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ENVIRONMENTAL FACTORS TO BE CONSIDERED IN GEOTHERMAL EXPLORATION/PRODUCTION IN DOMINICA

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ABSTRACT

Dominica forms a part of the Volcanic Caribbees in the Lesser Antilles Island Arc and has nine active volcanoes whereas the other islands have one volcano per island. Southern Dominica is the most active part of the island and includes the Wotten Waven area, one of the sites due for geothermal exploration. Preliminary surface exploration in Wotten Waven suggests the possibility of the existence of a deep high-temperature reservoir.

Dominica is known as the “Nature Island” of the Caribbean and therefore promotes eco-tourism. Very often geothermal sites are found in environmentally sensitive areas, often of historic and cultural importance. Wotten Waven falls into this category, hence the recommendations suggested. The purpose of this report is to serve as a guideline to the Government of the Commonwealth of Dominica regarding geothermal development. In the event of geothermal development, and despite being a clean and sustainable source, there are several factors to be taken into consideration due to potential impacts on the environment.

1. INTRODUCTION

The Lesser Antilles Island Arc is a chain of islands, 740 km long which stretches from the Anegada Passage in the north to the South American continental margin. Dating as far back as the Eocene period, this area has been one of high seismicity, tectonic activity and active volcanism. The Island Arc was formed as a result of the subduction of the North American plate under the Caribbean plate.

The Lesser Antilles presents a very interesting structure. North of Dominica the island arc divides into two giving rise to the Limestone Caribbees which refers to all the islands found on the northeast end of the arc while the Volcanic Caribbees are in the more active part of the arc and comprise all the islands found on the western side or inner arc from Saba in the north, to Grenada in the south (Figure 1).

The volcanoes of the Lesser Antilles have produced a wide variety of eruptive products. The most abundant rock types are andesites. Dominica lies in the centre of the Lesser Antilles Island Arc and has a land area of 750 km². It is the most rugged of the islands; about 60% of the land is still covered

with lush green vegetation. There are nine active volcanoes in Dominica, unlike in the other volcanic islands of the Lesser Antilles which feature one apiece. There has been no major magmatic eruption in recent times. Two phreatic eruptions took place in the Valley of Desolation in 1880 and in 1997. Each of the major peaks has its own radial drainage system. Also known as “The Nature Island” of the Caribbean, Dominica has one of the densest water networks per area in the world. The island is characterized by vigorous and widespread geothermal outcrops and relatively frequent seismic episodes. Dominica boasts its three National Parks and World Heritage Site, Northern and Central Forest Reserves, its 365 rivers and streams, scenic and relatively challenging hiking trails (the level of difficulty varies), sulphur baths, bird watching, the Syndicate Parrot Reserve and much more.

The island enjoys a typical wet tropical climate with relatively high temperatures and abundant rainfall. Temperatures vary from 21-26°C during January to 22-30°C in June. At night there is very little variation in the temperature. The temperature may not vary greatly from month to month, but the precipitation does. Dominica has a rainy season from June to November, which is also called the Atlantic Hurricane Season. However, the rest of the year also sees rain but not as heavy. The average annual rainfall is about 5,000 millimetres. On the west coast (Leeward side) rainfall is much less abundant, only about 1,800 millimetres per year.

Two of the highest points in the Lesser Antilles Island Arc are found on the island of Dominica: Morne Diablotins which stands at 1,421 m and Morne Trois Pitons at 1,394 m. The southern part of Dominica is characterized by recent volcanic activity, less than 100,000 years old. The main volcanic centres are: Morne Trois Pitons, Morne Micotrin, Grand Soufriere Hills, Morne Paradis, Morne Plat Pays and Morne Patate. Two areas with high temperature and surface hydrothermal manifestations are recorded in the south part of the island, in connection with volcanic activity: the Wotten Waven area and the Soufriere area. They are considered potential geothermal resources.

Dominica is, in fact, the most active of all the Caribbean volcanic areas and the opinion that the island is long overdue for an eruption has been expressed by a few scientists. Sigurdsson and Carey (1980) concluded that about 30,000 years BP, a large Plinian eruption released about 58 km³ of pumiceous material / tephra in what was described as the largest eruption in the past 200,000 years in the Caribbean. The capital of Roseau and most of the island’s infrastructure lie on this pyroclastic flow fan and abound with ignimbrites, surge and airfall deposits derived from the Wotten Waven and Morne Trois Pitons caldera situated on the eastern outskirts of the capital. All conclusions indicate that the capital of Roseau is located in one of the most hazardous areas of the island.

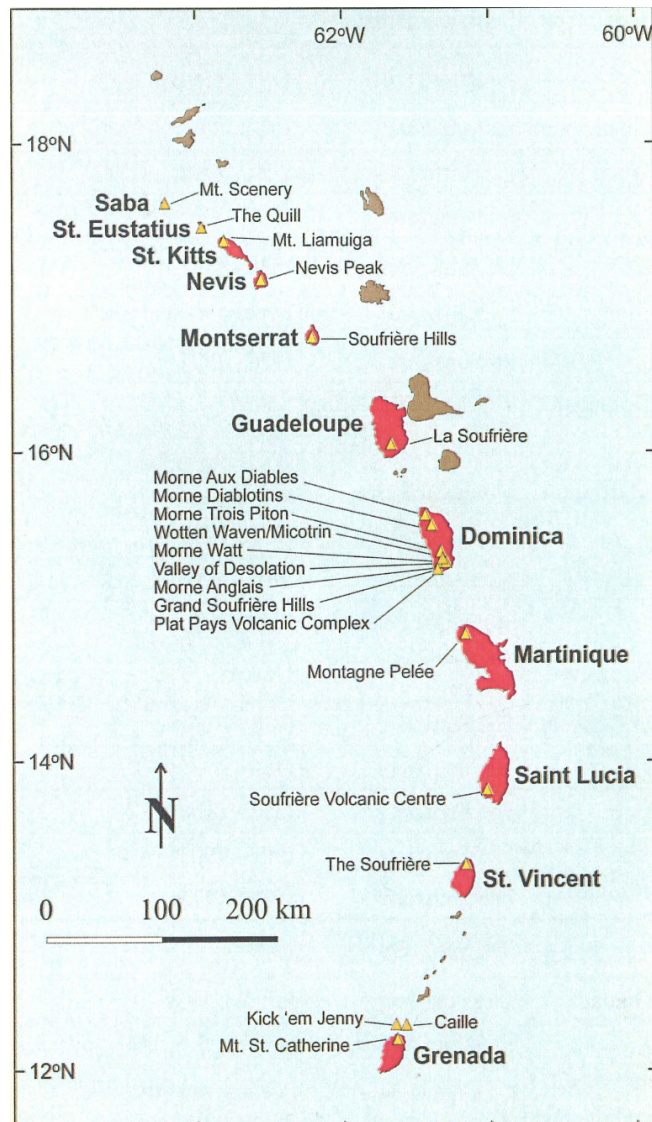


FIGURE 1: Map of the Volcanic Caribbean of the Lesser Antilles (Lindsay et al., 2005)

2. REVIEW

2.1 Thermal manifestations in the Wotten Waven area

Wotten Waven is situated roughly 8 km east-northeast of the capital of Roseau. There are several surface manifestations such as hot springs, fumaroles, phreatic craters etc. present. These are mainly concentrated in two spots: The Wotten Waven village and the Boiling Lake - Valley of Desolation.

The area is characterized by several bubbling pools and fumaroles of up to 99°C. The geothermal activity in Wotten Waven is situated in and adjacent to the River Blanc, a tributary of the Roseau River. Surface manifestations observed in and around the area have been classified into eight types: warm springs, hot springs, mineralized fluid hot springs, fumaroles, kaipohan, solfataras, fossil alteration areas, and phreatic craters (Table 1).

The geothermal activity associated with River Blanc is related to the fractured lava forming the Wotten Waven basement. Manifestations vary from steam vents, steaming ground and springs. Some springs discharge hot mineralized fluids while other springs discharge warm low-mineralized waters

TABLE 1: Types of surface manifestations recorded in the Wotten Waven geothermal field (adapted from Lasne and Traineau, 2005)

Cold spring	Spring discharging fluids at ambient temperature and conductivity lower than 100 $\mu\text{S}/\text{cm}$, characterized or not by light red-coloured Fe-hydroxide deposits, associated or not with diffuse degassing (H_2S).
Warm spring	Spring discharging warm fluids at a temperature lower than 50-60°C and conductivity lower than 1,000 $\mu\text{S}/\text{cm}$, usually isolated, characterized by red-coloured Fe-hydroxide deposits.
Hot spring	Spring discharging low-mineralized fluids (conductivity lower than 1,000 $\mu\text{S}/\text{cm}$) at a temperature higher than 60°C; isolated or observed within Solfatara areas along with other thermal manifestations; white-coloured deposits (silica, carbonates, zeolites), black-coloured deposits (Fe-sulphides), red-coloured Fe-hydroxide deposits.
Mineralized hot spring	Spring discharging fluids at a temperature higher than 60°C and conductivity higher than 2,000 $\mu\text{S}/\text{cm}$; isolated or observed within Solfatara areas along with other thermal manifestations; white coloured deposits (silica, carbonates, zeolites), black-coloured deposits (Fe-sulphides), red-coloured Fe-hydroxides deposits.
Fumaroles	Area characterized by steam discharge, steaming ground; no or low water flow rate; no native sulphur deposit.
Kaipohan	Area characterized by cold degassing and dead vegetation (according to Bogie et al., 1987).
Solfatara	Area with several thermal manifestations such as steam vents, fumaroles, steaming ground, mud pools, boiling pools, coloured water streams; springs may be observed or lacking; characterized by advanced argillic alteration with deposits of native sulphur, sulphate, Fe-sulphide, silica, clay material, carbonate.
Fossil alteration area	Area of extinct solfataras activity.
Phreatic crater	Vent resulting from a hydrothermal explosion; active or extinct; may be filled or not with a crater lake.

which give evidence to shallow aquifers heated by steam and gas. In the vicinity of the old Wotten Waven Lodge, and near the confluence of River Blanc and Trois Pitons River, phreatic craters are anticipated. Figure 2 shows the different types of surface manifestations along and around the River Blanc.

2.2 Structural geology

The principal sets of faults strike NE-SW, E-W and N-S. Most of these structures dip vertically or at angles larger than 60° (Lasne and Traineau, 2005). There is a correlation of the NE-SW and the NW-SE fracture sets with the main inferred faults mapped around the Wotten Waven area. The E-W set may be considered a buried structure since it does not have any identified surface manifestations according to the geological map (BRGM, 1983).

The most permeable fracture directions are presumed to be the fracture sets trending NE-SW, NW-SE and N-S. BRGM (1984, 1985) proposed that the NE-SW fracture set is parallel to a major transverse fault trending NE-SW and crossing the island. It preferentially controls shallow geothermal fluid circulation in the River Blanc valley. The NW-SE and N-S fracture sets are basically normal faults whose existence is corroborated by the alignment of the Morne Trois Pitons and Micotrin recent lava domes. This fracturing trend is observed in the vicinity of the Boiling Lake. Lasne and Traineau (2005) suggested that the geometry of the geothermal reservoir at depth is controlled by these NE-SW and NW-SE to N-S fracture networks, and secondarily by the E-W fractures (Figure 3).

One of the many characteristics of the Wotten Waven area is its active seismicity which contributes to fracturing, exemplified by the recent seismic episode recorded in 1998-99 (Young, 2005). This contention is supported by the presence of fractures in the most recent outcrop in the Wotten Waven area. The trends of the main fracture set striking NE-SW and the broad linear zone defined by the earthquake epicentres are seen to be similar.

2.3 Hydrothermal alteration

Hydrothermal alteration and deposition are widespread in the Wotten Waven area. Their products have been sampled in several places for X-Ray analysis. The mineral species identified are silica, zeolites, clays, carbonates, sulphates, Fe-sulphides, native sulphur and Fe-hydroxides.

Silica (cristobalite, quartz), native sulphur and sulphate (alunite) are the dominant mineral phases identified in the areas of high-temperature surface manifestations. Combined with pyrite and alunite, clay minerals such as smectites and kaolinite are also found precipitated in mud pools. They constitute an argillic type of alteration.

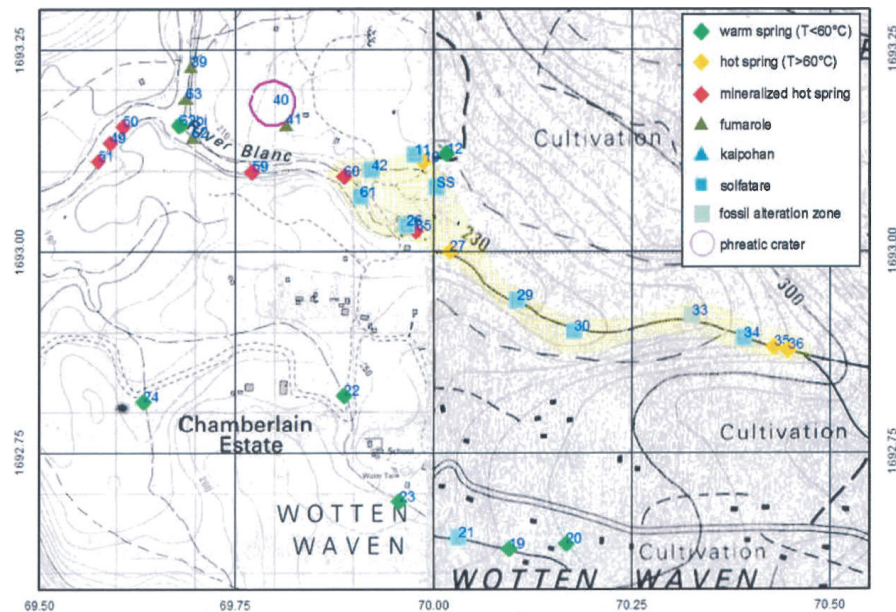


FIGURE 2: Location of the main hydrothermal manifestations in the lower section of the River Blanc, Roseau River and River Camelia (Sourced from CFG Services, 2005)

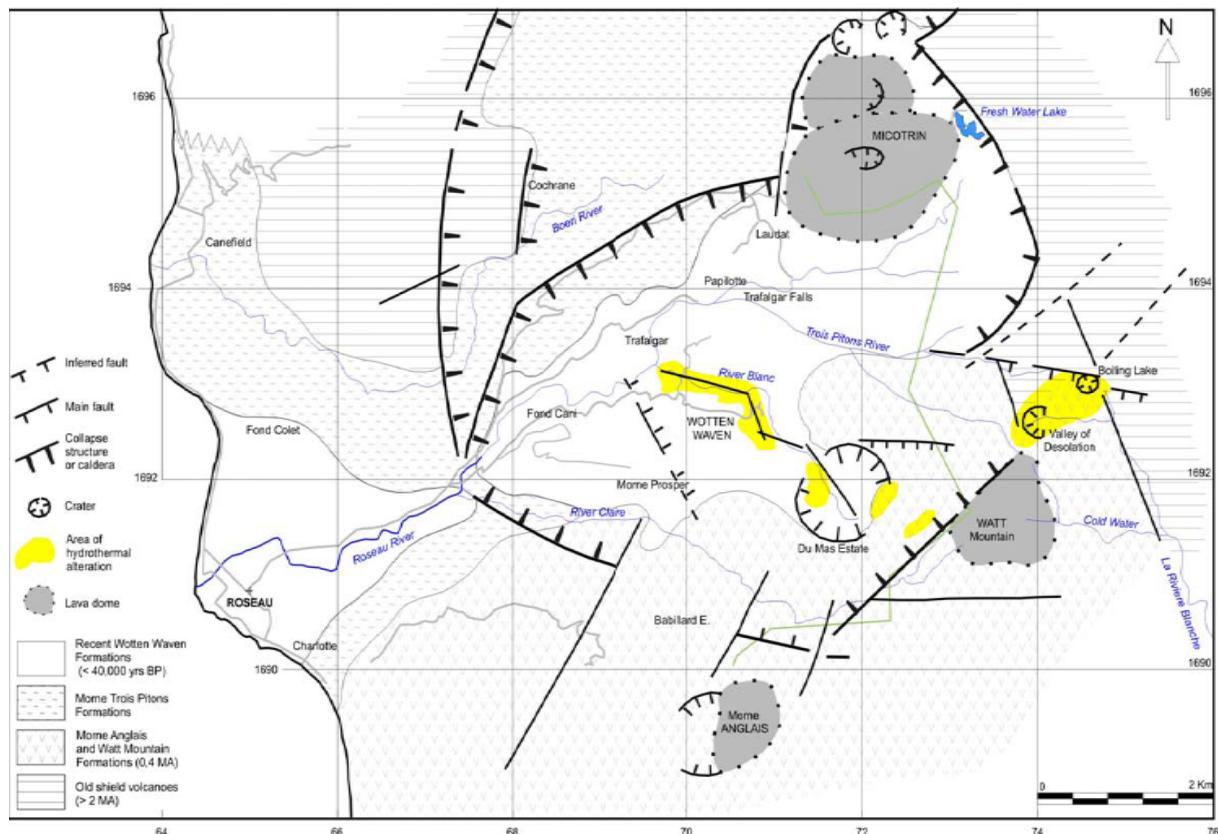


FIGURE 3: Geological and structural sketch of Wotten Waven region showing the main volcanic structures (taken from BRGM, 1984)

Deposits of white-coloured concretions from hot springs in the River Blanc are principally carbonates (calcite, dolomite) and silica (cristobalite, quartz). Veins sampled from massive lavas in the River Blanc comprise quartz, clays (smectites, kaolinite/chrysotile, and chlorite/clinochlore) and subordinate zeolites (clinoptilolite), carbonates (calcite, siderite), sulphate (alunogen), and sulphide (pyrite). The light-coloured coatings around warm springs are mainly amorphous carbonates (calcite, aragonite). The red-coloured vein deposits found around warm springs are predominantly goethite and hematite associated with silica (Traineau and Lasne, 2008).

2.4 Fluid geochemistry

2.4.1 General

Primary waters (Na-Cl type and Ca-Na-Cl type) and secondary waters (acid-sulphate type, Ca-Na-HCO₃ type and Na-HCO₃-SO₄ type) have been identified in the Wotten Waven area and the nearby Boiling Lake / Valley of Desolation area (BRGM, 1985; Lasne and Traineau, 2005).

High-temperature sodium chloride waters (TDS=1-5 g/l) are commonly representative of high enthalpy geothermal reservoirs. The main features of the new fluid analyses, collected during the field survey, revealing the distinct origin of hot mineralized fluids discharged in the River Blanc and the Valley of Desolation are:

- Sodium chloride waters, identified in four high-temperature springs located in River Blanc, are marked by the presence of seawater in various ratios (from 2.5 to 13% according to the Na and Cl contents). The other fundamental component of the fluid is highly diluted water very close to meteoric water. The high-temperature exchange between this mixed fluid and a hot reservoir

rock is proven by its chemical and isotopic characteristics (oxygen-18 shift, strontium isotopes, and geothermometers). Equilibrium with an andesite-basalt reservoir rock is reached at about 210-230°C.

- Very close to these springs, acid sulphate and sodium-bicarbonate waters emerge and are indicative of the presence of an underground steam heated aquifer. Low-temperature sodium carbonate springs are located in Trafalgar and Laudat and also in the Camelia River (Ty Kwen Glo Cho) and probably indicate the northern and southern boundaries of the shallow HCO₃ reservoir.
- Mineralized fluids discharged in the Valley of Desolation are slightly different. They contain no seawater and exhibit calcium-rich facies. Chemical geothermometers indicate a higher equilibrium temperature with the reservoir rocks, about 250-300°C.

As formerly proposed by Lasne and Traineau (2005), a field survey was carried out in 2008 to provide data on the geology of the Wotten Wave geothermal field.

- It emphasizes the link between the massive fractured lava formations belonging to the Wotten Waven basement and the discharge of mineralized, high-temperature fluids which could be related to a lateral outflow from a deep NaCl- type reservoir. The geothermal reservoir is thought to be developed within the fractured massive lava extruded during the old stages of the island building (i.e. the Watt mountain volcano). The thick layer of ignimbrite deposits covering a wide area south of the Micotrin lava dome (geological map) probably acts as a cap-rock above the massive fractured lavas.
- The N50° to N70° strike direction of the main fracture set observed at Station N°72 is very similar to the dominant NE-SW strike direction of the fracture population recorded in Wotten Waven by Lasne and Traineau (2005). This strike direction is thought to be dominant at depth within the Wotten Waven basement. Unfortunately, the dense vegetation and soil thickness prevent the mapping of fault zones (possible priority targets for well drilling) on the surface outcrops.
- The survey in the high valley of River Blanc (Robinson Estate, Du Mas Estate) does not provide evidence of the proximity of an eruptive vent related to the so-called 1300 years old Du Mas Estate eruption which emitted the debris flow deposit observed in the River Blanc and the Roseau River Valley.

2.4.2 The 2008 field survey

The 2008 survey focused on Na-Cl rich fluids. During this survey, two medium-temperature springs discharging Na-Cl waters were sampled: one in the Trois Pitons River (St70) and the other in the Roseau River (St72). They appear to be slightly more dilute than the Na-Cl waters sampled in the River Blanc in 2005.

Based on the interpretation of their chemical and isotopic composition, additional information on the Na-Cl rich fluid origin was obtained which supports the idea of the existence of a deep, high-temperature reservoir. Sodium, chloride and bromide have a marine origin. Their composition is described by a mixing model between sea and rain water. Part of the mineralization is brought about by intense water rock interaction of this mixed water at depth. Lithium, boron, arsenic, germanium and silica contents reveal good evidence of this process. The oxygen-18 shift also indicates an exchange with rocks at high temperatures.

The absence of tritium, reported by Lasne and Traineau (2005), and strontium isotopic ratios in the Na-Cl rich fluids, which indicate andesitic equilibrium values, suggests that the reservoir water transit time is long enough to ensure considerable water rock interaction in the reservoir and equilibrium at reservoir conditions.

The results from chemical and isotope geothermometers applied to sodium chloride waters are prone to variations. Lower temperatures (170-200°C) are obtained using silica geothermometers and higher temperatures with Na/K and Na/K/Ca ratio geothermometers (210-250°C).

Considering the behaviour of some minor elements such as boron, the idea of a common origin for the Wotten Waven and the Valley of Desolation mineralized fluids is not ruled out. They might be derived from a common deep, high-temperature fluid. Late deposits and mixing with different portions of rain water and seawater might explain the observed discrepancies pointed out by Lasne and Traineau (2005) between the Na-Cl fluids discharged in the lower section of River Blanc and the Ca-Na-Cl fluids discharged in the Valley of Desolation, hence supporting the idea of distinct origins. One of the main differences is the absence of seawater in the fluids of the Valley of Desolation.

The Ca-Na-Cl fluids of the Valley of Desolation appear to be less dilute and more representative of a deep Na-Cl parent fluid than the Wotten Waven fluid. Geothermometers indicate higher equilibrium temperatures (250-300°C), which is consistent with the hypothesis of a location closer to the deep reservoir (possible upflow zone?) (Traineau and Lasne, 2008).

2.5 Vulnerability and sensitivity of study area

2.5.1 Hydrological aspects of the study area

The Roseau River is one of the largest rivers on the island of Dominica and is fed by the Trois Pitons River, River Blanc and the Claire River. The Dominica Water Authority, DOWASCO, has four water production sites within or bordering the geothermal area; there are also two major Forestry water production sites in the vicinity (see Figure 4).

2.5.2 Ecology

Flora: Dominica has a very rich and diverse plant life. It is possible that every major group of plant life is represented. These include over one thousand species of flowering plants, such as orchids, palms, and other trees, shrubs, vines, bromeliads, sedges, grasses etc. The island also has almost two hundred species of ferns, fungi, mosses etc. A few species are found only in Dominica.

The study area and its surroundings are rather sensitive and most definitely subject to changes with respect to the environmental conditions to which they are exposed. The geothermal study area is well inside the Morne Trois Piton National Park and the World Heritage Site and thus is of great concern. The profile of the island, though small, has given rise to quite a variety of plants. The following eight types of vegetation regimes are found in Dominica:

- Dry forest;
- Savannah-type vegetation;
- Semi-deciduous forest;
- Tropical rainforest;
- Mountain forest;
- Elfin woodland;
- Fumarole vegetation;
- Wetlands.

The general area and surroundings of the geothermal site include wetlands, secondary and primary forest, fumarole vegetation and abandoned agricultural areas.

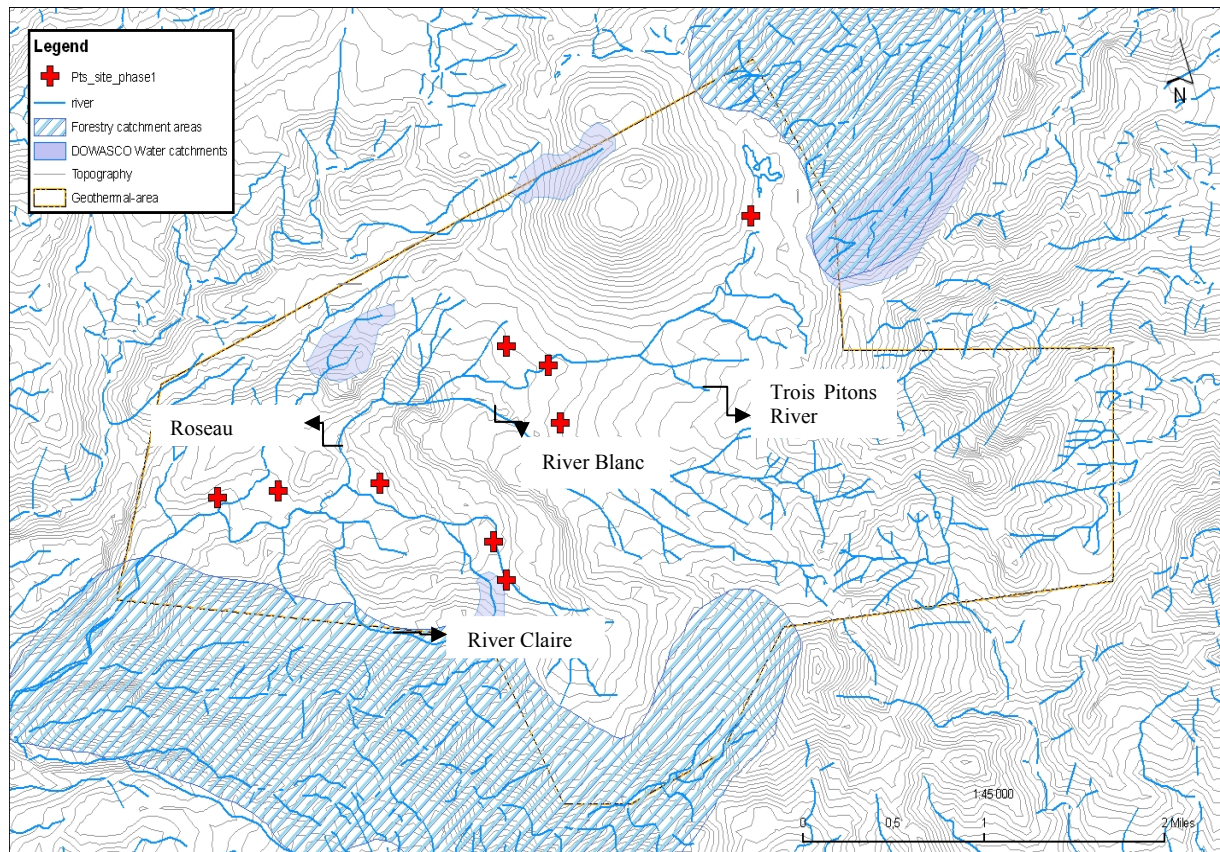


FIGURE 4: Hydrological network of the Roseau Valley (CFG Services, 2009)

Fauna: Roughly 176 species of birds have been recorded in Dominica. Fifty-nine of these live on the islands whilst a large percentage is migratory. The best known species are the two Amazona parrots, the Sisserou (*Amazona imperialis*), the island's national bird, and the Jaco (*Amazona arausiaca*), found nowhere else in the world. Among other species of interest are the Blue-headed Hummingbird (*Cyanophaia bicolor*) which lives in Dominica and Martinique only, and the very rare Black-capped Petrel (*Pterodroma hasistata*) locally known as the Diablotin, (once thought to be extinct in Dominica), the Red necked Parrot, which is endemic to Dominica only and the Plumbeous Warbler, endemic to Guadeloupe and Dominica.

Few animals were actually observed in the study area, but most of Dominica's major fauna is expected to be associated with the area of interest. There are: mammals (agouti, opossum and bats), reptiles (lizards, snakes and tortoise), amphibians (particularly the *Leptodactylus fallax* /Crapaud or Mountain Chicken as it is locally called), fresh water fish, crustaceans, insects and other small vertebrates.

Flora and fauna analysis was carried out at three points of the general geothermal area only which limits the overview of distribution and composition. Neither the observed plant nor animal species are known to be unique to the area and can certainly be found in other habitats on the island.

2.5.3 Vulnerability to natural hazards

Dominica's uniqueness also makes it vulnerable to several natural hazards.

Hurricanes: Dominica's geographical location places it in a hurricane zone. Situated in the centre of the Lesser Antilles Island Arc, Dominica has almost always been affected during the Atlantic Hurricane Season. The systems mostly develop off the western coast of Africa and frequently move in a north-westward direction, very often affecting the island. The Atlantic hurricane season runs from June 1 to November 30.

The extent of storm damage from hurricanes is on the increase in the Caribbean. As significant wind events, hurricanes continue to have an impact on a greater number of buildings each year. In developing a high-wind hazard map, data derived from a wind hazard model were considered. The entire area of interest falls within the relatively moderate to very high range on the wind hazard map.

Seismic activity and volcanic hazard: There are various indicators of active volcanism, for example:

- Seismic activity;
- Volcanic eruptions;
- Gas emissions;
- Ground deformation;
- Mass movement;
- Hot springs and geysers;
- Sulphur mounds.

The sulphur mounds at Soufriere, the pH of the nearby streams, the fumaroles and geysers of Wotten Waven, the volcanic mud and the general geothermal activity, and the frequent swarms of volcanic earthquakes in the north along with its sulphur springs all indicate that the island is underlain by an active magma body.

The Wotten Waven/Micotrin centre comprises the Wotten Waven caldera, the twin Pelean domes and the associated craters of Micotrin. There is visible evidence of past eruptive history characterized by large explosive Plinian eruptions generating ignimbrites. The more recent activity has taken the form of Pelean dome-forming eruptions producing block and ash flows and smaller pumiceous pyroclastic flows. The Wotten Waven/Micotrin centre is one of the nine active volcanic centres on the island. This area also suffers seismic activity which is of both volcanic and tectonic origin. Wotten Waven lies in a very high volcanic hazard zone but a relatively moderate seismic hazard zone.

Floods: Dominica has a very dense water network, and there is significant water density in the general area. However most of the island's difficulty with flooding has been in the low-lying and coastal areas. Nonetheless, this does not imply that there are not small localities in the interior susceptible to floods. Generally, Wotten Waven is situated in a relatively low flood risk zone.

Landslides: Landslides are among the most common hazards in Dominica. The rugged terrain, steep slopes, volcanic and clay soils, thermal alteration, seismic activity, heavy rainfall, poor road construction and anthropogenic activities are some of the many factors which contribute to these. The general location of Wotten Waven lies within a moderate to very high risk area with regard to landslides.

2.6 Socio-cultural context and economic impact

A geothermal project will bring about significant changes to the Wotten Waven and surrounding communities. The influence of traffic congestion and disturbance, noise due to drilling and vehicular circulation, landscape issues including drill rigs and building construction, the evolution of the identity of the Roseau Valley and the existing cultural and/ or historical heritage are a few of the issues that the neighbouring communities, and Dominicans in general, are going to have to come to terms with.

The main source of livelihood in the Wotten Waven area is tourism. The tourists who visit the sites will be disturbed by the noise, but even so the installation of geothermal plants will be an opportunity to generate technical tourism.

A geothermal project will create employment for several locals. Regular maintenance of the activity of the power station will be required. In addition to supplying all Dominica's electrical needs, the surplus electricity can be exported, hence generating additional revenue for the country.

3. ENVIRONMENTAL ASPECTS OF GEOTHERMAL UTILIZATION AND MITIGATING MEASURES

3.1 General

In the event of geothermal development, there are several factors to be taken into consideration due to their potential impact on the environment, regardless of the fact that geothermal energy is a clean and sustainable source. Environmental effects vary considerably from one geothermal field and power plant to another, depending on the special characteristics of the field and power plant in question. In this respect the geology and the subsurface structure as well as the type of reservoir and the type of utilization play major roles. All possible changes must be appraised in an environmental assessment report prior to exploitation and an optimum solution devised. Environmental Impact Assessment (EIA) has proven to be a powerful tool for environmental safeguarding in geothermal project planning. In this respect it is of utmost importance to have knowledge of the natural behaviour of the area; monitoring of the field is needed several years prior to development (Kristmannsdóttir and Ármannsson, 2003; Ármannsson et al., 2000).

3.2 Impact on the environment

Geothermal utilization can present several environmental issues such as:

- Surface disturbances;
- Physical effects of fluid withdrawal;
- Noise;
- Thermal effects;
- Chemical pollution;
- Biological effects;
- Protection of natural features;
- Socio-economic effects.

3.3 Mitigation

3.3.1 Preliminary action and monitoring

A fair amount of information on environmental factors in geothermal areas should be available prior to production. Surface manifestations may change significantly even though there is no production, as has been observed in the Theistareykir area in Northern Iceland (Torfason, 1992; Ármannsson et al. 2000). A thorough monitoring programme has to be devised and supervised by an outside authority. The objective of this is to be able to compare detailed information on the geothermal areas prior to and after geothermal utilization. In order to accomplish this, the degree of compliance has to be constantly monitored with respect to: applicable national regulations, requirements for the environmental assessment process, environmental policy, and safety and social responsibility issues. The biology and ecological status of the area must be established as well as the concentration of potentially hazardous chemicals in the atmosphere and groundwater (Ármannsson and Kristmannsdóttir, 1993). Monitoring

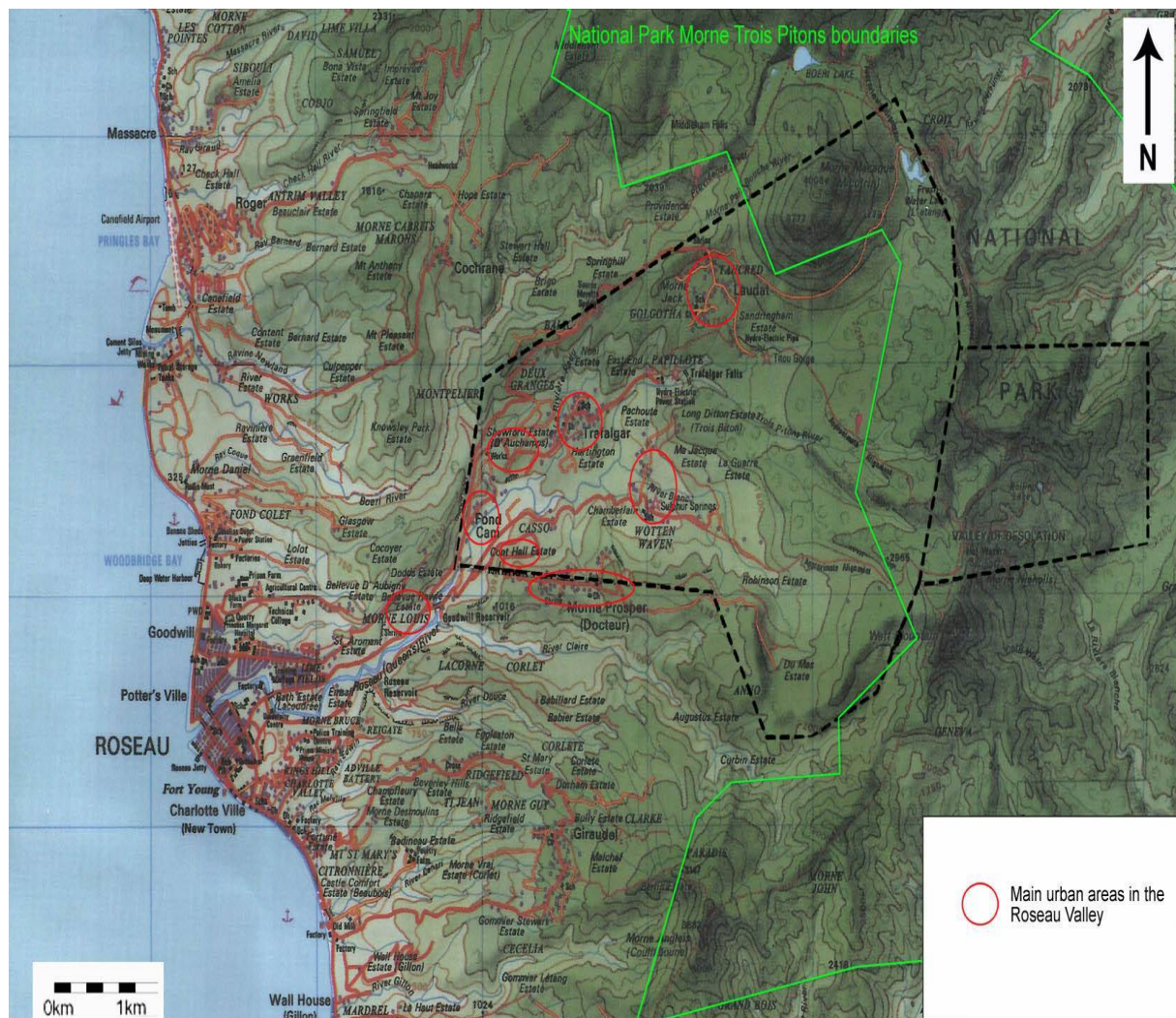


FIGURE 5: Location of urban areas in the Roseau Valley
(source CFG Services– Environmental Feasibility Study, 2009)

programmes must be activated. The aim is to be able to capture the changes induced and verify whether they occurred naturally or from outside sources and to identify deviations to be corrected.

Every geothermal area, and thus every project, is unique. Legal and institutional considerations vary from location to location. Each resource and each well drilled into a given resource varies in characteristics. The fluids produced from geothermal wells require the use of different types of pipes and other equipment materials. The physical location of each project affects the availability and quality of goods and services. Figure 5 highlights the Roseau valley.

Monitoring the quality of the environment can be carried out through programmes which consist of systematic observation, measurements and evaluation of the various parameters using appropriate methods and technology. For example:

- Monitoring programmes for air and noise quality;
- Monitoring programmes for surface and ground water quality;
- Monitoring programmes for soil quality.

The information obtained from monitoring programmes and its interpretation can be collected in a periodic monitoring report on environmental quality which should be presented to the national regulatory bodies. This certainly contributes to tracking and monitoring, and allows for continuous

verification of the status of the environment and the company's efforts and performance to fulfil its part of the contract.

3.3.2 Mitigation

Surface disturbances: Surface disturbances may take place during exploration and drilling activities, but are generally temporary and small scale (ponds are drained and the landscape is reshaped). Quite frequently, this would take place as a result of typical exploration and drilling activities, such as localized ground clearing, vehicular traffic, seismic testing, positioning of equipment, and drilling. Most impacts during the resource exploration and drilling phase are associated with development (improvements or construction) of access roads and flow testing of exploratory wells. Many of these impacts can be reduced by implementing good industrial practices and the restoration of disturbed areas once drilling activities have been completed. A drill-site usually extends over 2000-2500 m² and when more than one well is drilled the total surface area can be significantly reduced through directional drilling. Very often the source is utilized near the drill-site, hence the use of short pipelines.

Landslides: Geothermal fields are often associated with volcanic rocks such as pumice, as in Dominica. The upper basements in geothermal fields are often thermally altered and this may increase during utilization. Landslides are liable to take place in these areas and may place constraints on the sites chosen for construction. There exist several examples of landslides that were directly connected to the installation of geothermal plants (Goff and Goff, 1997); therefore, the landslide factor must be carefully monitored.

Scenery: The scenery must be attended to since the research field is situated in an area of outstanding beauty with endemic species, of both touristic importance and historical significance. However, one of the positive effects of utilization is that it can serve as an added tourist attraction. Since geothermal plants are not a very common sight and many people do not pay attention to science unless they are immediately affected by it, one of the main attractions at the power plant could be in the form of an active educational programme like those at the Nesjavellir and Hellisheidi power plants. The plants in Iceland are very well designed and kept. The well heads are scattered, but are impressively housed not only for protection, but also, so as not to cause an eye-sore. The Blue Lagoon is one of the most popular attractions in Iceland. It is, however, certainly very difficult now to have a second "Blue Lagoon" anywhere in the world, due to the emphasis placed on environmental protection. The silica rich brine is basically waste fluid from the Svartsengi power plant.

Untidiness: Untidiness at the construction sites and boreholes can be very unpleasant. Therefore, this feature should be incorporated in the monitoring programme and should be inspected regularly, preferably by an outside agency.

3.3.3 Fluid withdrawal

Fluid withdrawal can significantly affect surface manifestations. This may cause hot springs and geysers to disappear or to be transformed into fumaroles. In some cases it may lead to the relocation of activity. Fluid withdrawal can also cause land subsidence, lowering of the groundwater table and induced seismicity.

Subsidence: Land subsidence is known to occur as a consequence of fluid withdrawal from high-enthalpy reservoirs (Allis and Zhan, 1997; Allis, 2000; Eysteinnsson, 2000; Glowaca et al., 2000; Lee and Bacon, 2000). Subsidence takes place when fluid withdrawal exceeds the natural inflow into the reservoir. This net outflow causes loose formations at the top of the withdrawal site to compact, particularly in the case of clays and sediments. Key factors causing subsidence include:

- A pressure drop in the reservoir as a result of fluid withdrawal;

- The presence of a highly compressible geological rock formation above or in the upper part of a shallow reservoir;
- The presence of highly permeable paths between the reservoir and the formation, and between the reservoir and the ground surface.

If all these conditions are present, ground subsidence is likely to occur. In general, subsidence is greater in liquid-dominated fields because of the geological characteristics typically associated with each type of field. Generally, a large mass needs to be drawn from a liquid-dominated area for production. These effects are local but can trigger the instability of pipelines, drains, and well casings. They can also cause the formation of ponds and cracks in the ground and, if the site is close to a populated area, can lead to the instability of buildings. There is evidence of subsidence from all utilized areas but the magnitude varies considerably. The largest recorded subsidence is found in Wairakei, New Zealand where the maximum subsidence is 15 m (400 mm/year); at Larderello, Italy, subsidence (25 mm/year) is much less than that at Wairakei, but greater than that of Svartsengi, Iceland where the total subsidence is less than 28 cm (10 mm/year) (Hunt, 2001; Allis, 2000, Eysteinnsson, 2000; Aust and Sustrac, 1992).

Lowering of groundwater table: Mixing of fluids between aquifers and an inflow of corrosive water (seawater) may occur due to the lowering of the groundwater table. This may also cause the disappearance of springs and fumaroles or changes in surface activity (Glover et al., 2000). In addition, it can also lead to the formation or accelerated growth of a steam pillow and subsequent boiling and degassing of the field. Such a development may induce major explosions (blow-outs), the like of which has killed a number of people in the past (Hunt, 2001; Goff and Goff, 1997).

Seismicity: The natural seismicity may also be affected by fluid withdrawal as observed in Svartsengi (Brandsdóttir et al., 2002). Likewise, reinjection may induce microseismicity (Hunt, 2001). Such occurrences can mostly be avoided by a sensible choice of a reinjection site.

Fluid re-injection or, in cases where re-injection of the geothermal fluid is unsuitable, injection of different fluids into geothermal systems can help reduce the pressure drop, subsidence and other effects of fluid withdrawal (Björnsson and Steingrímsson, 1991). The effectiveness depends on where the fluid is re-injected and on the permeability in the field. Commonly, re-injection is carried out at some distance from the production well to avoid cooling of the production fluid but may not, however, help prevent subsidence. Efficiency varies with the reinjection strategy used. The main factors which determine how effective reinjection may turn out are: location, injection pressure and chemical treatment. There must be a pressure connection between the production well and the reinjection well. The injection wells must be located within the productive area in order to provide pressure support and reservoir sweep. Separating and injecting the water at high pressure keeps temperatures high, provide great support to reservoir pressures and also reduce the effects of silica deposition. There is a flip side, however, resulting in the loss of some of the energy that could have been extracted if the water had been flashed in a second stage to provide additional steam.

3.3.4 Noise

The primary sources of noise associated with exploration include earth-moving equipment (related to road, well pad, and sump pit construction), vehicular traffic, seismic surveys, blasting, and drill rig operations. Well drilling is estimated to produce noise levels ranging from about 90 dB; and the noise from the discharge of boreholes may exceed the pain threshold of 120 dB with frequencies ranging from 2 to 4000 Hz at the site boundary.

During the exploration phase, cost is kept to a minimum and adaptability may be needed in the choice of a silencer. Once the plant has started operation there are several different silencer designs that can be used to keep the environmental noise below the 65 dB limit applicable in or near to an inhabited area. If the location is in an isolated remote area, the limit may be as high as 85 dB. Silencers, such as

brine silencers (Thórólfsson, 2010), have to be adapted to the prevailing conditions. Knowledge of the existing environment, the chemistry and the behaviour of silica scaling is essential when designing the power plant and its components.

Taking into consideration the sensitivity of the geothermal sites in Dominica, perhaps it would be best to keep the noise to a minimum and carry out well testing outside of the tourist season.

Types of silencers: Silencer/separator; rock muffler; and concrete.

3.3.5 Thermal effects

Geothermal energy is a clean energy source compared to that of fossil-fuel combustion; thus, using it as a replacement for fossil-fuel energy is beneficial to the environment. However, geothermal energy has its down side which may incur some negative impacts on the local environment. The fluid brought to the surface from high-enthalpy geothermal reservoirs usually contains constituents which may significantly affect surface and groundwater if not disposed of properly. Metals, minerals, and gases are leached into the geothermal steam or hot water as it passes through the rocks. The large amounts of chemicals released through steam when geothermal fields are tapped for commercial production can be hazardous or objectionable to locals. Excess heat emitted in the form of steam may affect cloud formation and change the weather locally, and waste water piped into streams, rivers, lakes or local groundwaters may seriously affect the biology and ecological system (vegetation, wildlife, aquatic biota, special status species, and their habitats).

Over the last few decades many steps have been taken to reduce the environmental impacts of geothermal utilization. These include:

- Directional drilling which aims at reducing damage to scenery, undesirable visual effects and soil erosion;
- Injection of waste water and condensate into bedrock, which reduces chemical pollution of local surface and groundwaters while helping to bolster reservoir pressure and prolong the resource's productive existence. Technologies have also been developed to remove Hg, B and As from steam, thus reducing pollution by these elements;
- Multiple use of the resource is efficient and also contributes to the reduction of heat wastage. As demonstrated in the Lindal diagram (Lindal 1973), there are uses for the heat down to low temperatures. In warm countries like Dominica and the other Caribbean islands, the excess heat could be used for air-cooling by means of heat pumps.

3.3.6 Chemical pollution

In geothermal utilization, chemical pollution is due to the discharge of chemicals into the atmosphere via steam; the spent liquid may also contain dissolved chemicals of potential harm to the environment. Spray, which constitutes a problem mainly during well testing, could damage vegetation.

Wastes produced by drilling include drilling fluid and mud, geothermal fluids (and remaining sludge in sump pits after evaporation), used oil and filters, spilt fuel, drill cuttings, spent and unused solvents, scrap metal, solid waste, and garbage. Wastes may also include hydraulic fluids, pipe dope, rigwash, drums and containers, paint and paint washes, sandblast media. Wastes associated with drilling fluids include oil derivatives (e.g. polycyclic aromatic hydrocarbons [PAHs], spilled chemicals, suspended and dissolved solids, phenols, cadmium, chromium, copper, lead, mercury, nickel, and drilling mud additives, including potentially harmful contaminants such as chromate and barite). Adverse impacts can result if hazardous wastes are not properly handled and released to the environment.

The main pollutant chemicals in the liquid fraction are hydrogen sulphide (H₂S), arsenic (As), boron (B), mercury (Hg); other heavy metals such as lead (Pb), cadmium (Cd), iron (Fe), zinc (Zn) and

manganese (Mn). Lithium (Li) and ammonia (NH₃), as well as aluminium (Al), may also occur in harmful concentrations. In cases where the geothermal fluids are brines, they may have direct negative impacts on the environment due to the very high salt content.

Disposal of this type of water is critical and the best and most effective method for avoiding water pollution, thus far, is through the reinjection of the spent fluid. If waste is released into rivers or lakes instead of being injected into the geothermal field, these pollutants could damage aquatic life and make the water unsafe for drinking or irrigation. As and Hg, in particular, may accumulate in sediments and organisms while boron, on the other hand, in very high concentrations is very harmful to plants.

3.3.7 Gaseous emissions

Geothermal fluids contain dissolved gases which are released into the atmosphere. The main polluting gases are carbon dioxide (CO₂) and hydrogen sulphide (H₂S). Both are denser than air and may accumulate in pits, depressions and confined spaces. These gases are a recognized hazard for people working in geothermal stations or bore fields. Other contributing offenders are methane, mercury, radon, ammonia and boron. Carbon dioxide, which is usually the major constituent of the gas present in geothermal fields, and methane, usually a minor constituent, are both greenhouse gases contributing to potential climate change. However, geothermal extraction releases far less greenhouse gas per unit of electricity generated than burning fossil fuels such as coal or gas to produce electricity. Investigations from volcanic terrains strongly suggest that the development of geothermal fields makes no difference to the total CO₂ emanating from them (Bertani, 2001). It has also been pointed out that the CO₂ emitted from geothermal plants is not created by power generation but is CO₂ that would have been vented out gradually and naturally through the earth (Ármansson et al., 2001).

Hydrogen sulphide probably causes the greatest concern due to its repulsive smell and toxicity (even at moderate concentrations). Although geothermal plants do not emit sulphur dioxide directly, it is alleged that once H₂S is released into the atmosphere, it eventually changes into sulphur dioxide and sulphuric acid. This is a matter of debate because little evidence has been found of such an effect within the vicinity of power plants and it has not been demonstrated that the H₂S is indeed oxidized to SO₂ to any degree. It has been shown, however, that a considerable portion of H₂S is washed out of the steam and precipitated as elemental sulphur. It has been observed that the concentration of H₂S in borehole steam increases relatively more than the CO₂ concentration compared to their concentrations in naturally emitted steam as a result of geothermal utilization. Probably this is due to the higher reactivity of H₂S.

There are several surface manifestations in Wotten Waven. Some of these are used directly as sulphur pools for therapeutic baths. The area is known for the strong scent of H₂S, which is sometimes apparent in the city of Roseau. Villagers have also complained of heavy corrosion of their appliances. It was also brought to my attention that some of the visitors who bathe in the hot sulphur pools have complained of dizziness while in the pools. This may be due to the emission of H₂S and CO₂ present in the steam and the length of time people are immersed in the pools and inhaling these gases. However, no research has been carried out to determine the actual cause.

4. CASE STUDY

Power generation of any kind presents some degree of risk to the environment and this holds true for geothermal energy as well. While this level of risk exists, it has been confirmed that with proper maintenance measures, monitoring programmes and waste disposal management, these negative impacts can be minimized.

There are several countries in the world that produce geothermal energy or have the capacity to do so. These countries range from: Italy, with over 100 years of electricity production; France, with space heating since the 14th century; The first large geothermal project in Iceland, the Reykjavik Heating System started over 80 years ago (1928); Costa Rica started in 1994; El Salvador in 1975; Hawaii in 1982; and Guadeloupe in 1984. Presently, Dominica, in the Lesser Antilles, is in the exploratory phase of a geothermal project.

Successful operation of geothermal plants did not happen overnight in these countries. There were cases of poor management throughout the years of operation where strategies had to be redefined in order to continue production - for example in Hawaii.

The Hawaii Geothermal Resources Assessment Program was initiated in 1978. An experimental 3 MW power plant went online in 1982, but it was shut down after eight years of production (Boyd, 2002). This plant was actually built as a two year demonstration project. The plant was closed down permanently due to inadequate maintenance of the equipment and operation at a loss. Furthermore, the effluent abatement systems and brine systems were neither efficient nor acceptable to the community and the regulatory agencies. The company did accomplish a lot despite being shut down. The facility demonstrated that reservoir fluids required special maintenance and handling, but also showed that this issue could be managed. It was after this experience that the Hawaiian regulatory agencies became aware of the issues regarding geothermal development that could affect the community. Due to emission releases, the extent of brine ponds beyond the plant boundaries and an unkempt appearance of the plant itself because of limited maintenance, this experimental HGP-A power plant, as it was called, was not well received at all.

The people expressed their concerns over several issues including impacts on Hawaiian culture and religious values, potential geological hazards, public health and loss of native rainforest as well as a change in the rural nature of the area. This had a negative impact on future exploration. As a matter of fact further exploration was opposed. The Puna Geothermal Venture plant was eventually established over a decade later. Residents have accepted the plant as a part of the power supply, but there are still lingering health and environmental concerns among residents near the plant. As a result, an investigation was carried out by the Environmental Protection Agency and a programme documenting residents' health problems which they attributed to geothermal emissions.

When the Puna Geothermal Venture lost control of their wells during drilling and allowed the uncontrolled release of steam from their exploration well in June 1991, this only added insult to injury. The drilling permits were suspended by the state regulatory agency not only for the Puna Geothermal Venture, but also for another geothermal company - The True Geothermal Energy Company which had already spent quite some years haggling with the regulatory bodies trying to develop the central rift area. This ultimately led to the abandonment of the True Geothermal Energy project.

The Puna Geothermal Venture was able to produce 35 MWe despite the delays and at a much higher cost than had been anticipated. The facility still faces technical challenges, but has been able to produce power with a minimum of "blowouts" to the community and likewise a minimum of public controversy. This facility is now producing 60 MWe, but there are no current plans to expand their production capacity.

There are also global environmental issues on the emission of greenhouse gases. Geothermal energy plays a very important role in this area as it is renewable and it is an environmentally friendly source of energy. The emission of greenhouse gases has to be reduced.

Iceland is an ideal example of the effectiveness of geothermal utilization. In Iceland 83% of the greenhouse gas emission are CO₂. The use of fossil fuel accounts for 70% of these. In the year 2000, the total emission of CO₂ in Iceland was 3.3 million tonnes, of which 36% came from industry, 31% from transport (excluding international flights), 26% from the fishing fleet, 5% from high-temperature

geothermal plants, 1% from homes and 1% from other sources. CO₂ emission has been reduced significantly in Iceland since 89% of the houses are now heated using geothermal energy for space heating, which gradually replaced fossil fuels in the 1930s with the largest increase during the 1970s following the first oil crisis. It is very important to understand that this emission from geothermal fields is not a result of the production of greenhouse gases but rather a displacement of naturally occurring gas in high-temperature fields.

The use of geothermal energy has advanced over the years in many countries and Iceland is a good example. For centuries it was only used for bathing and washing. Presently, this resource is used both for electricity generation and direct heat application. Space heating is the most widespread form of direct utilization of geothermal energy in Iceland covering 89% of all buildings in the country. Other areas of direct use include swimming pools, snow melting, industry, greenhouses and fish farming. Electricity generation with geothermal energy has rapidly increased throughout the past few years, principally due to the increased demand from energy intensive industry.

5. CONCLUSIONS AND RECOMMENDATIONS

Global warming and climate change are much discussed topics and many ethnic groups and organizations are having increasing concerns for the environment especially since it is an anthropogenic problem. It is, therefore, critical that greater emphasis be placed on the utilization of clean and sustainable energy sources such as geothermal energy. Geothermal energy is considered a relatively clean source of energy. All possible environmental impacts can, to a large extent, be foreseen and this paves the way to take measures to minimize their effects prior to utilization. Knowing beforehand the contributing factors to possible environmental degradation due to geothermal production and recognizing the areas that are most sensitive and vulnerable enables stakeholders to establish an effective mitigating programme.

In Dominica, the site due for geothermal development is in a significantly delicate location where various species and their habitats, and the neighbouring rivers will be affected one way or another. Consequently, it is imperative that this geothermal field be carefully and continuously monitored and that the necessary means be taken and applied in order to minimize the gravity of the impacts on the environment. One of the first questions asked in such cases is “are we absolutely certain that this geothermal field in such a unique and delicate area is worth the risk?” If yes, then proceed to ask:

- Was the surface exploration thoroughly carried out?
- In which areas will permission for entering be granted?
- If development of this area is not successful, can the area be recovered/restored to its natural self?
- How does the company dispose of the material cleared?
- Where will roads be built and will the location affect any wildlife trails?
- How big is the drilling plant?
- How does the company propose to approach the environmental aspect of the project?
- How does it propose to protect the unique wildlife and habitats?
- Will a camp be set up at the site?
- How will waste be discarded?
- How long will exploratory drilling last?
- What about waste fluid disposal during this phase?

There are two phases to consider: the exploration drilling phase and the production phase. Some things to consider during the exploration drilling phase are:

- The advantage of seismic sounding before drilling;
- The fluid should not come in contact with ground/surface water;
- The drilling fluid should not or have a minimal effect on the surface conditions of the area;
- Duration of testing (long or short period), as this will affect waste fluid disposal;
- Caution should be taken with any road construction so that animal trails are not crossed;
- Avoid the main areas of hunting and feeding grounds of indigenous species;
- Well testing should be carried out outside of the tourist season because of noise and possible spray;
- A separate environmental impact assessment should be considered during this phase;
- The advantage of drilling according to a “production” well programme as opposed to a slim well programme;
- The possibilities and advantages of drilling directional wells.

During the production phase, the plan is basically permanent. Production drilling is carried out during the project planning phase of geothermal development. Attention is paid to the reservoir temperature and pressure, reservoir rock type and flow paths, fluid chemistry, hydrological reservoir parameters and well productivity (injectivity). These investigations are carried out with the objective of revising the conceptual model and the potential generating capacity in order to design and construct the plant. At this point the most reliable and trusted form of environmental protection is reinjection of the fluids.

It is true that Iceland is a unique country in respect to its geothermal production capacity and utilization and this is due to its fortunate geographical location. Energy use in Iceland differs from that of other countries. The energy use is higher per capita and the ratio of sustainable energy sources is also high. Many countries do not enjoy the widely established and stable range of utilization found in Iceland. For developing countries like Dominica, applications will not be as diverse. Nonetheless, geothermal energy can be put to multiple uses in Dominica. The island lies in the tropics and does not have snow, but cooling is greatly needed. It can also be used for greenhouses, fish drying and for the production of commercial liquid carbon dioxide derived from the geothermal fluid, to name a few.

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