Modelling H_2S Dispersion from San Jacinto-Tizate Geothermal Power Plant, Nicaragua

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ABSTRACT

One of the main environmental concerns during the operation of geothermal power plants is related to hydrogen sulphide (H_2S) emissions, which negatively affect the air quality in its environs. National ambient air guidelines for H_2S have not been developed in Nicaragua; hence, project developers voluntarily follow international guidelines for atmospheric concentration and occupational safety. Solution-mineral equilibria considerations and assumed steam consumption of the 72 MW power plant in San Jacinto-Tizate were used to constrain the annual H_2S emission at 1400 tons/year. Dispersion modelling of the H_2S emission from the power plant was carried out using AERMOD model to predict H_2S ground level concentrations in the vicinity of the project. The prevailing spatial distribution of the plume was to the west of the power plant, spreading towards west-northwest and west-southwest. The modelling results show that the operation of the San Jacinto-Tizate geothermal power plant does not have significant impact on air quality of the neighbouring communities, since populated areas are located outside of the predominant plume pathway during the modelled period January-December 2012. A comparison of the model predictions with measured concentrations averaged over 24 hours within 1.5 km distance from the power plant shows an underestimation of the measured values at most of the monitoring points, suggesting that the model predictions should be considered indicative rather than accurate. Several sources of uncertainty that may contribute to this differences were identified, namely the source input data used for modelling, the characteristics of the location of the control points, the operation conditions of the power plant when the measurements were made as well as the influence of natural sources of H_2S in the measured concentrations. The results, however, provide useful information to analyse the spatial distribution and the extent of the plume during a given period, and can assist policy makers and project developer to review and improve the air quality monitoring plans.

1. INTRODUCTION

Nicaragua, the largest country in Central America (129,500 km^2), has the greatest potential for developing geothermal resources in the region (Zúñiga, 2003). Despite the geothermal potential in the country, this renewable energy resource has not been widely utilised so far. The most significant project in the last decade was the commissioning of a 72 MW Power Plant in the San Jacinto-Tizate Geothermal field, in north western Nicaragua.

Polaris Energy Nicaragua S.A. (PENSA), subsidiary of Ram Power Corporation, has the concession rights for the development of a 40 km^2 area in the San Jacinto-Tizate geothermal field. A 10 MW$_e$ power plant with 2x5 MW back pressure units was operated from June 2005 to April 2012. The project expansion works began in 2008 for a new 2x36 MW condensing units power plant. In December 2012, the installed capacity of the power plant was brought to 72 MW$_e$. To date, full electricity production has not been reached due to lack of steam and PENSA is currently conducting a remediation program to increase the steam resource of the field and to bring the total generation to approximately 59 - 63 MW (Ram Power, 2013).

Geothermal fluids naturally contain various non-condensable gases (NCG), which are also naturally vented to the atmosphere through diffusive gas discharges from areas of natural leakage, including hot springs, fumaroles, geysers, hot pools, and mud pots. These natural discharges have taken place throughout the history of the Earth and continue today independent of geothermal power production (Holm *et al.*, 2012).

The amount of gases that are present in the geothermal fluid and which might be emitted to the environment depends on a variety of factors. The main factors are the resource fluid chemistry, fluid phase (dry steam or liquid), and temperature, but the type of power plant (back pressure, flash, dry steam, binary, or combined cycle) and the plant characteristics (efficiency and gas abatement systems) also influence emission levels (Bloomfield *et al.*, 2003). Gas concentrations and compositions cover a wide range, but the predominant gases are carbon dioxide (CO_2) and hydrogen sulphide (H_2S). The emissions are mainly from the gas exhausters of the power station, often discharged through a cooling tower (Hunt, 2000).

In liquid dominated reservoirs, the majority of the gases are dissolved in the fluid in the geothermal system. During utilization and depressurisation of the geothermal fluid the gases are concentrated in the steam phase and are finally vented out of the condensers of the turbines to the atmosphere (Gunnarsson *et al.*, 2013). In vapour-dominated fields in which all waste fluids are re-injected, non-condensable gases in steam are the most important discharges from an environmental perspective (Hunt, 2000). The gas emission inevitably affects the air quality around the power plants as the concentration of the geothermal gases increases. Under certain weather conditions and if good distribution of the gases at the disposal site is not secured, the gases can affect air quality tens of kilometres from the power plant site (Gunnarsson *et al.*, 2013; Thorsteinsson *et al.*, 2013).

Studies on H_2S emissions to the atmosphere have been made in many geothermal areas around the world. In some countries with extensive geothermal development and utilisation, H_2S emissions have posed the utmost environmental concern. The studies have shown that after the development of geothermal areas, the air quality has been negatively affected in nearby towns and villages (e.g.

Iceland and New Zealand). As a result new regulations on atmospheric concentration of H_2S have been set and the geothermal industry is required to lower gas emission from geothermal power plants, focusing on H_2S abatement (Gunnarsson *et al.*, 2013).

Hydrogen sulphide is heavier than air and it can accumulate in closed and/or depressed areas. Some of the fatal incidents with volcanic gases have been attributed to the effect of H_2S released by low temperature fumarolic vents or by gas bubbling through thermal springs (D'Alessandro, 2006). H_2S is both an irritant and asphyxiate gas. Levels of up to 20 ppm have generally no effects on healthy people while for asthmatic persons this level has to be reduced to 2 ppm (WHO, 2003). Concentrations above 20 ppm may irritate the eyes and respiratory tract, above 50-100 ppm neurotoxic effects appear and 500-1000 ppm are considered of immediate life danger (WHO, 2003). Although the human odour threshold is very low (0.02 ppm), at a concentration of 150 ppm it leads to loss of smell.

In the San Jacinto-Tizate geothermal field in Nicaragua, a moderate low gas concentration in the steam has been reported (CNE, 2001; IDB, 2010). Ambient air concentrations of H_2S in the range of 0.001-0.02 ppm averaged over 24 hours have been reported in the vicinity of the power plant site (PENSA, 2012); however, studies on the dispersion and spatial distribution of the emissions have not been carried out to date.

Many countries do not have ambient air quality guidelines for H_2S, as it is not perceived as a problem in most regions (IVHHN, 2014). The ambient air standards are generally health-based guideline values to protect people's health and well-being. The World Health Organization (WHO) Air Quality Guidelines set an ambient air value of 150 $\mu g/m^3$ averaged over 24 hours and also gives a value for smell to become a nuisance at 7 $\mu g/m^3$ over at 30 minute average. Likewise, occupational exposure standards provide threshold limits for chemical substances in the working environment based on health effects safety guidelines. International occupational exposure limits for H_2S averaged over 8 hours vary from 7100 - 14200 $\mu g/m^3$, European Commission (2009) and ACGIH (2009) respectively.

In Nicaragua, a national ambient air guideline for H_2S has not been developed so far, hence project developers are encouraged to follow international standards, usually the WHO guidelines. With the recent change of technology and increased installed capacity of the San Jacinto-Tizate power plant, concerns about the effects of the H_2S emissions on air quality in the area have arisen. Villages located near the San Jacinto-Tizate project may be exposed to H_2S ambient air concentrations due to emissions from the power plant; however this has not been yet studied in relation to the extents and relevance of the impacts. To date, the only background data on air quality in the area consist of reports prepared by the project developer PENSA, based on limited air quality monitoring carried out at the project site twice a year since 2006.

Dispersion software based on Gaussian plume equation has been widely applied to estimate the dispersion of various air pollutants (Seangkiatiyuth *et al.*, 2011; Thorsteinsson *et al.*, 2013). The present study attempts to identify the temporal and spatial distribution of H_2S emissions from the San Jacinto-Tizate power plant through a dispersion model (AERMOD) and the question of whether the concentration of H_2S in the vicinity of the geothermal power plant could exceed ambient air standards when the it operates at full load is addressed.

2. STUDY AREA

2.1 Location and Site Description

The San Jacinto-Tizate geothermal field is located in the municipality of Telica, Department of León, Nicaragua. The geothermal concession covers an area of 40 km^2 with an estimated potential of 200 MW. The project site is concentrated in the eastern sector of the concession, encompassing an area of about 4 km^2 at an elevation about 150 to 200 m.a.s.l.

The San Jacinto village is located about 2 km to the south of the project site (Figure 1), with an estimated population of 1,400 inhabitants and isolated from the project area by low hills. Four settlements dispersed into small dwellings are found in the eastern sector of the concession area: El Chorro with a population around 245 inhabitants, El Apante Central with 401 inhabitants, La Cruz del Apante with 243 inhabitants and El Ojochal de Liston with 128 inhabitants (IDB, 2010). Sparse subsistence farming and low-scale non-intensive livestock activities prevail in the area.

The geothermal concession overlaps with a protected area; the Volcanic Complex Telica-Rota Nature Reserve, mainly located in the western sector of the concession. The Reserve area is delimited in the 300 m elevation contour line, covering an area of approximately 9,053 ha. It has been classified within Category IV in the International Union for Conservation of Nature (IUCN), which management approach is to maintain, conserve and restore species and habitats in areas that have already undergone substantial modification, necessitating protection of remaining fragments, with or without intervention (IUCN, 2014).

The project site is located in highly intervened fragmented dry habitat, which is sparsely inhabited. No threatened or endangered species have been documented in the area (PENSA, 2008). A large part of the vegetation in the vicinity of the project has been extremely modified by agriculture activities, cattle grazing and firewood extraction. A substantial part of the area is covered by pasture land. There are abundant grazing lands, vast prairies, and thin forests with somewhat dense tree patches (4 - 10 m in height), where *caducifolias* or *subcaducifolias* prevail. Arboreal species are limited to more elevated zones in the volcanic complexes and in in areas with high geothermal activity, the vegetation is scarce (IDB, 2010). Throughout the concession area, natural geothermal manifestations such as fumaroles, mud pools and hot springs are found.
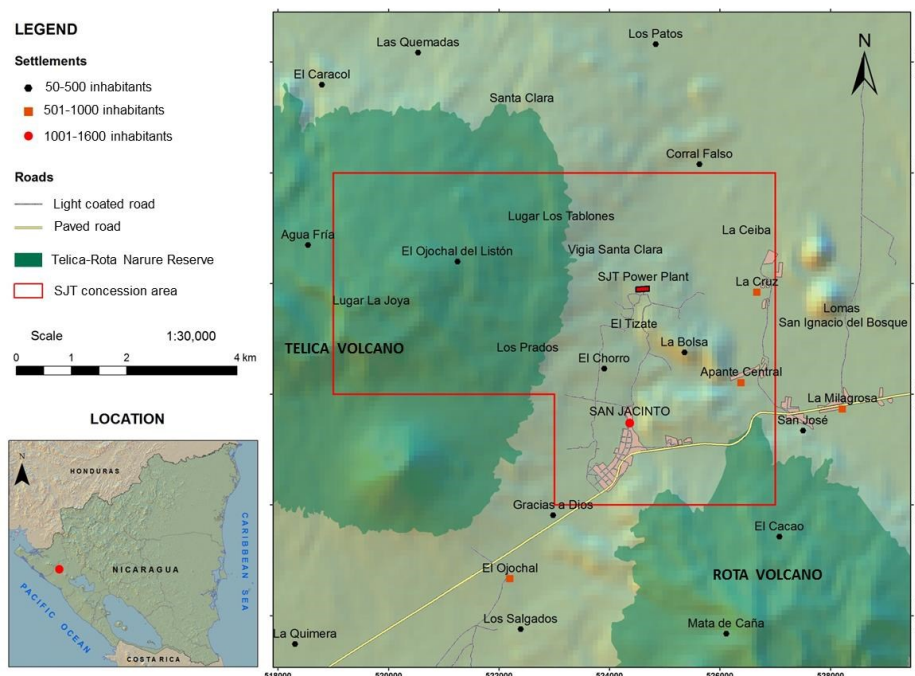
Figure 1: Location and features of the San Jacinto-Tizate geothermal concession area.

2.2 Geological Settings

The San Jacinto-Tizate geothermal field is located in north-western Nicaragua. The geological and tectonic history of the western region has been related to the geodynamic evolution of the pacific continental margin, characterized by subduction of the Cocos Ocean plate beneath the Caribbean Continental Plate (CNE, 2001)

The surface geology of San Jacinto largely consist products from the surrounding volcanic centres of Telica, Santa Clara and Rota, which overlie a suite of older volcanic and epiclastic rocks that are locally intruded by porphyritic diorites. Similarly, extrusive volcanic rocks (lavas and tuffs) and related breccias, mainly of andesitic composition, with some intercalated volcanogenic sediments and intrusive diorites have been largely encountered in wells (White *et al.*, 2008).

The geological succession of the field consists mostly of igneous, pyroclastic and intrusive rocks of basic-to-intermediate composition and sedimentary deposits of primary volcanic origin. The age of the rocks varies from late Miocene to Holocene. Different stratigraphic units have been identified, including pyroclastic-effusive units of the recent San Jacinto, Santa Clara and Rota volcanoes, a late Pleistocene unit of the El Chorro-Tizate volcano, the extrusive domes of Ignacio del Bosque, proluvial sediments of the San Jacinto Depression, and other units encountered only in the deep wells (Spektor, 1994).

2.2.1 Alteration Mineralogy

The hydrothermal alteration produces different alteration mineral assemblages in the rock at progressively increasing temperatures in the geothermal system. In the San Jacinto-Tizate geothermal field, hydrothermal alteration has been studied based on examination of drill cuttings. Depth-mineral zonation, which reflects the temperature stability of the hydrothermal minerals, is displayed at San Jacinto-Tizate in agreement with typically observed in high temperature geothermal systems.

According to White *et al.* (2008), five alteration assemblages have been identified in the wells drilled in San Jacinto-Tizate, although only three of these are common. With increasing depth from surface, these are:

1. Argillic: smectite and interlayered clays (chlorite-smectite and illite-smectite) are accompanied by zeolites (clinoptilolite, chabazite, epistilbite/heulandite, stilbite/mordenite), quartz, pyrite, iron oxides, calcite and chlorite, with rare opal and cristobalite. The zeolites are more or less zoned according to their temperature ranges in the shallower sections.

2. Mixed argillic-prophylitic: epidote is typically encountered at a depth of about 400-600 m, before illite replaces interlayered clays, meaning that instead of a purely phyllic zone, there is a zone of mixed argillic and prophylitic minerals.

3. Prophylitic: epidote is accompanied by minerals such as illite, laumontite, wairakite, adularia, prehnite, quartz, chlorite, calcite and pyrite.

4. High temperature prophylitic: rare amphibole, indicative of higher temperatures, occurs at depth in SJ9-2.

5. Contact metamorphic: minor biotite, amphibole and garnet were observed adjacent to diorite in SJ10-1.

Petrographic studies reveal disequilibrium mineral assemblages in all of the wells examined to date, with the coexistence of epidote with interlayered illite-smectite being one of the most obvious signs. This indicates that reservoir conditions have fluctuated over time (White *et al.*, 2008). The relatively low calcite content compared with the common presence of zeolites is consistent with low

gas in the deep fluids, while the general absence of minerals such as alunite indicates that acid fluids are restricted in their distribution, if they occur at all in this part of the system (White *et al.*, 2008). From the hydrothermal minerals reported in San Jacinto-Tizate geothermal system, of outmost interest to this study is the alteration minerals involved in controlling the activity of dissolved gases. In the case of H_2S these are: epidote, quartz, prehnite, pyrite, pyrrhotite, wollastonite, anhydrite and magnetite.

Epidote ($Ca_2 (Al, Fe)_3 Si_3 (OH)$) is a common mineral in geothermal reservoirs, being recognized as a key index mineral related to temperature, permeability, and fluid composition (Bird and Spieler, 2004). In well SJ9-2 at San Jacinto-Tizate, epidote is first identified at 600 m depth, increasing in abundance below 921 m depth. Epidote is usually associated with wairakite and quartz (Quintero-Roman, 2010). The composition of epidote in active geothermal systems indicates a near complete solid solution between clinozoisite ($Ca_2Al_3Si_3(OH)$) and epidote ($Ca_2Al_2FeSi_3(OH)$), involving substitution of Fe^{3+} for Al^{3+} on one of the three octahedral sites. The Fe end-member ($Ca_2Fe_3Si_3(OH)$) is referred to as pistachite and the composition of epidote minerals is commonly expressed in terms of mole fraction of pistachite (X_{ps}) which is defined as:

$$X_{ps} = \frac{n_{Fe}}{n_{Fe}+n_{Al}}$$
(1)

Epidote composition in the San Jacinto-Tizate geothermal field has not been reported to date.

Quartz (SiO_2) is commonly reported in all wells and through all depths. In well SJ9-2 quartz first appears around 129 m depth, as a small crystal ($\geq$160-190°C). With increasing depth it occurs as euhedral and anhedral crystals, often replacing other minerals especially plagioclase or zeolite. It also occurs as vesicles fillings or as fine veins. In thin sections quartz is associated with epidote, calcite, wairakite and clay (Quintero-Roman, 2010).

Prehnite ($Ca_2Al_2Si_3O_{10}(OH)$) commonly occurs as a secondary mineral in basalts and related rocks. In well SJ9-2 at San Jacinto-Tizate appears as a small crystal at 681 m, where it is associated with epidote, being scarce in the entire well (Quintero-Roman, 2010). Prehnite is a common mineral in geothermal fields, where it generally forms at temperatures between 250 and 350°C (Bird *et al.*, 1984). Prehnite composition depends on the substitution of ferric iron (Fe^{3+}) for aluminium (Al^{3+}) in the octahedral sites, defined as moles of Fe^{3+} per formula unit equivalent $X_{Fe,\ preh}=n_{Fe}$. The composition of prehnite in San-Jacinto Tizate geothermal field is unknown.

Pyrite (FeS_2) has been reported at different depths in well SJ9-2. The stratigraphy in the well consists primarily of interlayered andesitic lavas and tuffs, where pyrite is observed disseminated in the rock and also filling vesicles and veins (Quintero-Roman, 2010).

Anhydrite ($CaSO_4$) is a common mineral in saline geothermal areas or in sedimentary hosted geothermal system where inflow of fluid with a saline composition commonly results in the precipitation of anhydrite. This mineral was rare in SJ9-2, just observed in thin sections at 600 m and 1350 m depth (Quintero-Roman, 2010).

The hydrothermal minerals wollastonite ($CaSiO_3$), pyrrhotite (FeS) and magnetite (Fe_3O_4) have not been reported in wells from San Jacinto-Tizate.

2.2.2 Geochemistry

According to data from well testing and gas chemistry, the San Jacinto-Tizate is a liquid-dominated reservoir with outflows of steam and water to surface thermal areas (CNE, 2001). The deep fluid from the reservoir has been sampled from production wells, reporting a slightly alkaline, medium salinity, Na-Cl waters (CNE, 2001; White *et al.*, 2008). The chemistry of the wells is quite uniform, with calculated reservoir chloride concentrations falling in a range of 1,800 to 2,400 ppm and approximately neutral pH, typical of high temperatures hydrothermal systems developed in young volcanic rocks (CNE, 2001).

The composition of the gas dissolved in the deep liquid is represented by 95% in volume of CO_2 and 1% - 5% in volume of H_2S. The proportion of gases in the steam is of approximately 0.5% to 1.5% in weight, and the concentration of H_2S in the steam is approximately 300 to 600 ppm in weight (CNE, 2001). The gas content in the steam from San Jacinto-Tizate reservoir has also been reported by IDB (2010), presenting a moderate low concentration (in production to date) with measured amounts of 0.45% in weight, from which only about 8% is H_2S. This represents an H_2S concentration of about 360 ppm in the steam.

3. CONSTRAINTS ON THE H_2S EMISSION OF THE SAN JACINTO-TIZATE GEOTHERMAL POWER PLANT

Detailed information on the concentration of dissolved gases in the steam from the San Jacinto-Tizate geothermal field was not available for this study nor was the steam flow from wells and geochemistry of the deep liquid in the geothermal system. Therefore an alternative method for estimating the content of dissolved gases in the geothermal fluid was used, being the gas of interest hydrogen sulphide (H_2S). The known installed capacity of the power plant (72 MW) and its estimated efficiency (in terms of MW per kg of steam) was used to estimate the steam flow. Mineral equilibrium considerations in the geothermal system were used to assess the H_2S concentration in the steam.
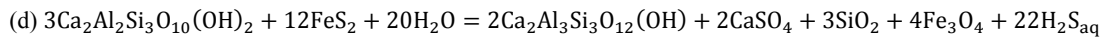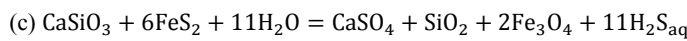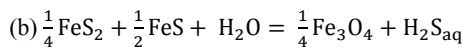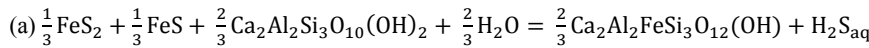
3.1 Approach

Fluids from geothermal systems contain dissolved gases, such as CO_2, H_2S, H_2, N_2, CH_4 and Ar. The concentration of individual gases varies depending on geological settings, temperature and composition of the geothermal reservoir (Gunnarsson *et al.*, 2013). Recent studies have successfully demonstrated that the gas concentration in geothermal well discharges is controlled by temperature-dependent equilibria between alteration minerals in the reservoir rock and gas concentration or gas ratios in the producing aquifer (Arnórsson and Gunnlaugsson, 1985). A similar approach is used to estimate H_2S gas concentration in the deep liquid from the San-Jacinto Tizate geothermal system, given the alteration mineralogy and temperature reported for this geothermal field.

Karingithi (2002) studied the state of equilibrium between the reactive gases and selected hydrothermal mineral buffers in the liquid-dominated, volcanic geothermal system Olkaria in Kenya. Subsequently, Karingithi et al. (2010) used chemical geothermometers to evaluate which processes controlled the aquifer fluid compositions in the same geothermal system. The approach largely focused on minerals that constitute assemblages that potentially could control the aquifer liquid water concentration of the reactive gases, CO_2, H_2S and H_2. González-Contreras (2010) analysed secondary mineral assemblages that could be involved in controlling the concentration of components present in the fluid such as CO_2, H_2S and H_2 in the Reykjanes Geothermal system, SW Iceland. In this study, the control of mineral buffers on the gas chemistry in the geothermal fluid was analysed, determining trends of gas concentration as a function of temperature.

Here the activity of dissolved H_2S in the deep geothermal liquid from the San Jacinto-Tizate geothermal system is predicted assuming equilibrium with the mineral assemblages proposed by González-Contreras (2010) and Karingithi et al. (2010), as follows: pyrite, pyrrhotite, prehnite and epidote; pyrite, pyrrhotite and magnetite; wollastonite, pyrite, anhydrite, quartz and magnetite; prehnite, pyrite, clinozoisite, anhydrite, quartz and magnetite.

The following balanced chemical reactions represent mineral buffers that may control H_2S in a given geothermal system:

(a) $\frac{1}{3}FeS_2 + \frac{1}{3}FeS + \frac{2}{3}Ca_2Al_2Si_3O_{10}(OH)_2 + \frac{2}{3}H_2O = \frac{2}{3}Ca_2Al_2FeSi_3O_{12}(OH) + H_2S_{aq}$

(b) $\frac{1}{4}FeS_2 + \frac{1}{2}FeS + H_2O = \frac{1}{4}Fe_3O_4 + H_2S_{aq}$

(c) $CaSiO_3 + 6FeS_2 + 11H_2O = CaSO_4 + SiO_2 + 2Fe_3O_4 + 11H_2S_{aq}$

(d) $3Ca_2Al_2Si_3O_{10}(OH)_2 + 12FeS_2 + 20H_2O = 2Ca_2Al_3Si_3O_{12}(OH) + 2CaSO_4 + 3SiO_2 + 4Fe_3O_4 + 22H_2S_{aq}$

Each of these reactions was solved numerically for gas concentration for a given temperature. Equilibrium constants (K) as a function of temperature were computed with SUPCRT92 software (Johnson et al., 1992) for reactions **c** and **d** and for reactions **a** and **b**, K was computed based on temperature equations for equilibrium constants presented by Karingithi et al. (2010).

For the evaluation of mineral control of gas concentration, the activity of dissolved species is calculated. The aqueous solutions composition presented in terms of molality (*m*) is related to the activity (a_i) by an activity coefficient (γ_i).

$$a_i = m_i * \gamma_i \tag{2}$$

The activity model most commonly used in geochemical studies (Debye-Huckle model) assumes that the natural logarithm of the activity coefficient of a given dissolved species is a function of its charge. As a result the value of the activity coefficient for the uncharged species is equal to unity and thus the activity equal to molality. Hydrothermal minerals such as quartz (SiO_2), calcite ($CaCO_3$), pyrite (FeS_2), pyrrhotite (FeS), anhydrite ($CaSO_4$), magnetite (Fe_3O_4), wollastonite ($CaSiO_3$) and water were considered to be pure and therefore their activity equal to 1. In the case of solid solutions as prehnite ($Ca_2Al_2Si_3O_{10}(OH)_2$) and epidote ($Ca_2(Al,Fe)_3Si_3O_{12}(OH)$), activity values were computed from data published by Bird and Spieler (2004), where the mineralogical characteristics and composition of epidote in active geothermal systems by global tectonic setting is presented.

In the case of convergent plate boundaries of the Circum-Pacific Margin, where Central America is located, epidote and prehnite composition from Miravalles geothermal system in Costa Rica has been reported. For this study, the composition from the above mentioned minerals in Miravalles geothermal system was deemed to be representative of the San Jacinto- Tizate geothermal system in Nicaragua, given the similarity of geothermal areas located within the same region. In the Miravalles geothermal field, epidote compositions range from X_{ps}=0.18 - 0.32, and prehnite from X_{Fe}=0.04 - 0.24 (Bird and Spieler, 2004). A mean value for composition of epidote X_{ps}=0.25 and prehnite X_{Fe}=0.14 is used for obtaining the following activity values: a_{ep}≈0.75, a_{Czo}≈0.25 and a_{Preh}≈0.86.

For the mineral buffers considered to be controlling H_2S, equilibrium constants are used according to the following principle in terms of activities of the species,

$$A + \beta B = \gamma C + \delta D \tag{3}$$

$$K = \frac{[C]^\gamma [D]^\delta}{[A]^\alpha [B]^\beta} \tag{4}$$

The predicted concentrations of H_2S as a function of temperature in the deep liquid for each mineral buffer considered is calculated for the reported temperatures in San Jacinto-Tizate geothermal system, 250-290°C (Figure 2). Reactions for reduced conditions in the geothermal system (lines **a** and **b** in Figure 2) predict high H_2S concentration values, while reactions for oxidised conditions (lines **c** and **d)** predict low concentration of H_2S in the geothermal system. The variation in the predicted concentration depends on the mineral assemblages controlling H_2S in the geothermal system. Different scenarios can be inferred depending of the conditions in the geothermal system. The low concentrations predicted by reactions **c** and **d**, are representative of geothermal systems controlled by oxidised conditions, as is the case of saline geothermal systems.

The concentration of H_2S in the San Jacinto-Tizate geothermal system is assumed to be controlled by mineral assemblages considered in reaction **b** (reduced conditions), which represents the second worst case scenario for H_2S emissions. Highly reduced conditions, represented by reaction **a**, have not been reported for the San Jacinto-Tizate geothermal field.
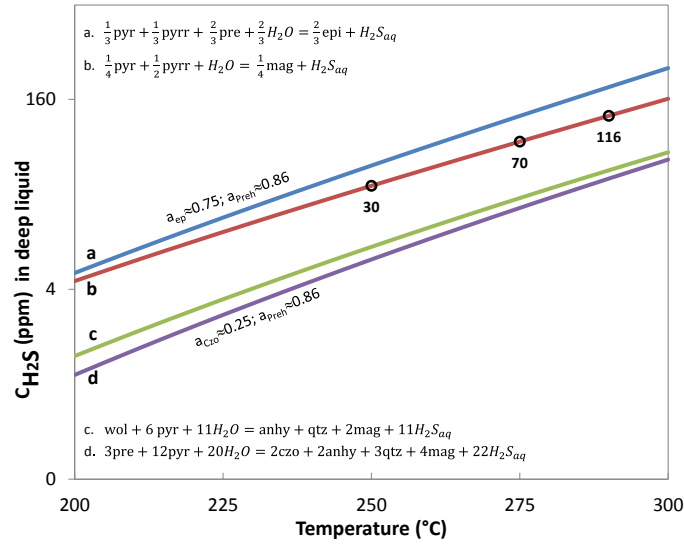
Figure 2: H₂S gas concentration in the deep liquid as a function of temperature for theoretical mineral equilibrium, where lines a and b represent reduced conditions and lines b and c, oxidised conditions.

3.2 Concentration of H₂S in steam

Given the concentration of H₂S in the deep liquid from San Jacinto-Tizate geothermal system, the H₂S concentration in the steam can be computed under the assumption that all the gas is contained in the steam phase when the deep liquid boils. The gas concentration corresponds to the ratio between the concentration in the deep fluid and the steam fraction correspondent to a reference temperature and pressure.

The steam fraction is computed assuming that the San Jacinto-Tizate geothermal system is liquid dominated, the temperature of the deep liquid ranges from 250-290°C and a separation pressure of 10 bar-a. Boiling in the geothermal system is taken to be adiabatic, when the fluid rises to the surface it boils due to reduced hydrostatic pressure. Likewise, conservation of enthalpy is assumed and no heat or mass is lost or gained to the environment when the fluid rises, the enthalpy content is constant.

The steam fraction is computed in terms of enthalpy by the following equation,

$$X = \frac{h_t^{dl} - h_{ps}^l}{h_{ps}^s - h_{ps}^l} \qquad (5)$$

where h refers to enthalpy, the superscripts *dl, l* and *s* refer to deep liquid, liquid and vapour phases, respectively. Subscripts refer to reference temperature (*t*) and separation pressure (*ps*). For the considered temperature range in the San Jacinto-Tizate geothermal system, the calculated steam fraction varies from 0.160 to 0.262.

The H₂S gas concentration in steam is calculated from the following equation, assuming all the gas is contained in then steam phase,

$$m_i^{dl} = X m_i^s + (1 - X) m_i^l \qquad (6)$$

$$m_i^s = \frac{m_i^{dl}}{X} \qquad (7)$$

where m_i refers to the concentration of the gas *i*, the superscripts, *dl, s,* and *l* refer to deep liquid, steam phase and liquid phase, respectively and *X* refers to the steam fraction for the reference conditions.

For the purpose of the present study, the concentration of H₂S in San Jacinto-Tizate geothermal system is assumed to be controlled by reaction **b**, representing the second worst case scenario in terms of H₂S emissions (Figure 3). Taking reaction **b** as reference, the predicted concentration of H₂S in steam will be 64% higher if the system is controlled by minerals in reaction **a**; and 67% to 73% lower if H₂S is controlled by minerals in reaction **c** and **d** respectively.

In the San Jacinto-Tizate geothermal field, a temperature in the range of 250-290°C has been reported in boreholes. Assuming that the mineral assemblages considered in reaction **b** represent the conditions in the geothermal system, an H₂S concentration in steam in the range of 186-445 ppm is predicted. In this study, a mean temperature of the deep liquid at 275°C is assumed, resulting in a concentration of 317 ppm of H₂S in the steam. This value is within the H₂S concentration range of 300-600 ppm reported by CNE (2001) in the steam from San Jacinto-Tizate, and in good agreement with the concentration reported by IDB (2010) of 360 ppm.
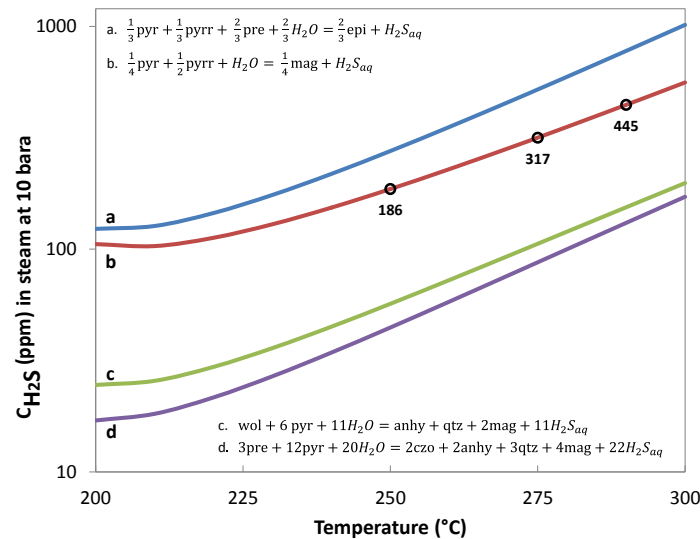
Figure 3: H$_2$S concentration in the steam from San Jacinto-Tizate geothermal system, where lines a and b represent reduced conditions and lines b and c, oxidised conditions.

3.3 Hydrogen Sulphide Emissions

The known installed capacity of the power plant (72 MW) and its estimated efficiency (in terms of MW per kg of steam) is used to estimate the steam flow. Given the concentration of H$_2$S of 317 ppm in the steam and a steam consumption of 2 kg/s per MW in a standard condensing turbine (Dickson and Fanelli, 2004), the H$_2$S emissions from San Jacinto-Tizate power plant when it operates at full load for a whole year was estimated as 1400 tons/year.

4. DISPERSION MODELLING

4.1 Meteorological Data

Hourly measurements of wind speed, wind direction, air temperature, pressure, relative humidity and precipitation from the weather station run by the project developer, PENSA in the San Jacinto-Tizate geothermal power plant site were obtained for the period January 2012 to June 2013. Daytime cloud cover reports for the same period were obtained from León weather station (code 64043), run by Nicaraguan Institute for Territorial Studies (INETER) 22 km west of the project site. Night time cloud cover was estimated using a linear interpolation function available within R statistic software (R Core Team, 2013).

Easterly winds were identified in the project area (Figure 4), with prevailing ENE (15.6% of the time), E (14%) and SSW (13.7%) winds with a mean wind speed of 3 ± 2 m/s. The average air temperature reported is 27 ± 3°C and the average relative humidity (RH) 63 ± 16%.
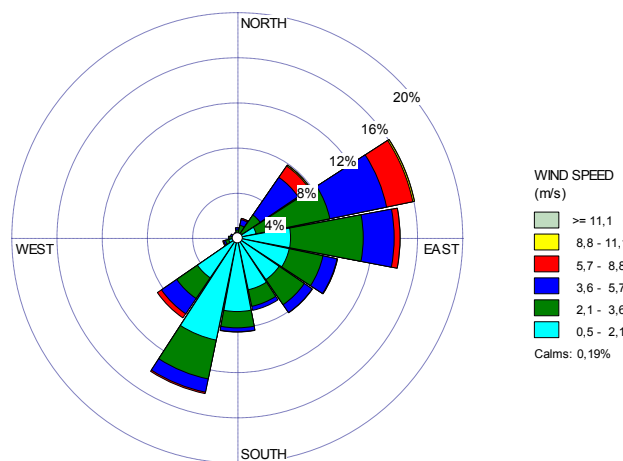

Figure 4: Wind Rose for the SJT Weather Station January-December 2012.

4.2 AERMOD Model

AERMOD software for atmospheric dispersion modelling was used to predict the H$_2$S concentrations in the vicinity of San Jacinto-Tizate Geothermal Power Plant. AERMOD is a steady-state Gaussian plume model designed to estimate the near-field (less than 50 km) concentration of air pollutants. The model runs with a minimum of observed meteorological parameters and treats both surface and elevated sources on simple and complex terrain (Cimorelli *et al.*, 2004).

AERMOD input data is prepared from output files from AERMET and AERMAP, its meteorological and terrain pre-processors. AERMET uses meteorological data and surface characteristics to calculate boundary layer parameters (e.g. mixing height, friction

velocity, etc.) needed by AERMOD. AERMAP uses gridded terrain data to calculate a representative terrain-influence height and elevation for each receptor. The input data for AERMAP was supplied in the format of a Digital Elevation Model (DEM) with a resolution of 30 m of posting interval and 7-14 m accuracy downloaded from ASTER GDEM.

Time series of weather parameters (hourly surface observations) were input to AERMET meteorological pre-processor and upper air data (vertical temperature gradient and wind profile) was computed by the upper air estimator within AERMET, based on hourly surface data. The surface parameter coefficients (albedo, Bowen ratio and surface roughness) for AERMET meteorological pre-processor were set to summer conditions for both wet and dry season model simulations of the climate in Nicaragua, considered the closest analogue for seasonal conditions in the US and Canada, where the model was developed. Variable surface roughness parameters were used based on the land cover around the SJT weather station. The Wieringa- Davenport roughness classification (Wieringa, 1992) was used as reference for selecting the values to use within AERMET options. The classification used was "Roughly open" ($z_0 = 0.1$ m) for cultivated areas with low crops or plant covers, "Rough" ($z_0 = 0.2$ m) for cultivated areas with crops of varying heights and "Very rough" for areas with clumps of trees and bush land ($z_0 = 0.8$ m).

AERMOD also incorporates the buildings downwash effect in the modelling results. The movement of air over and around buildings generates areas of flow circulation, which can lead to increased ground level concentrations in the building wakes (RPS, 2009). In the San Jacinto-Tizate project area, the only buildings likely to affect dispersion are the power house and the cooling towers' own structure. Rectangular buildings were selected to represent the layout of the power plant, using a dimension (*L, W, H*) of 74.7 x 18.7 x 12 m for the cooling towers and 77.8 x 32 x 16 m for the powerhouse.

Discrete Cartesian receptors and uniform Cartesian grids were defined within the modelling domain to identify areas of maximum predicted H_2S concentrations. Populated areas in the vicinity of San-Jacinto Tizate power plant were set as discrete receptors, as well as control points defined in agreement with points from the air quality monitoring program implemented by PENSA.

In the San Jacinto-Tizate geothermal power plant, the H_2S emissions are made through the cooling towers. The NCG are discharged below the cooling tower fans to ensure mixing with the air and steam as it is blown high into the atmosphere. The H_2S is then mixed in the plume emitted through five closely spaced outlets in the cooling tower. There is a cooling tower for each 36 MW condensing unit in San Jacinto-Tizate Power Plant. The cooling tower outlets are modelled as one point source with a combined area of all five outlets with the characteristics shown in Table 1. Based on preliminary design parameters of the San Jacinto-Tizate power plant, the gas temperature used is the steam temperature in the cooling tower exhaust (~40°C) and the gas exit velocity was estimated from the airflow through the cooling tower based on a simplified scheme of the cooling needs in the system (condenser-cooling tower).

Table 1: Source Input Data for AERMOD

SJT Power Plant	6-7 June 2013	Full year
Electricity generation (MW)	59	72
Emission rate (g/s)	37.3	45.5
Number of stacks	2	2
Base elevation (m.a.s.l.)	185	185
Release Height (m)	14	14
Gas exit velocity (m/s)	3	3
Gas exit temperature (°C)	40	40
Stack inside diameter (m)	24.6	24.6

4.3 Modelling Results

Two different periods were modelled in AERMOD. The first one considering the San Jacinto-Tizate power plant operating at full load (72 MW) for a whole year, using meteorological data from the period January-December 2012. The second one represents a short period on 6-7 June 2013 which was modelled in agreement with the H_2S monitoring dates in the project area by PENSA.

4.3.1 Annual Average

The dispersion of the H_2S emission from the San Jacinto-Tizate power plant operating at full load for a whole year was modelled in AERMOD. In the model, long-term averages do not include calm winds or missing hours in the calculations. The annual average is the sum of the concentrations from the non-calm/non-missing hours divided by the number of non-calm/non-missing hours.

The modelling showed that the highest concentrations are to be expected in the immediate vicinity of the power plant (Figure 5). The maximum concentration predicted was 116μg/m^3 and occurs next to the power plant building. The San Jacinto village and other smaller settlements are located outside of the plume pathway, except for few isolated dwellings or farms located in the places identified as Receptor A, Los Prados and El Ojochal del Listón.
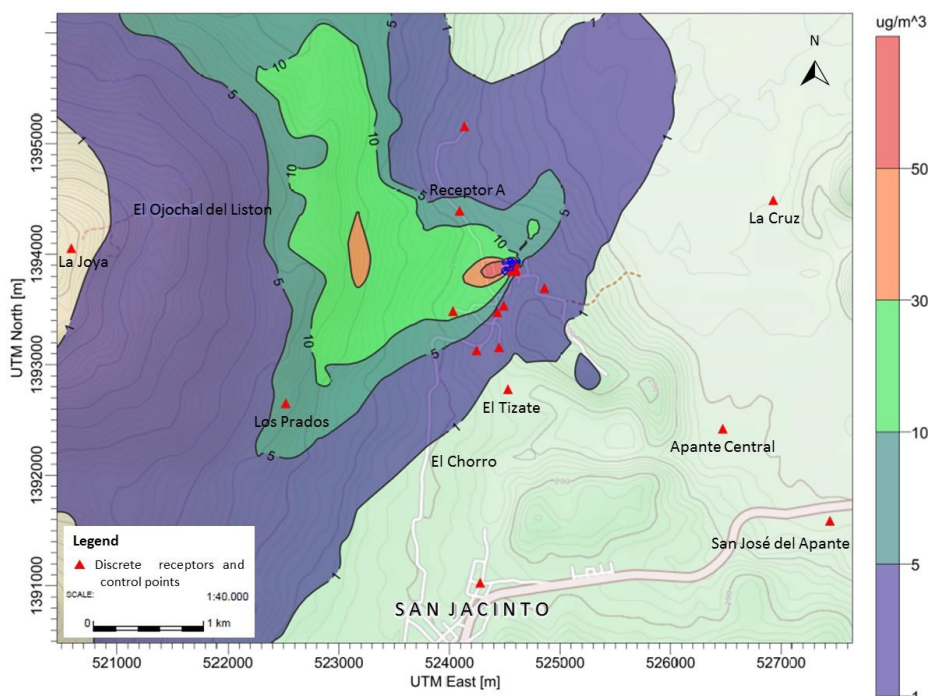
Figure 5: Annual average H$_2$S concentration for the modelled conditions in 2012

4.3.2 Highest 24 Hour Average

The short term average results from AERMOD represent the highest concentrations reported by receptor for the averaging period. The contours are based in the highest 24h average concentration by receptor, occurring at different times for different locations. The spatial distribution of the plume for 24h averaging time extends over a wider area than the annual average, including populated places, where H$_2$S concentrations up to 50 µg/m^3 are predicted (Figure 6). The highest concentration occurs about 1.2 km west from the source, and also near the power plant building, where a peak value of 1462.2 µg/m^3 is predicted on 7 March, 2012. In these places, the WHO ambient air guideline of 150 µg/m^3 averaged over 24 h is greatly exceeded.

The number of times that the WHO ambient air guideline is exceeded in a year is also predicted by AERMOD. According to the model, the guideline value is exceeded at least 1-5 times within a distance about 1 km from the power plant in the W, WNW and WSW direction. In the immediate vicinity of the power plant the guideline value is exceeded numerous times, predicting up to 77 times next to the exhaust from the cooling towers.
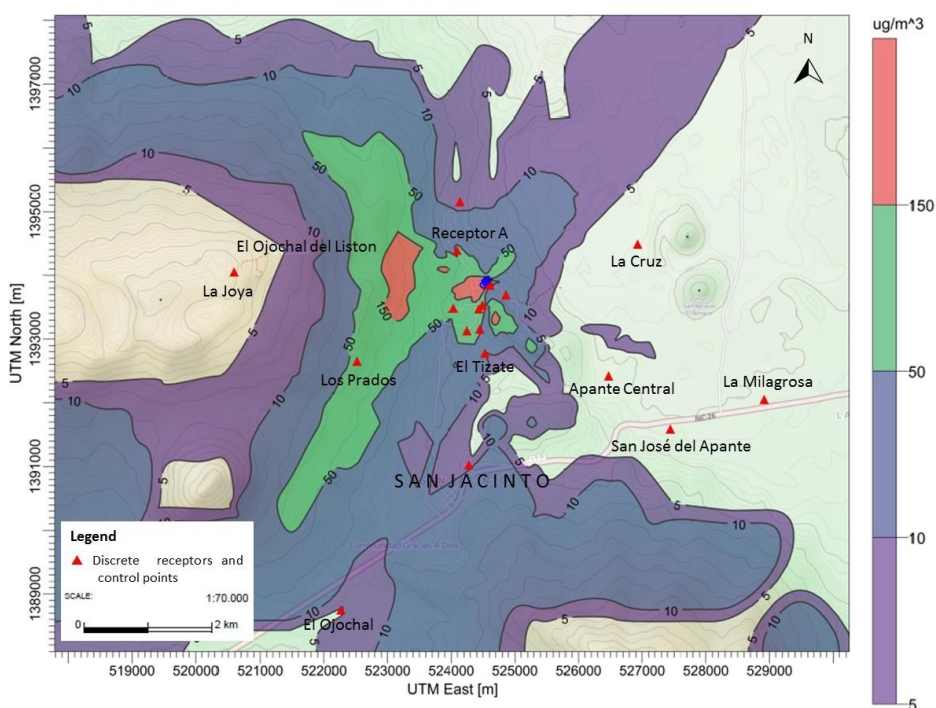

Figure 6: Highest H$_2$S 24 hour average concentration at any given location for the modelled year 2012

9

4.3.3 Highest 8 Hour Average

The highest concentration in an 8 hour averaging time was also modelled. The results show that the concentration can reach really high levels in the immediate vicinity of the power plant, reporting a peak value of 2382 µg/m³ on 7 March, 2012 from 16:00-00:00, located in between the Power House building and the Cooling Tower 1 structure (Figure 7). In most of the populated places the H_2S concentration ranges from 10-150 µg/m³. The 8 h average concentration is mainly used for occupational safety purposes, where the exposure limit may vary from 7100 - 14200 µg/m³ (European Commission and ACGIH respectively). None of these exposure limits for 8-hour averaging period is exceeded in the study area.
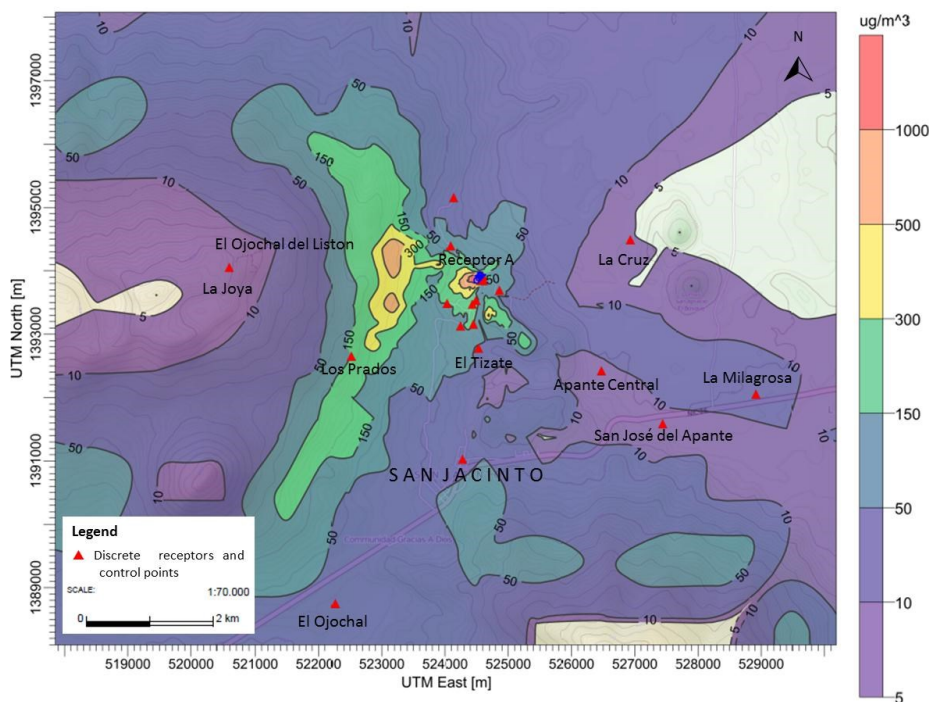

Figure 7: Highest H_2S 8 hour average concentration at any given location for the modelled year 2012

The location of maximum concentrations for all the modelled averaging periods occurs at the same site, the west sector of the power plant site. This result is in agreement with the prevailing ENE and E winds in the San Jacinto-Tizate project area. The peak concentration values occurred in between the Cooling Tower 1 structure and the Power House building for all averaging times. This can be associated to building downwash effects, since the movement of air over and around buildings generates areas of flow circulation, which can lead to high ground level concentrations in the building wakes (RPS, 2009).

4.3.4 Comparison of Predicted and Measured Concentrations on 6-7 June 2013

The modelled period for comparing the model predictions started on 19 June at 15:00 and ended on 20 June at 14:00, covering the same hours considered in the reported averaged concentrations. For these days, the average air temperature was 27 ± 3°C and the average wind speed was 2 ± 1 m/s, with prevailing SSW (29 % of the time), SSE (21%) and SW (14%) winds.

During the modelled period, the majority of the H_2S monitoring/control points were located within the plume (Figure 6a) and the maximum predicted concentration occurred some 0.3 km WNW from the power plant. The comparison of the measured and predicted averaged concentrations showed that monitoring points located outside of the modelled plume and close to the edge were underestimated (Figure 6a and Figure 6b). Some points were fairly predicted (Cooling Tower, Power plant Unit 3 and Unit 4) and two points located northwest from the power plant (Receptor A and SJ-11) were largely overestimated by the model.

The modelling showed a better agreement with measured concentrations when the monitoring points were located closer to the source whereas the agreement was generally very poor for points located near the plume edge. However it should be noticed that the fair prediction of some of the measured values at some monitoring points indicates that assumptions made to constrain the H_2S concentration as well as other source characteristics like emission temperature and velocity are not completely off from real values but in a range of divergence.

The concentration contours obtained from modelling are certainly a useful visualization tool. It has to be underlined; however, that a model is a simplification of a complex process in which many factors interact and therefore the results are approximations that may not accurately reproduce or fit to measured concentrations in a given place.
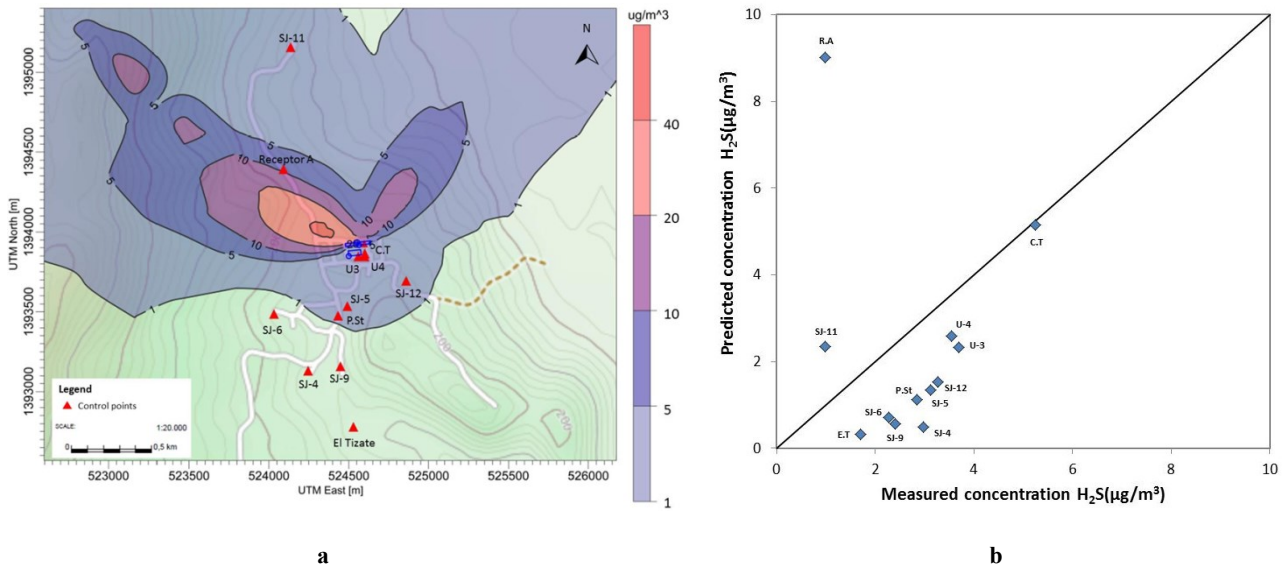
a

b

Figure 6: a) Spatial distribution of the plume on 6-7 June 2013, b) Comparison of predicted and measured concentrations

5. DISCUSSION

The results from modelling show that the operation of the San Jacinto-Tizate geothermal power plant does not significantly affect the air quality of the neighbouring communities. Populated places are located outside the prevailing plume pathway during the modelled periods, in agreement with prevailing winds blowing from ENE, E and SSW in the area.

When modelling the San Jacinto-Tizate geothermal power plant operating at full load for a whole year, using weather data from 2012, AERMOD model shows that H_2S emission mostly affects the air quality in the immediate vicinity of the power plant. The plume centreline is oriented towards west, spreading to NW and SW most of the time. The surrounding villages are located outside of the most common plume pathway, however when modelling a shorter averaging time (8h) over a whole year, concentrations in the range of 50 -150 $\mu g/m^3$ are predicted at some populated places.

The WHO ambient air guideline value for H_2S (150 $\mu g/m^3$ averaged over 24 h) is only exceeded within 1.2 km distance from the power plant in the west direction. Nevertheless, the occupational safety guidelines (7000-14200 $\mu g/m^3$ averaged over 8 h) are never exceeded at any location in the study area.

Sensitivity analysis was conducted on two source input parameters, the gas exit velocity and the concentration of H_2S in the steam release from the power plant, the latter based on two possible conditions that could control the H_2S concentration in the the geothermal system. If the concentration of H_2S in the geothermal reservoir was controlled by the more reducing reaction **a** instead of reaction **b**, the predicted concentrations at ground level will increase by a constant factor (linear increase) at each receptor or monitoring point considered, predicting 64% higher values. This however is unlikely to occur in the San Jacinto-Tizate geothermal reservoir, because the mineral assemblages considered in reaction **a** represent highly reduced conditions in a geothermal system, a condition that has not been reported for this geothermal field. When reducing the gas exit velocity from 3 m/s to 2 m/s the predicted concentrations increased by variable rates, depending of the location of the specific monitoring points. In the case of points located very close to the source, the predicted concentration increased up to 200% while for points located further away the concentration increase is about 20-40%.

When comparing the results from AERMOD model with measured averaged concentrations during the period 6-7 June 2013, the model predicts lower concentrations for the majority of the monitoring points. For two specific points located north from the source (Receptor A and SJ-11), the model predicted much higher concentrations. Many factors can explain the mismatch in the model predictions including accuracy of the coordinates of control points in the model, the source input data used, the characteristics of the location of the control points and the particular operation conditions of the power plant during the air quality monitoring period, which are unknown. In addition, natural release of H_2S from fumaroles in the project area is not accounted for in the model; although these natural sources can affect the average measured concentrations used for comparison with predicted concentrations by the model.

To provide a better analysis of the relevance of the model results in relation to measured concentrations, some adjustment in the input data should be made in accordance to the real operation conditions in the power plant, meaning the use of measured H_2S concentration in the steam and air flow in the cooling towers to compute the exact gas exit velocity. In addition, increasing the number of monitoring points to cover a wider area in the west direction from the source could provide better background data for comparison with the modelling results. The current H_2S measurements are made at locations aligned to the north and south from the source, without providing a wider spatial distribution to account for some spreading of the plume.

6. CONCLUSIONS AND RECOMMENDATIONS

The method used to constrain the gas concentration in the geothermal fluid and the emissions from the power plant can be used as an alternative approach in cases where no reference data is available. The H_2S emissions from San Jacinto-Tizate power plant when it operates at full load for a whole year were estimated as 1400 tons/year. The same approach could be later used for planning purposes prior to project development in certain areas.

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The results from AERMOD modelling for a whole year when the San Jacinto-Tizate power plant operated at full load (72 MW) shows that H_2S concentration at ground level can exceed the WHO ambient air guideline (150 $\mu g/m^3$ averaged over 24 h) in the immediate vicinity of the power plant (within 1 km W), but not in populated places and surrounding villages.

When comparing AERMOD predictions with measured H_2S concentrations during the period 6-7 June 2013, the model underestimated the concentrations in most of the monitoring points, except for two points that were greatly overestimated to the north of the power plant. The discrepancy can be associated to factors like the source input data used for modelling and the characteristics of the location of the control points, as well as the specific operation conditions of the power plant when the measurements are done and the influence of H_2S natural sources in the reported measured concentration.

To better assess the relevance of the model predictions, additional information is needed along with the measured H_2S concentrations, specially the power plant operation conditions. The modelling could be refined based on reliable data from the San Jacinto-Tizate Power plant, meaning the composition of the steam as well as the air flow in the cooling towers where H_2S is emitted to the atmosphere. Based on this, a better analysis of correlation between the model predictions and measured concentrations could be done and additional sources of discrepancies in the results could be identified.

The spatial distribution of the plume was identified predominantly in the W direction of the power plant, spreading towards WNW and WSW for the modelled periods. The air quality trend in case of future expansion of the power plant could be easily identified based on the modelling results, as well as the extent of the new impacted area. The most important weather conditions affecting the modelling results are the wind speed and direction along with the atmospheric stability during different hours of the day.

The results from AERMOD model provide useful information to analyse the spatial distribution and the extent of the plume during a given period; nevertheless the predicted H_2S concentration at specific locations should be considered indicative rather than accurate predictions of ground level concentrations. The modelling results however can assist policy makers and project developers to review and propose improvements to the air quality monitoring plans as well as mitigating measures if needed.

The installation of a H_2S continuous monitoring station at the project site is highly recommended to document the changes in air quality in real time. While this measure is not implemented, the air quality monitoring plan of the project should be improved by increasing the duration and frequency of the monitoring periods.

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