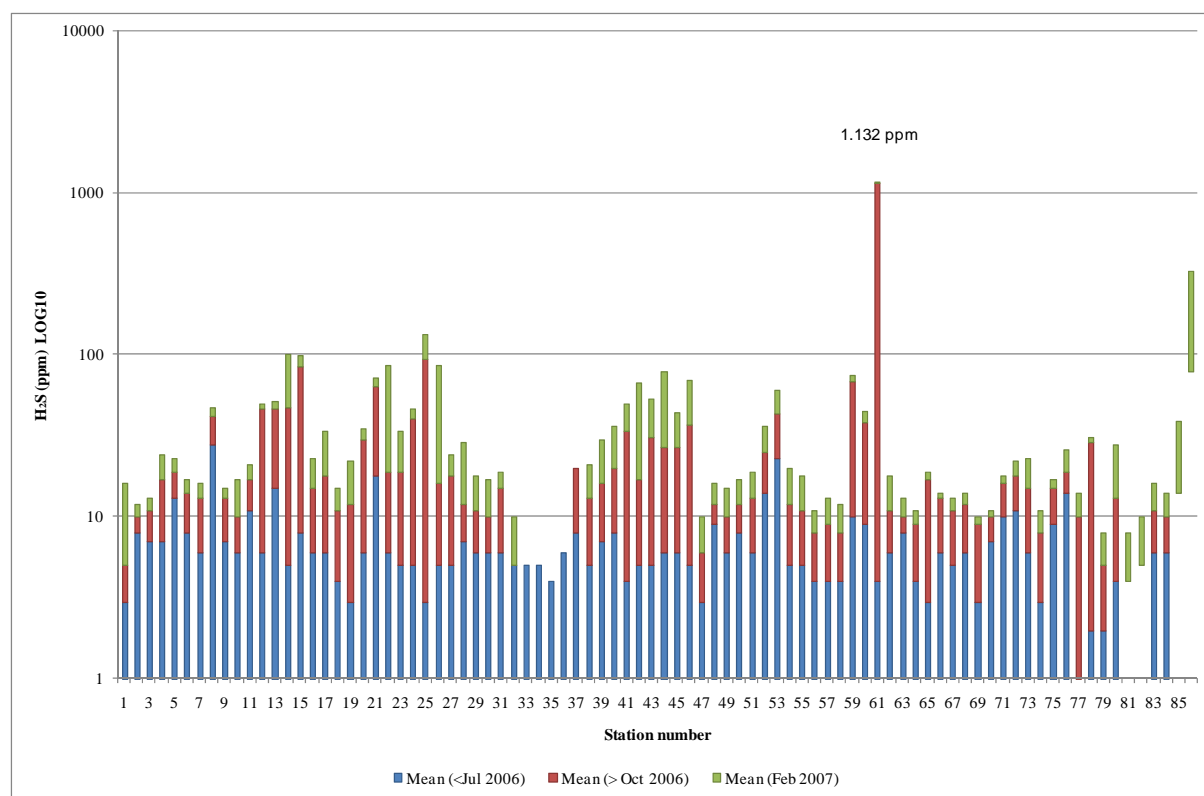


FIGURE 10: Logarithmic increase of hydrogen sulphide concentrations in the Hellisheidi area in the three periods studied

However, the mean values measured for the third period demonstrate a reduction of hydrogen sulphide concentration in comparison with the second period at 42 (49%) of the stations; giving 0.4 times the level. The mean value calculated for the third period is 0.014 ppm. The same value was determined for the second period omitting station 61; but it is twice the mean value determined for the first period when the power plant had not started operation.

In a more exhaustive analysis, the third period showed a substantial reduction of hydrogen sulphide concentration in measurements in comparison with the second period. Stations 12, 15, 24, 25, 41, 43, 46, 59, 61, 77 and 78, which previously showed the highest increased variations in hydrogen sulphide concentration, show reduced levels in the third period. The previous mean value at station 61 for October 2006 was 1.132 ppm; but in February 2007, it was reduced to 0.031 ppm.

The monitoring stations that measured higher concentrations are located within a 5 km radius of the power plant; the concentrations dispersed from the northwest and west sides of the emission source towards Reykjavík and from the southeast side in the direction of Hveragerdi. This distribution of high concentrations of hydrogen sulphide will be explained in Section 4.3 with the dispersion plume model created for the second and third periods when the power plant began functioning.

4.2 Comparative analysis of the concentrations measured at the monitoring stations of the Reykjavík area

Data from before production at Hellisheidi power plant:

The data used in this section is based on measurements taken from the monitoring station located at Grensásvegur 15, and cover the period prior to the opening of Hellisheidi power plant and after, from June 2006 to February 2007. The first analysis corresponds to the measurements before the power plant began production, covering a four month range from June to September 2006. The four graphs (Figures 11 to 14) represent the concentration measurements over a one hour interval each month. Within each month there are short-lived periods of higher concentrations, increasing in quantity from

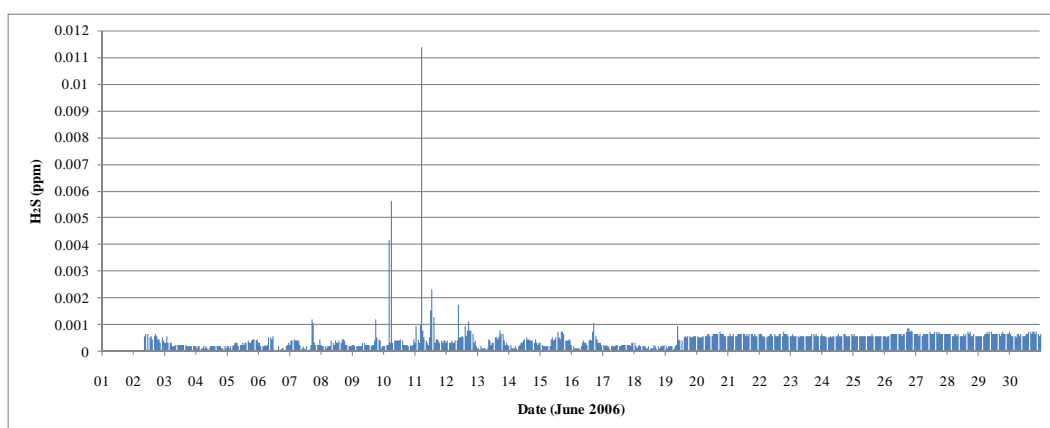


FIGURE 11: Hydrogen sulphide concentrations in the Reykjavík area during June 2006

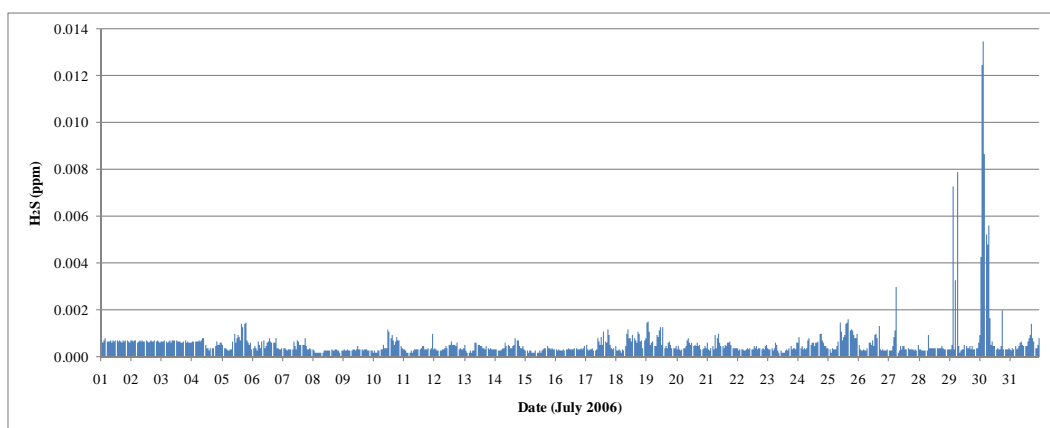


FIGURE 12: Hydrogen sulphide concentrations in the Reykjavík area during July 2006

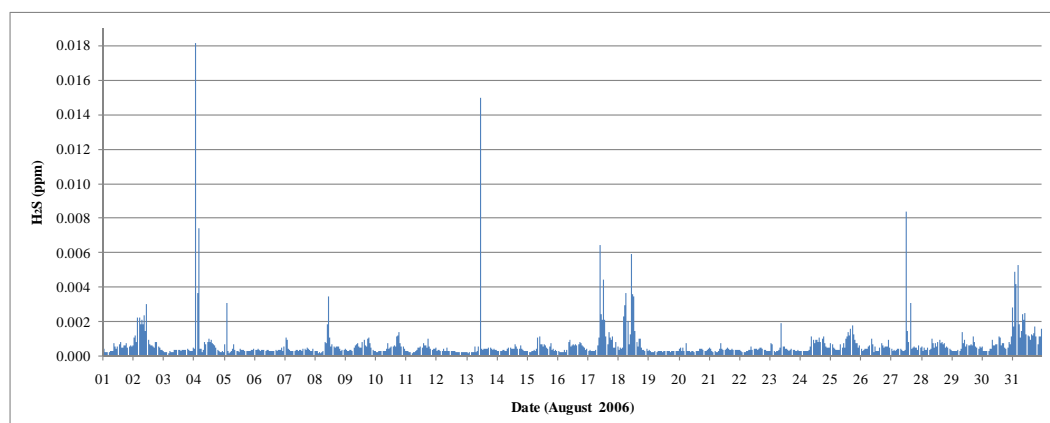


FIGURE 13: Hydrogen sulphide concentrations in the Reykjavík area during August 2006

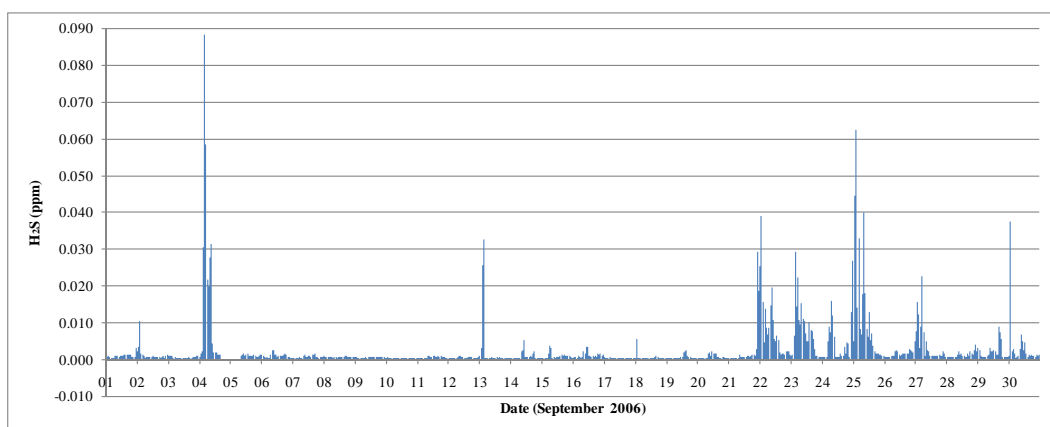


FIGURE 14: Hydrogen sulphide concentrations in the Reykjavík area during September 2006

June to September. The highest episode was on September 4 with concentrations reaching 0.09 ppm (Figure 14). The other months included episodes from 0.012 (June and July) to 0.018ppm (August). September presented the highest frequency of increased concentrations of hydrogen sulphide in the readings, coinciding with the period prior to initiation of operations in the Hellisheidi power plant when the wells drilled for production were being tested and bled.

Data collected after the Hellisheidi power plant started production:

The second group of analyses includes the measurements after Hellisheidi began production and is divided into four case studies: October 24, 2006; October 25, 2006; November 8, 2006; and February 7, 2007. Each case study covers a period of three days around the days selected. Because the first two case studies are so close in time, one analysis is presented for both of them. For the other two, individual analyses are presented.

Case study 1: October 24 and 25, 2006

Figure 15 presents hydrogen sulphide concentrations measured from October 21 to 28, 2006. It shows an increase in hydrogen sulphide concentrations during the dates prior to and after October 24 and 25. On October 21 and 22, peaks in concentration measurements occurred in contrast with stable concentrations on the following days: October 23, 24 and 25, and showing another increase on October 27 and 28. The highest concentration reached was on the 28th at 5:00 GMT in the amount of 0.036 ppm.

These dates correspond with the initial production period of Hellisheidi power plant, on October 21, coinciding with increased hydrogen sulphide concentrations in the Reykjavík area in the days surrounding this event.

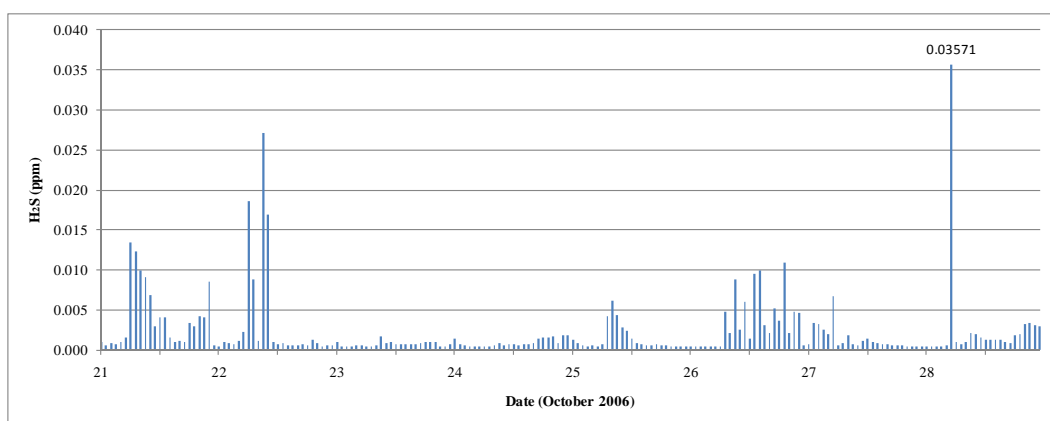


FIGURE 15: Hourly hydrogen sulphide concentrations measured in the Reykjavík area from October 21 to 28, 2006

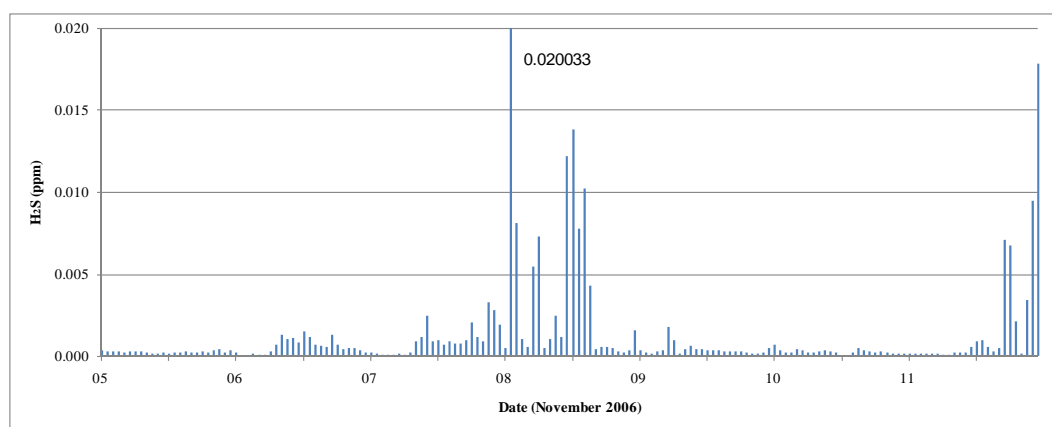


FIGURE 16: Hourly hydrogen sulphide concentrations measured in Reykjavík area from November 5 to 11, 2006

Case study 2: November 8, 2006

In the second case study, when analyzing November 8 and 3 days around this date, it can be observed (Figure 16) that the highest peaks of hydrogen sulphide concentration for this particular case were measured before and during that day. These concentrations were measured at 1:00 GMT giving the amounts of 0.020 ppm, at 11:00 GMT giving the amount of 0.012 ppm, and at 14:00 GMT with the amount of 0.010 ppm, all of them on November 8. This episode was later followed by stable concentrations of hydrogen sulphide with a minor increase on November 11 at 23:00 GMT with 0.017 ppm.

Case study 3: February 7, 2007

The last case study considered was February 7, 2007. Measurements taken during and around this date demonstrated a significant increase of hydrogen sulphide in the Reykjavík area (Figure 17). The highest peak in the measurements was on February 6 at 9:00 GMT with the amount of 0.115 ppm, followed by a decrease in the concentrations measured in the next days.

Comparison with wind conditions and temperatures:

The third analysis considered the wind conditions and temperatures in the Reykjavík area during the periods studied. On this account, four wind roses were plotted with the program WRPLOT View from AERMOD View software, based on wind direction and velocity readings from the Grensásvegur 15 monitoring station. The software established 10° sampling intervals, for 36 wind directions measured in metres per second.

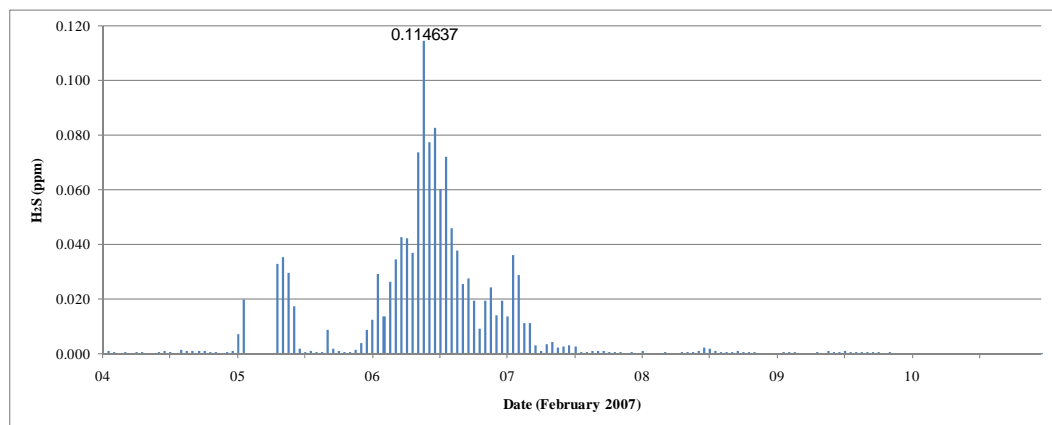


FIGURE 17: Hourly hydrogen sulphide concentrations measured in Reykjavík area from February 2007

In Figure 18, the four wind roses represent the wind direction from which the wind is blowing, and the velocity of the wind in m/s. In Figure 18a, the wind direction and velocity are plotted for the period of June to September 2006, before the power plant operation; and the graphs in Figures 18b, c and d show the wind rose plots for the case studies from the months of October 2006, November 2006 and February 2007.

The meteorological data show varying wind speeds and directions throughout the year. In summer time, during June to September, the wind blew from southeast to northwest with a higher velocity than from other directions, reaching 8.5 to 10 m/s. However, this is only in 0.4% of the cases. In 29.1% of the cases, wind velocity ranged between 2.4 and 3.9 m/s; in 18% it reached velocities from 1.4 to 1.9 m/s, and 16.8% velocities ranged from 3.9 to 5.5 m/s.

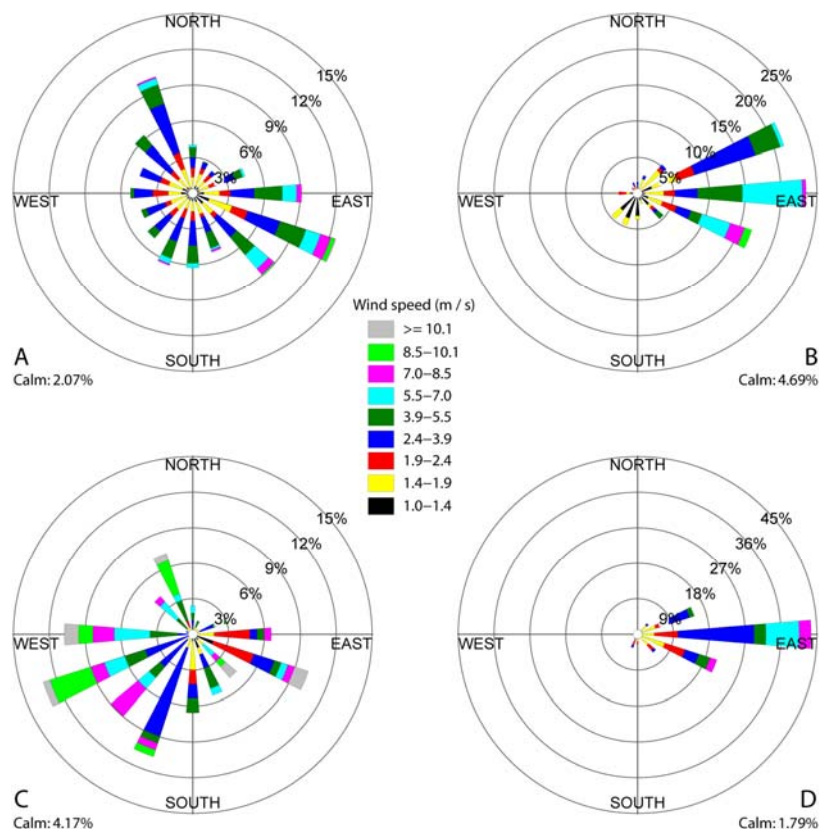


FIGURE 18: Wind roses for the Reykjavík area in the periods:
a) June to September 2006; b) October 21 to 28, 2006;
c) November, 5 to 11, 2006; d) February 5 to 11, 2007

In the later periods (Figure 18b, c and d), the highest velocity reached was more than 10.1 m/s in November; blowing from southwest to northeast. But the highest wind-frequency distribution for this week was 23.2%, in the range of 2.4-3.9 m/s. In the months of October 2006 and February 2007 (Figure 18b and d), the wind direction was predominantly easterly, reaching velocities of 7.0-8.5 m/s. In October, 21.4% of the cases showed measured velocities between 1.0 and 1.4 m/s and 18.8% between 1.4 and 1.9 m/s; and less for other velocities measured. In February, wind frequencies concentrated between the ranges of 1.0-1.4 m/s; 1.9-2.4 m/s and 2.4-3.9 m/s in 22.6%, 19.6% and 31% of the cases, respectively.

The temperature logs assessed for this study covered the periods selected: June to September 2006, October 2006, November 2006 and February 2007. During these periods, the temperature ranged from 20°C in summertime to -6°C in wintertime. The first period, June to September, gave a mean temperature of 13°C.

During the dates of increased hydrogen sulphide concentrations before production, there were no extreme changes in temperatures during the months June to September 2006. For the case studies, the temperature measurements showed variations ranging from 10 to -6°C. The lowest temperatures in October were registered on the 24th and 25th reaching -3°C. The lowest temperatures in November were registered on the 9th and 11th with -4°C. The lowest temperatures, -6°C, in February registered from the 4th to the 8th.

4.3 Hydrogen sulphide dispersion model for the Hellisheidi emissions

Before presenting the models for the three case studies, it is important to analyse the wind rose plots, as well as the temperature readings obtained for the period before and after the production start of the power plant as they have a great effect on the behaviour of gas released into the atmosphere and influence the plume of dispersion.

In Figure 19, the four wind roses represent wind directions from which the wind is blowing, and wind velocity in m/s for the studied periods from October 2006 to February 2007. In Figure 19a, the wind direction and velocity are plotted for all the periods, but divided for the three separate case studies in Figures 19b, c and d.

In Figure 19a, the wind rose shows a predominant northeasterly direction with velocities ranging from calm winds to 3.9 m/s within which 96% of the cases are distributed. The highest frequency of wind velocity ranged between 2.4 and 3.9 m/s in 23.9% of the cases.

In October 2006, the wind direction was predominantly northeasterly, with velocities ranging between calm winds and 3.9 m/s. The highest frequency range was between 1.0 and 1.4 m/s. In 19.8% of the cases, calm winds were registered. In November 2006 (Figure 19c), there was a shift in wind direction, changing from predominantly northeasterly to predominantly south-westerly with velocities reaching up to 7 m/s. However, the period measured registers mainly calm winds in 26.2% of its measurements, followed by 24.4% of the cases measuring 2.4 to 3.9 m/s. In February 2007 (Figure 19d), the wind rose showed a predominant north-easterly direction with velocities ranging from calm winds to 3.9 m/s. The highest frequency achieved in this period ranged between 1.4 and 1.9 m/s in 30.4% of the cases. Calm winds represented 14.3% of the cases.

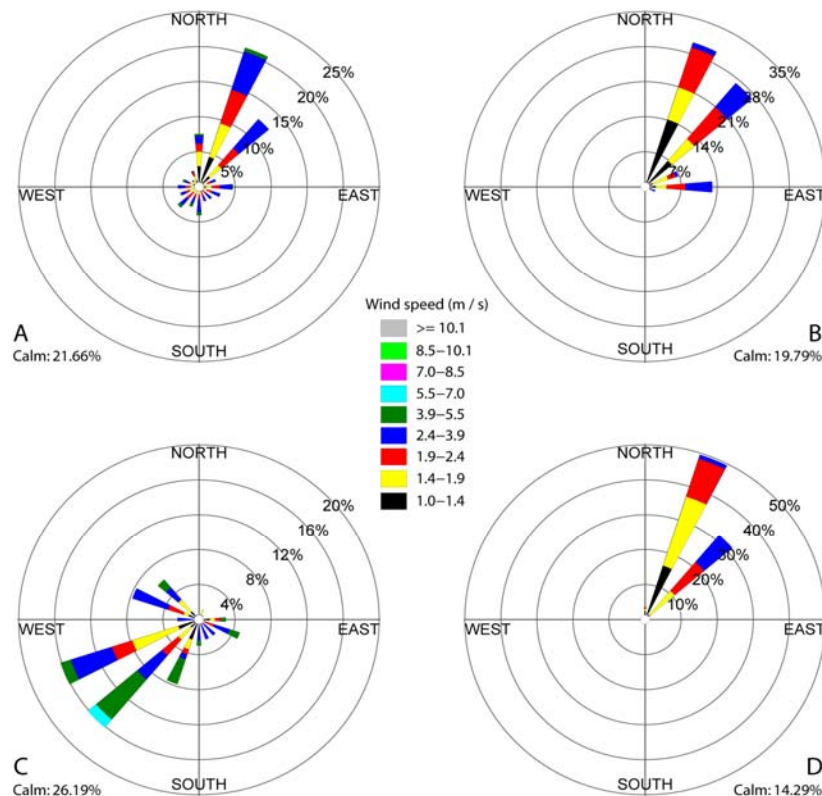


FIGURE 19: Wind roses for the Hellisheidi area in the periods;
a) October 2006 to February 2007; b) October 21 to 28, 2006;
c) November 5 to 11, 2006; d) February 5 to 11, 2007

The three case studies b, c and d (Figure 19) were analysed with the Gaussian dispersion modelling software AERMOD View 5.6 for the periods of 3-hours dispersion and 24-hours dispersion. The software applies meteorological, terrain, and infrastructure data with information provided from the emission points considered.

The models created considered:

- Basic meteorological data taken from meteorological station 31392 in the Hellisheidi area;
- Calculations of mixing height values through the mixing height estimator; and
- A flowrate of 180 kg/s based on information provided from Reykjavík Energy.

Even though the models accept terrain and precipitation data for elevation, 3D modelling and wet depositions, these parameters were not considered in this study. Therefore, the models illustrate a plume of dispersion of hydrogen sulphide with higher concentrations than the ones expected if all aspects were considered. In the air dispersion models, higher concentrations are shown closer to the emission point and lower concentrations at greater distances.

Case study 1: October 24 and 25, 2006

The first model (Figure 20) is based on the data gathered from October 21-28 2006. The model shows that higher concentrations of hydrogen sulphide were located within the surroundings of the power station, and reduced considerably when dispersed over long distances. The initial 3-hour model shows dispersion in north-easterly and south-westerly directions towards the mountains with lower concentrations being dispersed northwest and southeast. There is an increase in hydrogen sulphide concentration towards the southeast, with intermediate values. The 24-hour model shows dispersion to northeast and southwest. There is little dispersion towards the Reykjavík area, which is in the lowest concentrations.

Case study 2: November 8, 2006

The second model (Figure 21) is based on data gathered from November 2006, specifically from November 5-11. The model shows higher concentrations of hydrogen sulphide in the area of the power station spreading in all directions in the three-hour simulation, possibly due to turbulence reflected by unstable winds (see wind rose in Figure 19c). This turbulence contributes to the dispersion of the pollutant, reaching longer distances at higher concentrations than in the first study case. The dispersion plume for the 3-hour simulation (Figure 21a) moves in southwesterly, northeasterly and southeasterly directions. Higher concentrations are shown in the direction of Hveragerdi. The 24-hour model shows a reduction of hydrogen sulphide levels in the surrounding areas of the emission point and the dispersion plume stretches northeast and southeast, in the direction of Hveragerdi. Neither of these two models for November 2006 show higher concentrations of hydrogen sulphide moving towards Reykjavík city.

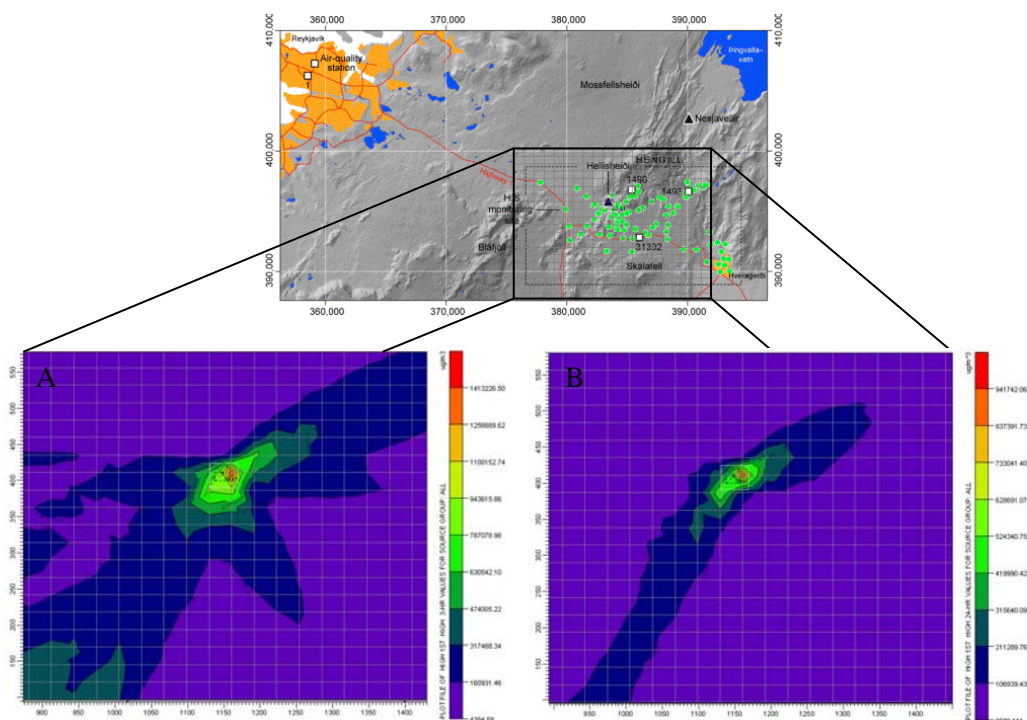


FIGURE 20: Gaussian model for the dispersion plume of hydrogen sulphide in the Hellisheidi area, October, 2006: a) 3-hour simulation, b) 24-hour simulation

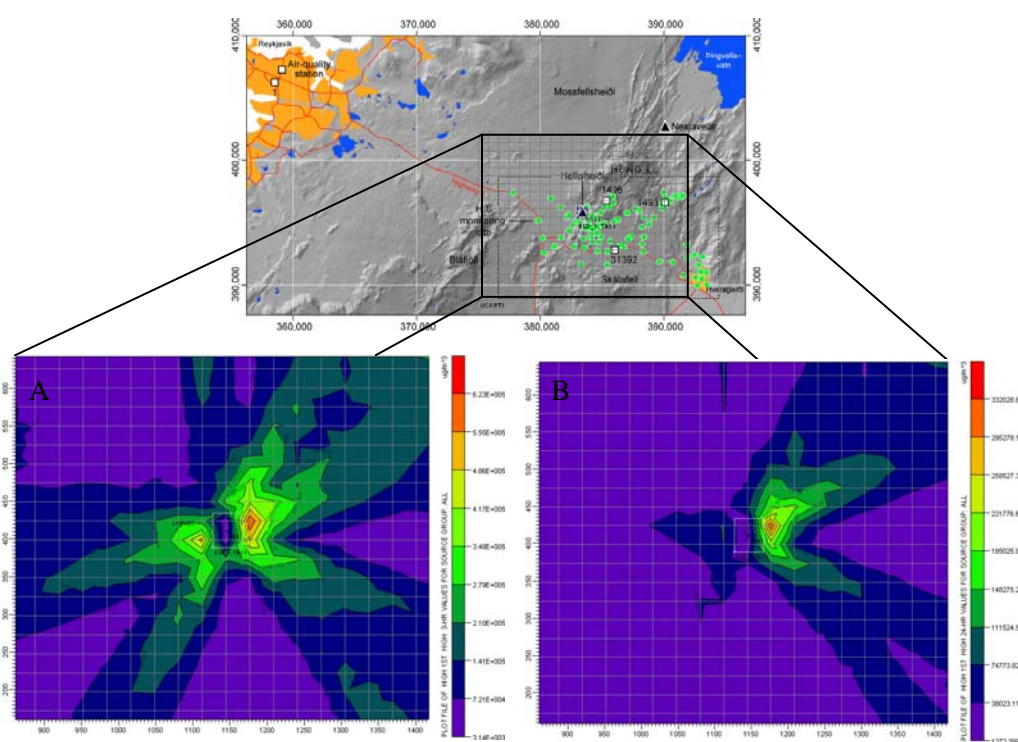


FIGURE 21: Gaussian model for the dispersion plume of hydrogen sulphide in the Hellisheidi area, November, 2006; a) 3-hour simulation, b) 24-hour simulation

Case study 3: February 7, 2007

The third model (Figure 22) is based on data gathered from February 2007, specifically from February 5-11. In Figure 22, the model shows uni-directional dispersion of hydrogen sulphide towards the southwest side of the emissions point, with the lowest concentrations towards Hveragerdi and Reykjavík. The 3-hour and 24-hour simulation models are very similar, meaning that the plume of dispersion is moving very slowly during this period due to stable winds and velocities that can be seen in the wind rose plot (Figure 19d).

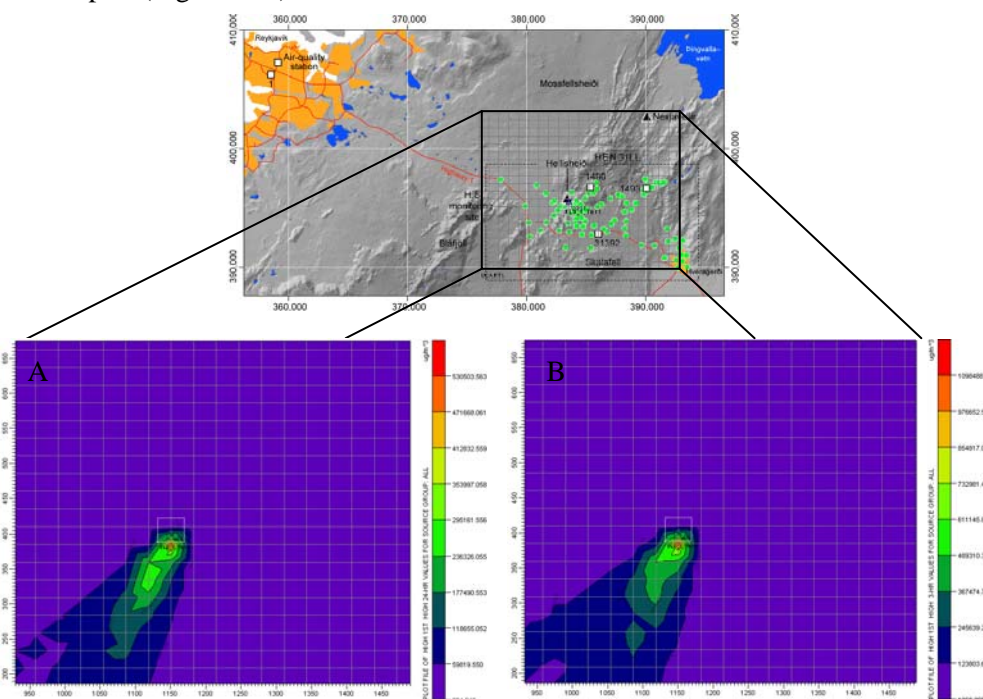


FIGURE 22: Gaussian model for the dispersion plume of hydrogen sulphide in the Hellisheidi area, February 2007; a) 3-hour simulation, b) 24-hour simulation

5. DISCUSSION

5.1 Factors affecting dispersal of hydrogen sulphide

There are several factors that affect the dispersal of hydrogen sulphide in the atmosphere such as: weather conditions, topography of the terrain and chemical reactions.

Wind direction and speed determine the direction of the plume of dispersion, and even the distance that can be achieved, as hydrogen sulphide does not stay that long in the atmosphere, mostly between one and three days, or 42 days in wintertime (Bottenheim and Strausz, 1980). Topography of the terrain may affect and change wind direction and velocity, causing alterations in the plume of dispersion of the pollutant. Precipitation can change the concentration levels of hydrogen sulphide in the atmosphere, because hydrogen sulphide reacts with other elements in the atmosphere, such as water, to form acid rain or sulphuric acid that is later precipitated to the soil, plants and infrastructure.

5.2 Connection between hydrogen sulphide emissions in Hellisheidi and increased hydrogen sulphide concentrations in Reykjavík area

The hydrogen sulphide dispersion models coincide with the corresponding wind rose plots. The highest concentrations of hydrogen sulphide are around the emission source and disperse dependent on wind direction. Mostly the dispersion plume moves towards the southwest, northeast and southeast.

The results of the modelling indicate that very low concentrations of the gas move towards Reykjavík; only during special conditions such as low temperature, high wind speed, wind direction from northeast to southwest, it is considered that the Hellisheidi emissions affect Reykjavík's air quality.

There is a need to consider other sources of hydrogen sulphide that could be reaching the Reykjavík area, and to make more models considering all parameters during high peak readings in the Reykjavík monitoring station.

5.3 Prospect of increased concentrations of hydrogen sulphide due to the expansion of Hellisheidi power plant

Taking into consideration the results of this study and the expansion plans the Hellisheidi power plant has for the following years, it is expected that higher emission rates of hydrogen sulphide will be experienced and that these emissions will disperse in the surrounding area; this could also affect the air quality of the towns closest to the power station, especially Hveragerdi and Reykjavík city. However, if the wind patterns and weather conditions are the same as those shown in the models, there is a higher probability that Hveragerdi will be most affected by the expansion of Hellisheidi power plant.

An expansion from 90 to 300 MWe means an increase of 3.33 times the emissions measured during this study. Therefore, some actions may need to be considered to avoid future problems with the surrounding population. This could mean implementing processes for hydrogen sulphide abatement.

5.4 Limitations of the model

The accuracy of the model depends on data quality. For these models, only essential data were used. Terrain and precipitation data would have provided a more detailed and precise model of the studied cases. However, not including these parameters allowed a worst-case scenario of the dispersion of the plume. In general, models have a degree of uncertainty due to variability of weather patterns and

emission conditions. This makes them useful for the period they are simulating, but more details are required for other periods. Projections based on these models can also be useful, considering weather conditions and emission source conditions that are similar to those provided.

6. CONCLUSIONS

The results revealed that:

- The highest concentrations registered in Hellisheidi surround the power station, as shown in the comparison charts of measurements taken in the 86 monitoring stations and supported by the model simulation.
- The model simulated a dispersion plume in the most extreme conditions: without topographic interference, no wet depositions, and highest emissions of hydrogen sulphide from the power plant. All of these conditions simulated the maximum plume dispersion, and revealed that hydrogen sulphide emissions, in the conditions studied, do not move towards Reykjavík, unless special conditions are present; the hydrogen sulphide concentration, once spread throughout the area, is in the range of 1-3ppm.
- When Hellisheidi began operations, the highest concentrations registered for Reykjavík in the months of October and November 2006 reached 0.035 and 0.02 ppm, which is not that high an increase compared with concentrations measured in the months of June, July and August. The highest peaks registered after the power plant began operating occurred in February 2007 when the weather conditions changed, with lower temperatures registered and wind patterns for the Reykjavík area showed winds blowing from the southeast where the power plant is located.
- The increase in concentrations in the Reykjavík area in September, prior to the opening of the power plant, has a high probability of being related to the testing and bleeding of wells before initiating operations and the unstable wind patterns experienced during that period.
- It is recommended that a more consistent monitoring programme for hydrogen sulphide emissions in Hellisheidi be implemented since the power plant is expanding its production and this could increase hydrogen sulphide emissions and affect the air quality of Reykjavík. It is also recommended that deposition levels and identifying relationships between emissions, atmospheric loadings, and effects on human health and the environment be better characterised.

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APPENDIX I: Environmental definitions of hydrogen sulphide

| Compound | Hydrogen sulphide |
|--|---|
| Synonyms | Hydrogen sulphide, sulphur hydride, sulphuretted hydrogen, stink damp |
| Melting point (°C) | -82.4 |
| Boiling point (°C) | -60.4 |
| Flammability range (%) | 4.3-45 |
| Odour threshold ($\mu\text{g}/\text{m}^3$) | 0.76 |
| Environmental assessment level: | |
| short term ($\mu\text{g}/\text{m}^3$) | 150 |
| long term ($\mu\text{g}/\text{m}^3$) | 140 |
| Occupational exposure standard: | |
| short term (mg/m^3) | 21 |
| long term (mg/m^3) | 14 |
| Health effects | Irritant to eyes, mucous membranes in upper respiratory system. Acute central nervous system poison at higher concentration, causing headaches, dizziness, nausea and death |

Source: WHO, 2000

APPENDIX II: Monitoring instrument for hydrogen sulphide emissions used by Reykjavík Energy in the 86 monitoring stations

The information provided in this appendix was taken from: ABLE Instruments & Controls (2007), web page: www.able.co.uk/631-X.htm

Jerome 631XE**Applications**

Ambient air analysis
 Odour nuisance monitoring
 Regulatory compliance
 Control room corrosion monitoring
 Quality control
 Scrubber efficiency testing

Accuracy check for other hydrogen sulphide monitors and control systems
 Hydrogen sulphide source detection
 Leak detection
 Applied research projects

Specifications

| | |
|-----------------------|--|
| Resolution | 0.001 at range 0 to 0.1 ppm at range 3 |
| Detection range | 0.003-50 ppm |
| Precision | 5% relative standard deviation |
| Accuracy | Range 0: ± 0.003 ppm at 0.050 ppm Range 1: ± 0.03 ppm at 0.50 ppm Range 2: ± 0.3 ppm at 5.0 ppm Range 3: ± 2 ppm at 25 ppm |
| Response time | Sample mode: 10-50 ppm in 13 s 1.0-10.0 ppm in 16 s 0.10-1.00 ppm in 25 s 0.001-0.100 ppm in 30 s Survey mode: 10-50 ppm in 3 s 1.0-10.0 ppm in 6 s 0.10-1.00 ppm in 15 s 0.001-0.100 ppm in 20 s |
| Flowrate | 150 cc/min or 0.15 l/min |
| Power requirements | 100-120 V ~ 50/60 Hz, 1 A or 220-240 V ~ 50/60 Hz, 1 A |
| Internal battery pack | Rechargeable nickel-cadmium |
| Environmental range | 0-40 °C, non-condensing, non-explosive |
| Interfaces | RS-232 PC using JCI software |
| Dimensions | 6" W x 13" L x 4" H |
| Weight | 7 lb / 3Kg |
| Warranty | One year, factory parts and labour |
| Certifications | European Communities (CE) for 220-240 V~ model only |

**APPENDIX III: Monitoring instrument for hydrogen sulphide emissions used by
Department of Environment of Reykjavík city in the monitoring station at Grensásvegur 15**

The information provided in this appendix was taken from the web page of Database of Air Pollution Continuous Monitoring Technology in Japan (2007).

Ambient monitor HORIBA APSA-360A

Combined use of the H₂S converter unit and the APSA-360 SO₂ monitor makes H₂S measurement possible.

The H₂S converter unit contains two types of catalyst tubes: SO_x scrubber and H₂S converter. SO_x is removed by SO_x scrubber, and then the H₂S that has passed through is converted into SO₂ by the H₂S converter. This SO₂ is then measured by the APSA-360 SO₂ Monitor for display as H₂S concentration.

