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APPLICATION OF GIS AND REMOTE SENSING IN EXPLORATION AND ENVIRONMENTAL MANAGEMENT OF NÁMAFJALL GEOTHERMAL AREA, N-ICELAND

MSc thesis
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by

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INTRODUCTION

The Geothermal Training Programme of the United Nations University (UNU) has operated in Iceland since 1979 with six month annual courses for professionals from developing countries. The aim is to assist developing countries with significant geothermal potential to build up groups of specialists that cover most aspects of geothermal exploration and development. During 1979-2004, 318 scientists and engineers from 39 countries have completed the six month courses. They have come from Asia (44%), Africa (26%), Central America (14%), and Central and Eastern Europe (16%). There is a steady flow of requests from all over the world for the six month training and we can only meet a portion of the requests. Most of the trainees are awarded UNU Fellowships financed by the UNU and the Government of Iceland.

Candidates for the six month specialized training must have at least a BSc degree and a minimum of one year practical experience in geothermal work in their home countries prior to the training. Many of our trainees have already completed their MSc or PhD degrees when they come to Iceland, but several excellent students who have only BSc degrees have made requests to come again to Iceland for a higher academic degree. In 1999, it was decided to start admitting one or two UNU Fellows per year to continue their studies and study for MSc degrees in geothermal science or engineering in co-operation with the University of Iceland. An agreement to this effect was signed with the University of Iceland. The six month studies at the UNU Geothermal Training Programme form a part of the graduate programme.

It is a pleasure to introduce the sixth UNU Fellow to complete the MSc studies at the University of Iceland under the co-operation agreement. Mr. Younes Noorollahi, BSc in Biology, of the Renewable Energy Organization of Iran - SUNA, completed the six months specialized training at the UNU Geothermal Training Programme in October 1999. His research report was entitled "H_2S and CO_2 dispersion modelling for the Nesjavellir geothermal power plant, S-Iceland, and preliminary geothermal environmental impact assessment for the Theistareykir area, NE-Iceland". After almost four years of research work as inspector of an Environmental Impact Assessment of a geothermal power project in Meshkinshar in NW-Iran, he came back to Iceland for MSc studies at the Faculty of Science of the University of Iceland in September 2003. He defended his MSc thesis presented here, entitled "Application of GIS and remote sensing in exploration and environmental management of Námafjall geothermal area, N-Iceland" in January 2005. His studies in Iceland were financed by a fellowship from the Government of Iceland through the UNU Geothermal Training Programme. We congratulate him on his achievements and wish him all the best for the future. We thank the Faculty of Science of the University of Iceland for the co-operation, and his supervisors for the dedication.

Finally, I would like to mention that many of the beautiful colour maps in Younes' MSc thesis had to be printed in black and white. However, a colour version in a pdf format is available for downloading on our website at page *www.os.is/unugtp/yearbook/2005.*

With warmest wishes from Iceland,

Ingvar B. Fridleifsson, director,
United Nations University
Geothermal Training Programme

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I would like to thank the organizations that provided financial support; the Government of Iceland and the United Nations University (UNU). My employer, the Renewable Energy Organization of Iran (SUNA) granted me a study leave to attend this course, and I am sincerely grateful to the Management.

Finally, to my wife who played the role of a mother and a father during my absence, and my daughter Mahshid, you put up with my absence with a lot of patience, courage and understanding. I am indeed very grateful to you.

ABSTRACT

This research is focused on the applications of remote sensing and Geographical Information System (GIS) as a decision support system in geothermal exploration and environmental management. The project aim is to find out the best location for drill sites and site selection for a geothermal power plant in Bjarnarflag geothermal field in Námafjall high temperature geothermal area in North Iceland.

SPOT Satellite images are used as one of the important environmental, geographical and surface data sources in the work. Surface exploration data including geological, geochemical and geophysical survey data are used. GIS (ArcInfo 9.0) has been used in this work not only as a powerful tool in mapping and spatial visualization but also as a decision support system for suitability analysis.

Decision making on location of wells and a power plant in analogue methods has been defined mostly by reservoir engineering, geological, geochemical, hydrological, and environmental and other information and human errors were unavoidable during decision making. The proposed project contributes to the environmental and social economical roles in the decision making process for sustainable locating of well sites and power plant by effectively making use of GIS as decision support system, firstly to avoid human errors during decision making and secondly to find new, easy and automated computerized methods for geothermal exploration (well site selection) and power plant location.

In geological studies three data layers including geothermal manifestations, volcanic craters and faults and fractures are overlain and intersected and the common area is selected as a geologically suitable area. The geologically selected suitable area is overlain by the weighted geophysical and fractures distance raster maps and a weighted cell base raster calculation carried out and the suitable area based on exploration data selected.

In the environmental suitability analysis, the vegetation cover and vegetation cover density maps are first overlain and on the basis of a cell base weighted raster analysis a suitable area is selected. This map has been overlain by the weighted protected area map, slope and elevation map with predefined criteria and a special weighting for each one, and a suitable area has been selected.

In the final well site selection the exploration suitability map and environmental suitability map have been overlain and a weighted cell base raster analysis carried out. Based on the final analysis the suitable area has been ranked at three different levels of suitability and from the first priority sites two sites were selected as well fields for the first phase of geothermal exploration drilling.

For power plant site selection, three alternative sites have been defined by the project developer for a proposed power plant and in this work the environmental, natural risk potential and economical factors have been evaluated. Thirteen different factors in the two main groups including environmental factors and natural risk and economical factors are examined. Firstly each site is evaluated based on every factor and a relative value from 0 to 9, assigned to the sites according to the condition of the site related to the factor evaluated. Moreover, the 13 defined factors have been evaluated with respect to the importance of others. In this evaluation, all 13 factors have been given 100% value, but each one received a special weight with respect to its importance in environmental impact and economical effects. Finally a simple matrix analysis has been carried out to evaluate the sites A, B and C. In the result, site A is the best one, scoring 89% of the ideal site score, site B is second with 76% and site C comes least one with 66% of the score for the ideal available power plant site in study area.

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1.0 INTRODUCTION

1.1 Background

The Námafjall high temperature geothermal field is located in North Iceland. The field is located near to the well known Lake Mývatn tourist area. The Námafjall high-temperature geothermal area is a very active volcanic area. South of Krafla, this volcanic activity diminishes over a distance of a few km, but continues again with active volcanic fissures in the area of Bjarnarflag and in the western part of Námafjall.

Námafjall geothermal field is characterized by steaming ground with numerous pools and fumaroles precipitating native sulphur around them in an unusual quantity. The surface extension of the field is somewhat obscured by recent lava fields filled with ground water, but as judged from surface alteration, steaming ground etc., it is at least some 4-5 km^2 in size. The Námafjall geothermal field is considered a part of a more extensive high temperature area including the Krafla-Leirhnúkur fields for which the collective name Mývatn area has been proposed (Landsvirkjun, 2003).

The Laxá Power Works decided in early 1968 to build a pilot geothermal power plant at Námafjall, with the objective of gathering experience on geothermal power generation and at the same time reducing the use of the imported and expensive fuel for their diesel plant. In order to minimize the construction time a second hand 2.5 MW back pressure industrial turbine alternator set was purchased in England. The design and erection of the power plant were carried out in 7 working months, and it was test-run in March 1969, their operation continued successfully during the following years. Because of the continuing tectonic and volcanic activity during the Krafla fires period of 1975-1984 and the imminent danger of eruptions in the Bjarnarflag Area, the power station was disassembled at the end of 1980. After reinstallation it has delivered 2.53 MW. This geothermal power station delivered power to the somewhat power starved Lake Mývatn Area before the national grid was realized in 1980 and reduced the expensive diesel engine production in Akureyri.

Produced steam from Námafjall high temperature geothermal field has been utilized not only for operating a 2.5 MW back-pressure turbine unit, but also for drying of diatomaceous earth and heating of fresh water for space heating. A total of 12 wells have been drilled at Námafjall but only three of them are currently used for production.

In 1986 the National Power Company of Iceland purchased and took over the management of the Námafjall geothermal field and in the 1990's the company initialled plans for building a power plant. The various types of investigations have been carried out by different organizations and companies and the results of their studies have shown that the area has the capability for the installation of a 60 - 90 MW geothermal power station in the Námafjall area.

The environmental aspects of geothermal development are receiving increased attention with the shift in attitudes towards the world's natural resources. Not only is there a greater awareness of the effects of geothermal development on the surrounding ecosystems and landscape but a greater effort is also being made to use the resource in a sustainable manner. In the development of geothermal projects, selecting the location of wells and the location of power plant buildings are very important for sustainable development and management of resources and are fulfilled by using different data and information that have been obtained during different phases of project investigations, like geological, geochemical, geophysical, hydrological, hydrogeological, reservoir engineering and environmental studies. The information obtained from the above studies is used for finding out the appropriate area for drilling of wells and a suitable area for power plant buildings.

Various data sets from geological, geochemical and geophysical surveys, hydrological, remote sensing (RS) data (including satellite images and aerial photographs), and topographic data, have to be managed and integrated to define target areas. In the past, such integration of multiple data sets carried out in an analogue way and decisions were made by integrating different information from various sources, using experts' and engineers skill. Today this integration of data sets can be carried out digitally using a Geographic Information System (GIS) of Decision Support System (DSS) methods.

A GIS is a computer-based system whose main purpose is to provide support for making decisions using spatial data. This purpose can be achieved through organizing, visualizing, querying, combining, or analyzing data, or by making predictions using that data. The ultimate objective of using a GIS during geothermal exploration and development is to predict the approximate positions of new wells and power houses. For doing this, the data from exploration and reservoir engineering sources, surface data mostly from remote sensing sources and environmental data from RS and ground sources to be integrated should be indicative of the well's locations in the area under analysis.

Remote sensing data often constitutes an important part of the data base introduced into a GIS because of its intrinsic digital nature, and because it can be used as the base over which to overlap other data (Legg, 1992). Satellite RS provides invaluable help when carrying out exploration in remote areas with poor or not up-to-date topographic maps. Even without sophisticated treatment, RS data are a useful source of information to obtain different data and information, including recognition of roads, tracks, land use, land cover, topography, slope, aspect, vegetation type, presence of surface water and drainage system. If bands of satellite imagery are combined in a natural colour composite they can give a general idea of some geological and environmental characteristics. The use of RS data is useful and effective reducing costs and time spent on studies.

Spatial multicriteria decision problems typically involve a set of geographically defined alternatives (events) from which a choice of one or more alternatives is made with respect to a given set of evaluation criteria (Jankowski, 1995; Malczewski, 1996). In contrast to conventional Multi-Criteria Decision Making (MCDM) analysis, spatial multicriteria analysis requires information on criterion values and the geographical locations of alternatives in addition to the decision makers' preferences with respect to a set of evaluation criteria. This means analysis results depend not only on the geographical distribution of attributes, but also on the value judgments involved in the decision making process (Carver, 1991; Jankowski, 1995). Therefore, three considerations are of paramount importance for spatial multi-criteria decision analysis:

- Data acquisition (e.g., remote sensing and ground source data)
- The GIS component (e.g., data management, storage, retrieval, manipulation, and analysis capability)
- The MCDM analysis component (e.g., aggregation of spatial data and decision makers' preferences into discrete decision alternatives)

- The major elements involved in spatial multicriteria analysis are shown in Figure 1 (Malczewski, 1999). In Figure 1 there is presented a three-stage hierarchy of intelligence, design, and choice to represent the decision making process. In the intelligence phase, data are acquired, processed, and exploratory data analysis is performed. The design phase usually involves formal modelling/GIS interaction in order to develop a solution set of spatial decision alternatives. The integration of decision analytical techniques and GIS functions is critical for supporting the design phase. The selection phase involves selecting a particular alternative from those available. In this phase, specific decision rules are used to evaluate and rank alternatives. The three stages of decision making do not necessarily follow a linear path from intelligence, to design, and to selection (Malczewski, 1999).

The sustainable management of geothermal resources is best handled by state-of- the art tools, Remote Sensing, GIS and DSS. Remote Sensing and GIS, especially the spatial modeller and analyst has become an indispensable tool for land and water resources inventory at local, regional and global level. RS and GIS provide solutions to facilitate sustainable development of land and water resources, ecological balance and improve the socio-economic conditions of the environments concerned.

1.2 Definition of the project aim

This research is focused on the applications of geographical information systems (spatial analyst) and remote sensing to find out the best location for drill sites and power plant location in the Bjarnarflag geothermal field in the Námafjall high temperature geothermal area in North Iceland. Development of the geothermal field for a geothermal power plant is one of the ways of improving the social and economic situation of the area, and is an activity, that the local government has been trying to promote for many years. Due to the possibilities of the area, investments in geothermal project development can be attracted. An appropriate development plan of a prospecting project can be an important help in focusing management efforts for sustainable development of the area. In addition, they can be employed for planning the land use by predicting future development activities. The location of wells and power plant using analogue methods has been determined mostly with respect to geological and reservoir engineering aspects, but environmental and sustainability aspects have not had a reasonable share in such procedures in the past. The current project is going to contribute the share of environmental and socio-economical aspects in the decision making for sustainable location of well sites and power plant by the use of GIS and a decision support system.

1.3 Research question

This research is intended to answer three main questions:

- How is it possible to acquire the necessary environmentally important data and surface characteristic from RS images?
- How is it possible to define suitable locations for well sites by combining all engineering, geographical and environmental data and minimum environmental impacts and maximum resource extraction?
- How is it possible to define an environmentally suitable location for a power plant?

1.4 Research objectives

The main objectives of the research are:

- To produce an environmental sensitivity map by remote sensing and ground source data
- To find out suitable locations for well sites according to the reservoir engineering and environmental aspects.
- To find out a suitable location for the power plant with minimum environmental impacts.

2.0 METHODOLOGY

2.1 Remote sensing

2.1.1 Overview

Remote Sensing is the "science and art of obtaining information about an object, an area, or certain phenomena through the analysis of data acquired by a device that is not in contact with the object, area, or phenomena under investigation" (Lillesand, 1999). Normally this gives rise to some form of imagery which is further possessed and interpreted to produce useful data for application in agriculture, archaeology, forestry, geography, geology, environmental, planning, and some other fields. The primary objective of remote sensing is to extract environmental and natural resource data related to the earth (Lo, 1995).

Photography of the earth surface dates back to the early 1800s, when in 1839 Louis Daguerre publicly reported results of the images from photographic experiments. In 1858 the first aerial view from a balloon was produced and in 1910 Wilbur Smith piloted the plane that acquired a motion picture of the Centocelia in Italy. In the 1960s, in the beginning of the 1970s, a revolution in remote sensing technology began with the deployment of the Landsat satellites. Since 1972, several generations of Landsat satellites with their Multispectral Scanners (MSS) have been providing a continuous coverage of the Earth. The usefulness of satellites for remote sensing has resulted in several other organizations launching their own devices. In France, the SPOT (*Centre National d'Etudes Spatiales*) satellite program has launched four satellites since 1986.

Nowadays, remote sensing is one of the important sources of data and information in development projects. Satellite Remote Sensing, due to its inherent advantages, as listed below, has become an inevitable tool for land and water resources inventory at local, regional and global scales (Kumar, 2001):

- Synoptic, repetitive coverage on required scales
- Cost-and time effective
- Accurate database generation
- Multi-spectral nature of data helps greatly in the discrimination and mapping of various features in geothermal field
- Helps in the monitoring of various developmental activities being undertaken in the area
- Change detection capability.
-

With the availability of high resolution (spatial, temporal and spectral) satellite data, the scope and application of satellite data in combination with GIS has proved to be an extremely useful technology for micro-level planning and implementation. Thus remote sensing provides a solution to facilitate sustainable development of land and natural resources. A holistic and integrated approach is needed for the development of geothermal projects to ensure ecological balance and improve the socio-economic conditions of the surrounding communities concerned. In order to derive maximum benefits out of these resources in a sustainable way, it is preferable to treat the affected area as a single unit.

2.1.2 Incorporating remote sensing data into a GIS

Remote sensing and GIS technologies were initially developed for different purposes. However, both these resources can provide information about the earth's natural resources. Advancements in computer hardware and software technology now make it possible for data from these sources to be easily integrated.

Most GIS software packages allow remotely sensed data to be imported, or at least viewed, within the software application. This ability allows the analyst to overlay remote sensing data layers with other spatial data layers. Analysts use remotely sensed imagery with GIS data sets for a variety of reasons, including providing a continuous regional view of the areas and extracting GIS data layers, such as contours or building footprints (Skidmore, 2002).

2.1.3 Remote sensing application in the project

ERDAS IMAGINE 8.6 is remote sensing software which is used in the project. For the project remote sensing is going to be used first as a great data source of environmental data and surface characteristics such as topography, vegetation cover, land use, land cover, geothermal manifestation (hot springs, fumaroles and mud pots), soil classification, slope, aspect, faults and fracture maps and secondly using it as a spatial modeller of ERDAS IMAGINE for making effective maps and data layers in order to use in decision support system to find the best location for well sites and power plant building sites according to reservoir engineering, surface exploration and environmental data and information.

The satellite images used in this work have been received from National Land Survey of Iceland (Landmaelingar Íslands). The SPOT images were acquired on 3red, Oct. 2002 and have been used in the project. Two different SPOT images have been used, the single band panchromatic image with reference number SPVIEW_714_213_8_T_202_1 and multi spectral bands with reference SPVIEW_714_213_8_J_202_1 including bands 1, 2, 3, and 4.. The image is ortho-rectified and georeferenced (Projection: Lambert Conformal Conic, Datum: ISN93) without using Ground Control Points (GCPs). Horizontal accuracy for multi spectral image is 20 m and for panchromatic image it is 10 m.

The interpretation and analytical methods employed in this work are described for each relevant subject.

2.2 Decision support system (DSS)

Decision Support Systems (DSS) are a sub-class of management information systems which support analysts, planners, and managers in the decision making process. They can reflect different concepts of decision making and different decision situations. DSS are especially useful for semi-structured or unstructured problems where problem solving is enhanced by an interactive dialogue between the system and the user. Their primary feature is harnessing computer power to aid the Digital Model (DM) to explore the problem, and increase the level of understanding about which environment decisions are to be through access to data and models appropriate to the decision. They are aimed at generating and evaluating alternative solutions in order to gain insight into the problems, trade-offs between various objectives and support the decision making process (Sharifi et al., 2002).

Development involves making decisions as to the choice of a desired path to follow. Decision theory is, in and of itself, a highly complex field. Here, we take a very broad view of decision making as any situation where a decision taker has a choice between alternatives. In the simplest case there may be only one alternative and the decision is to take this or not. However, in reality there are usually numerous competing options or alternatives available in any course of action and thus the decision calculus is correspondingly more complex. In contexts where decision making involves action it is important to evaluate also the implementation and results of decisions (Sharifi et al., 2002).

When a deliberate course of action is laid out and subsequently implemented this constitutes planning. Decision making and planning may be at the group or individual level and in the former case reconciliation of different value systems is likely to be required. This may involve negotiation or trade-offs before a course of action that is acceptable to all groups is agreed upon.

2.2.1 Spatial decision making and process

Information system researchers and technologists have built up and investigated DSS for more than 35 years. The decision support system began with building the model-oriented DSS in the late 1960s, theory developments took place in the 1970s, and the implementation of financial planning systems and Group DSS in the early and mid 80s.

The primary intention of DSS is to assist specific DMs, individually or in groups, rather than the entire organization. This allows for custom design of the system, in which DMs can use the system interactively to build and more importantly, to change analytic models of the decision problem. Interactive use allows immediate changes in assumed parameters with rapid feedback, encouraging the learning process that is impossible when the DM has to wait for extended periods of time for output. Therefore, interaction and support for transferring the results of analysis to the DMs in a communicable, manageable, easily understandable and quick way is a central feature of any effective man-machine-system (Sharifi et al., 2002). A real time dialogue allows the user to define and explore a problem incrementally in response to immediate answers from the system. Fast and powerful systems with modern processor technology can offer the possibility to simulate the dynamic processes with animated output and provide a high degree of responsiveness that is essential to maintain a successful dialogue and direct control over the software.

DSS functions ranges from information retrieval and display, filtering and pattern recognition, extrapolation, multi-attribute utility theory, optimization techniques, inference and logical comparison to complex modelling. Decision support paradigms may include predictive models, which give unique answers but with limited accuracy and validity. Scenario analysis relaxes the initial assumptions by making them more conditional, but at the same time more dubious. Prescriptive analysis of decisions emphasizes the development, evaluation and application of techniques to facilitate decision-making. These studies rely upon the logic of mathematics and statistics and utilize the concepts of utility and probability to analyze decision problems. The concept of utility relates to the expression of preferences among alternative options, while probability serves to evaluate the likelihood of these preferences being utilized. The techniques adopted in these approaches incorporate explicit statements of preferences of DMs. Such preferences are represented by a weighting scheme, constraints, goal, utilities, and other parameters. They analyze and support decision through formal analysis of alternative options, their attributes vis-a-vis evaluation criteria, goals or objectives, and constraints (Sharifi et al., 2002).

Group decision support systems focus on expediting the exchange of ideas among participants, stimulating quieter members to participate, and organizing collective thought into a workable consensus. In this context a set of participatory multiple criteria and multiple objective evaluation techniques are needed that aim to place the GIS analyst as a mediator between the computer technology package and the DM.

GIS here can be seen as a possible vehicle for solving problems and a decision making process. Such types of systems enable a group to work together and participate in decision making concerning spatial issues by providing a set of generic tools, e.g., exchange of numerical, textual, graphical information, generation of solutions, group evaluation, consensus building and voting. These types of systems enable the stakeholders to collaborate in the decision making process with no limitations of space and time. Examples of possible applications may be environmental restorations, conservation planning, multiple resource use, and land use planning. The creation of a spatial database is the first step in micro-level planning. This is followed by spatial analysis to help identify problem areas and, finally, the steps towards planning to mitigate problems are taken by marking out action areas.

Malczewski (1998) identifies complexity, alternatives and multi-criteria characteristics as key features of a spatial problem. Spatial problems are complex because they are semi-structured or ill defined in the sense that the goals and objectives are not completely defined. Spatial problems are multi-dimensional and often related to non-spatial information. Each spatial problem can have a large number of decision alternative solutions. These alternative solutions to the spatial problems are normally characterized by multiple criteria upon which they are judged. As spatial aspects and non-spatial aspects can coexist in a spatial problem, we need to consider both aspects at the same time. It is difficult to model a complex spatial problem in a single step, but it is possible to model one aspect of a complex problem at a time e.g. create a spatial model to deal with spatial aspects, and a non-spatial model that caters for non-spatial aspects of the problem and then integrate them. A spatial modelling technique is used for finding relationships among geographic features and helping decision makers to address the spatial problem clearly and logically.

A spatial model contains spatial parameters that refer to the geographical features of a spatial problem. Vector-based spatial data in a GIS system can be categorized into three major groups i.e. spatial objects, spatial layers and spatial themes;

- A spatial object represents a single spatial item e.g. a point, a line or a polygon.
- A spatial layer contains a collection of spatial objects similar in nature and every spatial object belongs to a certain layer.
- A spatial theme comprises a number of spatial objects and/or spatial layers that represent a particular meaning to a particular spatial problem.

Every vector data is linked to non-spatial domain data through the spatial reference system. e.g. a point is associated with a well or a residential location, a line represents a fracture or a fissure. Each aspect of a spatial problem can be modelled in one layer. These layers are then integrated into a complex model that represents all aspects of the problem. A spatial decision-making process has been proposed (Figure 1) by synthesizing ideas of decision-making processes (Simon, 1960) as well as multi-criteria decision-making (Malczewski, 1998).

2.2.2 The DSS implementation

A prototype spatial Decision Support System (DSS) is implemented to prove the validity of the spatial decision making processes. The proposed spatial decision-making process is evaluated through five step scenarios across spatial decision problem domains including location, allocation, routing and/or layout.

Step I: Problem identification:

The problem presented in this session is to identify the optimal location of a property that maximizes "return" i.e. the satisfaction level that is measured on the basis of the three criteria:

- Geothermal exploration criteria e.g. geophysical data, reservoir temperature etc.
- Surface criteria such as slope, faults and fractures
- Environmental criteria e.g. vegetation, subsidence area, and other environmentally sensitive factors.

Some of these factors are difficult to evaluate or predict, as relative impacts for some of these factors on return remain unknown. It is hard to structure the problem in its entirety at one time i.e. precisely define and measure the objective for every possible solution. In the next step, the decision maker, models this problem using the proposed modelling approach by separating the spatial aspects into three main categories of a complex spatial problem.

Step II: Problem modelling:

These spatial dimensions need to be analyzed one by one in order to find a best location according to each layer. In this illustration, the decision maker first broadly selects a target area and then carries out suitability analysis. The analysis involves exploration and environmental spatial models and it uses spatial solvers. The problem is solved iteratively by firstly considering spatial data, models, solvers and scenarios, secondly applying spatial criteria and finally using goal-seeking and sensitivity analysis.

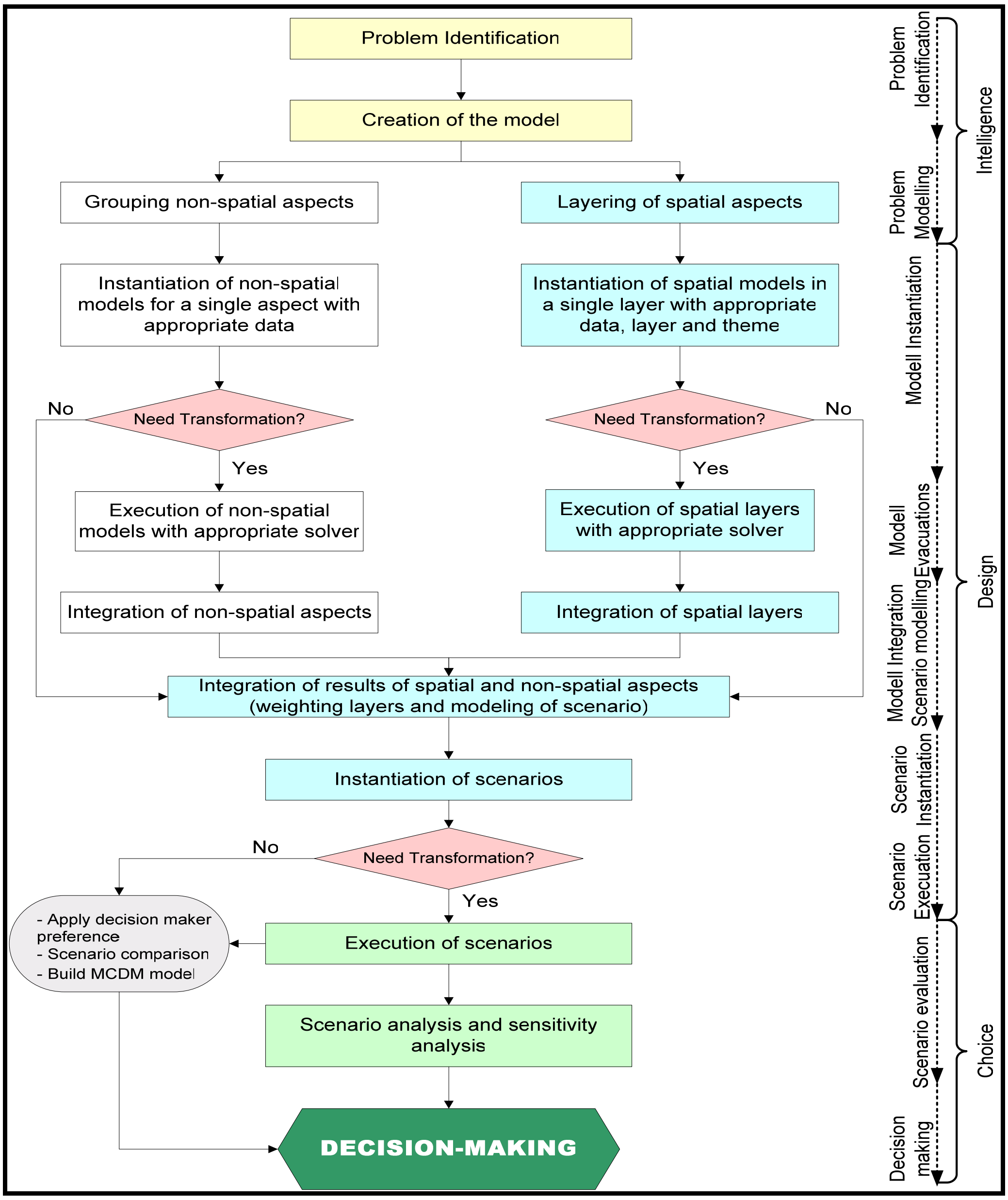

FIGURE 1: Spatial decision-making process (after Malczewski, 1998)

Steps III and IV: Scenario development:

The decision maker now needs to load relevant decision-making components. These are relevant maps and models in which the properties are located, the various models, solvers and visualizations to be used for building the different scenarios. A simple spatial scenario is developed separately at first; they are then integrated into a combined scenario. These scenarios are then transformed into a complex multi-criteria scenario through a structural integration process.

Steps V and VI: Scenario integration and instantiation:

The decision maker integrates the simple combined scenario structure with these newly developed distance parameters to develop a more complex scenario that contains all the criteria for the problem. The decision-making selects a scenario, and calculates each of the distance parameters. Once all the relevant distance values have been calculated, a scenario is then instantiated with these values. The process is iterative in nature until all scenario instances have been generated. The scenario template and its multiple instances are stored in the database as *Complex Scenario* and they can be retrieved for further analysis or evaluation.

Step VII: Scenario execution

Scenarios can be instantiated with the relevant data; model and a number of solvers can be applied for execution of the scenarios. The scenario can be executed in a simple process or using multiple steps. The integration of executed models (scenarios) is also the process of modelling the scenario itself. During the scenario execution process, one scenario is instantiated and executed using different solvers.

Step VIII: Scenario evaluation

The decision maker needs to build a multi critical decision making evaluation model by specifying parameters and assigning weight to each of these parameters. The evaluation model is instantiated with alternative scenario instances. These scenarios are executed using the solver that is tightly coupled within the evaluation model.

Step IX: Decision-Making

The decision maker selects the scenarios for evaluation in step I. Then, an evaluation model is built by selecting the appropriate criteria from the input scenario in step II. In step III, the decision maker assigns a weight to each of the criteria. Step IV evaluates the scenarios using the model template created in step II and step III. The built-in solver not only calculates values according to the formula but also ranks these values.

The decision maker can apply different evaluation models to explore the alternative scenarios by considering the uncertainty involved in the decision-making process. The uncertainty may be caused by the error in available information to the decision maker, or improper judgment regarding the relative importance of evaluation criteria. Some methods are more suitable in some situations, while others might be more suitable or accurate in other situations.

2.3 Geographical information system (GIS)

A Geographic Information System is a set of computerized tools (including both hardware and software) for collecting, storing, retrieving, transforming, and displaying spatial data. GIS is essentially a marriage between computerized mapping and data base management systems. Anything that can appear on a map can be encoded into a computer and then compared to anything on any other map, using any coordinate systems, in other words, GIS is a computer system capable of assembling, storing, manipulating, and displaying geographically referenced information to its locations. GIS technology can be used for scientific investigations, resource management, and community education.

GIS technology is increasingly being used in spatial decision support systems. A GIS system stores spatial data in a digital mapping of environment. A digital base map can be overlain with data or other layers of information onto a map in order to view spatial information and relationships. GIS allows better viewing and understanding physical features and the relationships that influence in a given critical environmental condition. Factors, such as steepness of slopes, aspects, and vegetation, can be viewed and overlain to determine various environmental parameters and resource analysis. The ability of GIS to integrate maps and data bases, using the geography as the common feature among them has been extremely effective in the context of planning development. The attribute data base can be analysed by multiple queries, linked to multiple databases related to different projects to arrive at a comprehensive picture of the current scenario in a given area (Keenan, 1997).

A GIS is a composite of computer based decision support tools for the integration of spatial data from different sources and for the analysis, manipulation and display of these data. It is therefore, an excellent tool for the management of large bodies of spatially extensive data with all the advantages of a computer environment: precision, consistency and absence of computational error. This powerful tool holds a very large potential in the field of regional and micro-level spatial planning particularly in planning, and resource management and exploitation. It also facilitates modelling to arrive at local specific solutions by integrating spatial and non-spatial data such as thematic layers and socio-economic data. The spatial database facilitates the authorities in planning and change monitoring and assists in understanding the effect of developmental activities undertaken by incorporating the data derived from the repetitive coverage of the satellite. Usefulness of GIS and spatial analysis are (ESRI, 2002):

- Accuracy
- Easy in operation
- Great analytical capabilities

To better understand the study area it may be necessary to view it from several different perspectives: aerial views, static and dynamic ground views. The aerial view corresponds to a flight through the aerial photographs or takes the satellite digital photograph, which gives a global perspective of the study area. This representation can be associated with the correspondent route of the flight over a map, allowing the interrelationship between the two spatial representations.

2.3.1 Using GIS to create models

GIS are useful for specifying different type of the models. GIS can also be used to analyze data for the creation of a model. Building a model requires (1) data exploration and analysis, (2) algorithm specification, and (3) accuracy assessment. GIS can be useful in all three steps.

Data exploration aids the understanding of relationships between variables for the development of hypotheses. Perhaps the oldest and most extensive use of GIS consists of queries for visualizing the distribution of information across space.

Queries tend to be heuristic whereas quantitative analysis relies on rigorous examination of a sufficient amount of sample data. Also called data mining, quantitive analysis reveals patterns in the data that can lead to the development of a hypothesis. For example, The United State Geological Survey (USGS) uses classification regression tree analysis in land cover mapping to explore the relationship between spectral response, existing GIS data layers, and land cover classes. Clusters generated from an unsupervised classification are examined with ancillary data including elevation, prior land cover data, census data, city lights data, national wetlands inventory data, a well as leave-off and leave-on satellite imagery to develop relationships between class occurrence, spectral response, and the other GIS data layers (ESRI, 2002).

Hypothesis development leads to the specification of algorithms that relate inputs to outputs. Model algorithms can be based on expert opinion, quantitative analysis, or a combination of both.

For a model to be useful, its accuracy must be assessed so that the model can be calibrated and so that decision makers can verify the model’s reliability. Accuracy assessment is the quantitative measurement and identification of map error.

2.3.2 GIS in decision support systems

GIS are gaining importance and widespread acceptance as a tools for decision support in land, infrastructure, resources, environmental management, Environmental Impact Assessment (EIA), spatial analysis, and in urban and regional development planning. With the development of GIS, environmental and natural resource managers increasingly have at their disposal information systems in which data are more readily accessible, more easily combined and more flexibly modified to meet the needs of environmental and natural resource decision making. It is thus reasonable to expect a better informed more explicitly reasoned, decision-making process. But despite the proliferation of GIS software systems and the surge of public interest in the application of the system to resolve the real world problems, the technology has commonly been seen as complex, inaccessible, and alienating to the decision makers (Fedra, 1993; Geertman and Stillwell, 2002).

The reasons for this estrangement are varied. In part the early development and commercial success of GIS were fuelled more by the need for efficient spatial inventory rather than decision support systems. As a result, few systems yet provide any explicit decision analysis tools. In addition the technology is built upon a very broad base of scientific disciplines, ranging from cartography, to remote sensing, to computer science, to statistics and the like. This implies that to become broadly involved in GIS use, an extensive background in digital data management, mapping sciences and information technology are required. Further, the technology has strong elements of modernity and scientific rigor that is strongly cultivated by vendors, consultants, and other advocates. As a result, GIS has become a field requiring a host of intermediaries between the end user and the data provider: technicians, system managers, analysts, user interfaces, query languages and so on added to this are the institutional and organizational issues of technology transfer. Although recent development in GIS software's and Web Technology has made GIS more user-friendly, therefore useable and accessible to more users (Geertman and Stillwell, 2002).

Information technology may either democratize information by making it more equitably accessible, or it may have the opposite effects of disproportionately empowering a selected sector of society. The lack of analytical tools to efficiently aid decision evaluation and policy formulation and the continuing mystification of the field have unfortunately often led to the latter in GIS (Fox 1991, Geertman and Stillwell, 2002). In many cases GIS has become a rifting technology, tending to divert the process of decision making away from decision makers and into the hands of GIS analyst and host of other highly trained technological intercessors

To alleviate the above problems GIS should be upgraded by DSS functionality in a user friendly and easy to use environment. However, there is a trade-off between the efficiency and ease of use, and the flexibility of the system. The more options are predetermined and available from the menu of choices, the more defaults are provided; the easier it becomes to use a system for an increasingly small sets of tasks. There is also trade-off between the ease of understanding and the precision of the results. Providing a visual or symbolic presentation changes the quality of the information in the course of transformation from quantitative to qualitative data sets. Finally, the easier the system the harder it is to make and maintain. Performing accurate and effective spatial analysis is the ultimate goal of implementing GIS.

2.3.3 GIS and project planning

A GIS is a dynamic and versatile technology capable of providing information to planners and decision-makers for efficient planning and implementation. The unique feature of GIS is its ability to provide answers to queries through rational and systematic analysis of the situation and aid planners to take quick decision. Traditionally, information available about natural resources, socio-economic and other attribute data are in the form of maps or tables or reports. Such information is not flexible enough to provide answers to the queries of instantly interest. GIS are used as a system for to help to decision makers to get the necessary information in project planning.

Two methods of the GIS approach that are used in implementing this work are described in this part and also some other techniques that are employed in the project are described in relevant parts.

2.3.4 Weighted overlay raster calculating method

The raster calculator provides a powerful tool for performing multiple tasks. It is possible to perform mathematical calculations using operators and functions, set up selection queries, or type in map algebra syntax. Inputs can be raster datasets or raster layers, coverage, shape files, tables, constants, and numbers.

Expressions are built in the raster calculator by using map algebra to weight rasters and combined as a part of a suitability model, to make selections from data in the form of queries, to apply mathematical operators and functions, or to type spatial analyst functions (ESRI, 2002).

Raster calculation is a suitable method to do the following tasks:

- Making selections
- Performing mathematical functions
- Weighting rasters
- Combining rasters

The weighted overlay raster calculating process makes it possible to take all these issues into consideration. It reclassifies values in the input rasters onto a common evaluation scale of suitability. The input rasters are weighted by importance and added to produce an output raster. The steps are summarized below:

- A numeric evaluation scale is chosen. This may be 0 to 5, 0 to 9, or any other scale. The highest value represents high suitability and the lowest value represents low suitability.
- The cell values for each input raster in the analysis are assigned values from the evaluation scale and reclassified to these values. This makes it possible to perform arithmetic operations on the rasters that originally held dissimilar types of values.
- Each input raster is weighted - assigned a percent influence based on its importance to the model. The total influence for all rasters equals 100 percent.
- The cell values of each input raster are multiplied by the rasters weighting.
- The resulting cell values are added to produce the output raster.

2.3.5 Intersecting method

The intersect tool calculates the geometric intersection of any number of feature classes and feature layers. The features or portion of features which are common to (intersect) all inputs will be written to the Output Feature Class. Intersect does the following:

- Determine the spatial reference for processing. This will also be the Output Feature Classes' spatial reference. All the input feature classes are projected (on the fly) into this spatial reference.
- Crack and cluster the features. Cracking inserts vertices at the intersection of feature edges, clustering snaps together vertices which are within the cluster tolerance.
- Discover geometric relationships (intersections) between features from all the feature classes or layers.
- Write these intersections as features (point, line or polygon) to the output.

To explicitly control the output spatial reference (Coordinate System and Domains) set the appropriate environments. The input feature classes can be any combination of geometry types (point, multi-point, line, and polygon). The output geometry type can only be of the same geometry or geometry of lower dimension than the input feature class with the lowest dimension geometry. Specifying different Output type will produce different types of intersection of the input feature classes. These are not a different representation of the same intersections; they are intersections which can only be represented by that geometry type (ESRI, 2002).

3.0 GEOTHERMAL ENERGY

3.1 Overview

Geothermal energy is energy derived from the heat contained in the earth. It is clean, abundant, and reliable. In other words, geothermal energy is a renewable energy source generated by the Earth's internal heat. If properly developed; it can offer a renewable and sustainable energy source. The use and study of geothermal energy has been greatly improved in the 1990's for supplying reusable energy for the increased worldwide energy demand (Dickson and Fanelli, 2004).

The presence of volcanoes, hot springs, and other thermal phenomena must have led our ancestors to surmise that parts of the interior of the earth were hot. However, it was not until in a period between the sixteenth and seventeenth century, when the first mines were excavated to a few hundred metres below ground level that man deduced, from simple physical sensations that the Earth's temperature increased with depth. The first measurements by thermometer were probably performed in 1740 by De Gensanne, in a mine near Belfort, in France (Buffon, 1778). By 1870, modern scientific methods were being used to study the thermal regime of the Earth (Bullard, 1965), but it was not until the twentieth century, and the discovery of the role played by radiogenic heat, that we could fully comprehend such phenomena as heat balance and the Earth's thermal history. All modern thermal models of the Earth, in fact, must take into account the heat continually generated by the decay of the long-lived radioactive isotopes of uranium (U^{238}, U^{235}), thorium (Th^{232}) and potassium (K^{40}), which are present in the Earth (Lubimova, 1968). Added to radiogenic heat, in uncertain proportions, are other potential sources of heat such as the primordial energy of planetary accretion. Realistic theories of these models were not available until the 1980s, when it was demonstrated that there was no equilibrium between the radiogenic heat generated in the Earth's interior and the heat dissipated into space from the Earth, and that our planet is slowly cooling down.

To give some idea of the phenomenon involved and its scale, we will cite a *heat balance* from Stacey and Loper (1988), in which the total flow of heat from the Earth is estimated at 42×10^{12} W (conduction, convection and radiation). Of this figure, 8×10^{12} W come from the crust, which represents only 2% of the total volume of the Earth but is rich in radioactive isotopes, 32.3×10^{12} W come from the mantle, which represents 82% of the total volume of the Earth, and 1.7×10^{12} W come from the core, which accounts for 16% of the total volume and contains no radioactive isotopes.

In more recent estimates, based on a greater number of data, the total flow of heat from the Earth is about 6 percent higher than the figure utilized by Stacey and Loper (1988). Even so, the cooling process is still very slow. The temperature of the mantle has decreased no more than 300 to 350 °C in three billion years, remaining at about 4000 °C at its base. It has been estimated that the total heat content of the Earth, estimated above an assumed average surface temperature of 15 °C, to be of the order of 12.6 x 10^{24} MJ, and that of the crust is of the order of 5.4 x 10^{21} MJ (Armstead, 1983). The thermal energy of the Earth is therefore immense, but only a fraction can be utilized by mankind. So far our utilization of this energy has been limited to areas in which geological conditions permit a carrier (water in the liquid phase or steam) to 'transfer' the heat from deep hot zones to or near the surface, thus giving rise to geothermal resources; in the near future, however, innovative techniques may offer new perspectives in this sector.

In many areas of life, practical applications precede scientific research and technological developments, and the geothermal sector is a good example of this. In the early part of the nineteenth century the geothermal fluids were already being used for their energy content. A chemical industry was set up in that period in Italy, to extract boric acid from the boric hot waters emerging naturally or from specially drilled shallow boreholes. The boric acid was obtained by evaporating the boric waters in iron boilers, using the wood from nearby forests as fuel. In 1827 Francesco Larderel, founder of this industry, developed a system for utilising the heat of the boric fluids in the evaporation process, rather than burning wood from the rapidly depleting forests (Dickson and Fanelli, 2004).

The use of natural steam for its mechanical energy began at much the same time. The geothermal steam was used to raise liquids in primitive gas lifts and later in reciprocating and centrifugal pumps and winches, all of which were used in drilling or the local boric acid industry. The oldest geothermal heating system was installed in the 14th century in Chuaude-Aiguse in France. Between 1910 and 1940 the low-pressure steam in Tuscany was brought into use to heat the industrial and residential buildings and greenhouses. Other countries also began developing their geothermal resources on an industrial scale. In 1892 the first geothermal district heating system began operations in Boise, Idaho (USA). In 1928 Iceland, another pioneer in the utilization of geothermal energy also began exploiting its geothermal fluids for domestic heating purposes (Dickson and Fanelli, 2004).

By 1904 the first attempt was made at generating electricity from geothermal steam at Larderello. The success of this experiment was a clear indication of the industrial value of geothermal energy and marked the beginning of a form of utilization that was to develop significantly from then on. Electricity generation at Larderello was a commercial success. By 1942 the installed geothermoelectric capacity had reached 127,650 kWe. Several countries were soon to follow the example set by Italy. In 1919 the first geothermal wells in Japan were drilled at Beppu, and in 1921 the first wells were drilled at The Geysers, California, USA. In 1958 a small geothermal power plant began operating in New Zealand, in 1959 another began in Mexico, in 1960 in the USA, followed by many other countries in the years to come.

Figure 2 is a simple representation of an ideal geothermal system.

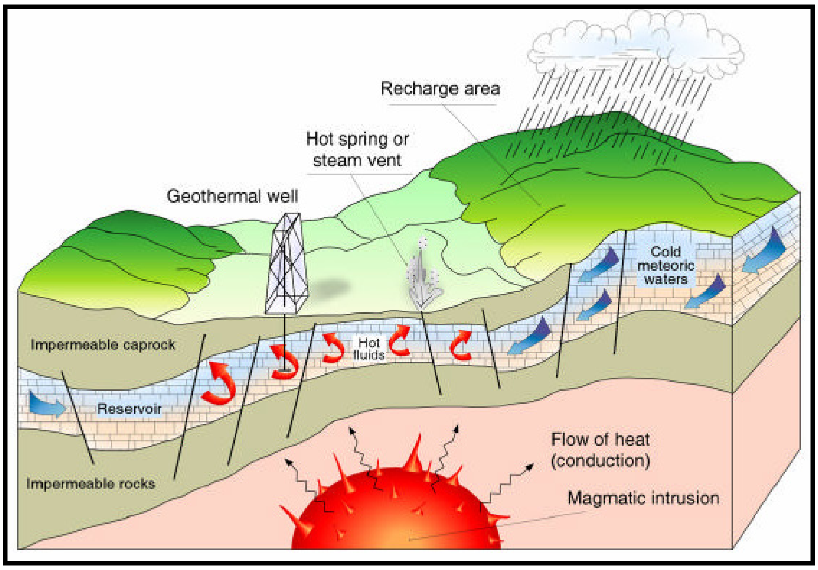

FIGURE 2: Simple representation of an ideal geothermal system
(Dickson and Fanelli, 2004)

3.2 Classification of resources

Geothermal systems and reservoirs are classified on the basis of different properties, such as reservoir temperature or enthalpy, physical state, their nature and geological setting (Axelsson and Gunnlaugsson, 2000). The most common criterion for classifying geothermal resources is, however, that based on the enthalpy of the geothermal fluids that act as the carrier transporting heat from the deep hot rocks to the surface. Enthalpy of the water phase, which can be considered more or less proportional to temperature, is used to express the heat (thermal energy) content of the fluid in liquid dominated systems, and gives a rough idea of their value. The resources are divided into low, medium and high enthalpy (or temperature) resources, according to criteria that are generally based on the energy content of the fluids and their potential forms of utilization. In T classifications proposed by a number of authors are listed.

TABLE 1: Classification of geothermal resources

Classes	Muffler and Cataldi (1978) ºC	Hochstein (1990) ºC	Benderitter and Cormy (1990) ºC	Nicholson (1993) ºC	Axelsson and Gunnlaugsson (2000) ºC
Low-enthalpy resources	< 90	<125	<100	≤150	≤190
Intermediate-enthalpy resources	90-150	125-225	100-200	-	-
High-enthalpy resources	>150	>225	>200	>150	>190

Geothermal systems and reservoirs are divided into four classes according to different properties are reviewed below (Axelsson and Gunnlaugsson, 2000).

3.2.1 Temperature basis

A classification based on the temperature at a depth of about 1 km in a geothermal reservoir is often employed in Iceland (Bodvarsson, 1964):

- Low-temperature (LT), systems with reservoir temperature below 150ºC and most often characterized by hot or boiling springs.
- High-temperature (HT), systems with reservoir temperature above 200ºC and characterized by fumaroles, steam vents, mud pools and highly altered ground.

Hardly any geothermal systems in Iceland fall in between these two definitions (150-200 ºC), but such systems may be termed Medium-temperature (MT) systems.

3.2.2 Enthalpy basis

Classification based on enthalpy constitutes two classes:

- Low-enthalpy, geothermal systems with reservoir fluid enthalpy less than 800 kJ/kg, corresponding to a temperature lower than about 190 ºC.
- High-enthalpy, geothermal systems with reservoir fluid enthalpy greater than 800 kJ/kg.

3.2.3 Physical basis

Geothermal reservoirs are more commonly classified on the basis of their physical state:

- Liquid-dominated: In liquid dominated geothermal reservoirs the water temperature is at, or below, the boiling point at the prevailing pressure and the water phase controls the pressure in the reservoir. Some steam may be present, however.
- Two-phase: In two-phase geothermal reservoirs the two phases co-exist and the temperature and pressure follow the boiling point curve.
- Vapour-dominated: In vapour dominated geothermal systems the temperature is at or above, the boiling point at the prevailing pressure and the steam phase controls the pressure in the reservoir. Some water may, however, be present.

Different parts of geothermal systems may be in different physical states and a geothermal reservoir may also evolve from one state to another. As an example a liquid-dominated reservoir may evolve into a two-phase reservoir when that is a pressure decline in the system. Low-temperature systems are always liquid-dominated, but high-temperature systems can either be liquid-dominated, two-phase or vapour-dominated.

3.2.4 Geological basis

Geothermal systems may be classified according to their nature and geological setting:

Volcanic systems are one way or another associated with volcanic activity. The heat sources for such system are hot intrusions or magma. They are most often situated inside, or close to, volcanic complexes such as calderas and/or spreading centers. Permeable fractures and fault zones mostly control the flow of water in volcanic systems. Numerous volcanic geothermal systems are found for example in the in countries like Iceland, New Zealand, the Philippines, Japan and Central America.

Convective systems heated by the heat sources from hot crust at depth in tectonically active areas, with above average heat-flow. Here the geothermal water has circulated to a considerable depth (> 1 km), through mostly vertical features, to mine the heat from the rocks. Geothermal systems of conductive types exist outside the volcanic zone in Iceland and outside the volcanic zone' in the SW United States and SE China.

Sedimentary systems are found in many of the major sedimentary basins of the world. These systems owe their existence to the occurrence of the permeable sedimentary layers at great depths (> 1 km) and above average geothermal gradients (> 30 C/km). These systems are conductive in nature rather than convective, even though fractures and faults play a role in some cases. Some convective systems may, however, be embedded in sedimentary rocks. Sedimentary geothermal systems are for example found in France, Central Eastern Europe and in NE China.

Geopressured systems are analogous to geopressured oil and gas reservoir where fluid caught in stratigraphic traps may have pressure close to lithostatic values. The geopressured systems are characteristically found in large sedimentary basins at depths of 3 - 7 km. The geopressured reservoirs consist of permeable sedimentary rocks, embedded within impermeable low-conductivity strata, containing pressurized hot water that remained trapped at the moment of deposition of the sediments. The hot water pressure approaches lithostatic pressure, greatly exceeding the hydrostatic pressure. The geopressured reservoirs can also contain significant amounts of methane. The geopressured systems could produce thermal and hydraulic energy (pressurized hot water) and methane gas. A typical geopressured system is found in the Northern Gulf of Mexico Basin in the USA, both offshore and onshore.

Hot Dry Rock systems consist of volumes of rock that have been heated to useful temperatures by volcanism or abnormally high heat flow, but are virtually impermeable. Therefore, they can not be utilized in a conventional way. However, experiments have been conducted in a number of locations to use hydro-fracturing to try to create artificial reservoirs in such systems. The most famous Hot Dry Rock project is the Fenton Hill project in New Mexico in the United States.

The most critical factor for the classification of geothermal energy as a renewable energy source is the rate of energy recharge. In the utilization of natural geothermal systems, energy recharge takes place by advection of thermal water on the same time scale as production from the resource. This justifies the classification of geothermal energy as a renewable energy resource. In the case of hot, dry rocks, and some of the hot water aquifers in sedimentary basins, energy recharge is only by thermal conduction; due to the slow rate of the latter process, however, hot dry rocks and some sedimentary reservoirs should be considered as finite energy resources (Stefánsson, 2000).

3.3 Exploration

All exploration programs begin with an examination and compilation of every available data. The ultimate objective of any exploration program is to locate a resource that can be economically developed. In the early stages of resource exploration, when areas to be investigated are large, rapid low-cost reconnaissance techniques are employed. As results accumulate and the search narrows, confidence increases and more expensive techniques can be utilized. In the case of geothermal exploration, this may continue until the most expensive technique, is used to test the prospect. The objective of geothermal exploration is obviously to locate a geothermal system from which energy can be economically extracted. Because high geothermal gradients are a prerequisite for any type of geothermal system, the initial exploration effort should concentrate on defining such anomalous areas using a variety of techniques (Edwards et al., 1982). When an area of high geothermal gradient or heat flow is identified, emphasis shifts to finding the necessary geological setting and evaluating of the permeability and hydrology of the area. Geochemical, geophysical investigations and exploratory drilling are the next steps for evaluating geothermal reservoirs. The main objectives of geothermal exploration are (Lumb, 1981):

- To identify geothermal phenomena.
- To ascertain that a useful geothermal production field exists.
- To estimate the size of the resource.
- To determine the type of geothermal field.
- To locate productive zones.
- To determine the heat content of the fluids that will be discharged by the wells.
- To compile a body of basic data against which the results of future monitoring can be viewed.
- To determine the pre-exploitation values of environmentally sensitive parameters.
- To acquire knowledge of any characteristics that might cause problems during field development.

3.3.1 Exploration methods

Geological and hydrogeological studies

Geological and hydrological studies are the starting point of any geothermal exploration program, and their basic function is that of identifying the location and extension of the areas worth investigating in greater detail and of recommending the most suitable exploration methods for these areas.

Careful geological mapping is the foundation on which any exploration program is built and all other data must be interpreted in terms of the observed geology. In geothermal exploration, geological studies should emphasize the mapping of young igneous rocks that could act as heat sources, potential reservoir rocks, distribution and nature of hydrothermal alteration, and the distribution, orientation and nature of fractures and faults. Geological investigations of igneous rocks (associated with the thermal anomaly), the potential reservoir rocks, and impermeable capping and aid in the definition of the size of the anomaly help predict fluid characteristics, which eventually will affect development and utilization. The investigations include determination of model composition, textural examinations, and fracture and alteration studies.

Knowledge of the frequency, size and orientation of fractures and faults is important in the exploration for and assessment of any type of geothermal reservoir. In most natural liquid-dominated systems, secondary permeability (fracture-controlled permeability) is the most important type of permeability that controls the production from the wells. For this reasons it is imperative, as part of any geothermal exploration program, to characterize the nature of fractures present within the area.

The hydrological and hydrogeological studies are a part of geothermal exploration, they are necessary for the evaluation of any type of geothermal resource. In liquid-dominated and geopressurized systems, naturally occurring aqueous fluids are the agent by which energy is transported from the reservoir to the earth's surface. This immediately implies an important role for hydrology in understanding the geothermal system. The objective of hydrological investigations is to determine the source of the fluids, area of recharge, infiltration rate, location, depth, pressure, composition and temperature of aquifers (Edwards et al., 1982).

Geological and hydrogeological studies play an important role in all subsequent phases of geothermal research, right up to the siting of exploratory and producing boreholes. They also provide the background information for interpreting the data obtained with other exploration methods and, finally, for constructing a realistic model of the geothermal system and assessing the potential of the resource. The information obtained from the geological and hydrogeological studies may also be used in the production phase, providing valuable information for the reservoir and production engineers. The duration and cost of exploration can be appreciably reduced if experienced geothermal geologists and hydrologists co-ordinate the exploration program.

Geochemical surveys
Geochemistry affords one of the cheaper tools available in geothermal exploration. It can even sometimes prevent the unnecessary wastage of exploration effort and expense at the very outset by demonstrating that some particular area is likely to prove to be geothermally worthless (Armstead, 1983).

The chemistry of thermal fluids emitted from hot springs and fumaroles is determined by the interaction of underground fluids and rock with which they come into contact. If the fluids are hot, chemical equilibrium will be achieved quite rapidly, and certain chemical features of fluids discharged at the surface are indicative of the temperature at which this equilibrium has been attained.

Several chemical geothermometers exist that can be used to predict reservoir temperature prior to drilling. Three principal indicators of deep reservoir temperatures, to be sought in hot spring chemistry, are silica, magnesium and sodium/potassium ratios. Silica concentrations are more reliable for hot springs of high discharge than for those of low discharge or minor seepages. Magnesium is of limited value as a temperature indicator, but its total absence could be suggestive of economically useful reservoir temperatures (at least 200 ºC), as magnesium is retained in clay materials which are stable at high temperature (the lower ratio the higher temperature). The presence of free hydrogen in fumaroles is another indicator of subterranean temperatures exceeding 200ºC (Armstead, 1983).

Geochemical studies are also a useful means of determining whether the geothermal system is liquid- or vapour-dominated, of estimating the minimum temperature expected at depth, of estimating the homogeneity of the water supply, of inferring the chemical characteristics of the deep fluid and of determining the source of recharge water (Combs and Muffler, 1973). Valuable information can also be obtained on what problems are likely to arise during the utilization phase (e.g. corrosion and scaling on pipes and plant installations, environmental impact) and on how to avoid or combat them. The geochemical survey consists of sampling and chemical and/or isotope analyses of the water and gas from geothermal manifestations (hot springs, fumaroles, etc.) in study area.

As the geochemical survey provides useful data for planning exploration and its cost is relatively low compared to other more sophisticated methods, such as geophysical surveys, the geochemical techniques should be utilized as much as possible before proceeding to other more expensive methodologies.

Geophysical surveys
A wide variety of geophysical techniques has been used in geothermal exploration and geophysical exploration techniques have been used successfully to locate the heat sources of geothermal systems and to characterize the permeability of the potential reservoir (Edwards et al., 1982).

Geophysical surveys are directed at obtaining indirectly, from the surface or from depth intervals close to the surface, the physical parameters of deep geological formations. These physical parameters include temperature (thermal survey), electrical conductivity (electrical and electromagnetic methods), propagation velocity of elastic waves (seismic survey), density (gravity survey) and magnetic susceptibility (magnetic survey). Some of these techniques, such as seismicity, gravity and magnetic profiling, which are traditionally adopted in oil research, can give valuable information on the shape, size, depth and other important characteristics of the deep geological structures that could constitute a geothermal reservoir, but they give little or no indication as to whether these structures actually contain the fluids that are the primary objective of research. These methodologies are, therefore, more suited to defining details during the final stages of exploration, before the exploratory wells are sited. Information on the existence of geothermal fluids in the geological structures can be obtained with electrical and electromagnetic prospecting, which is more sensitive than the other surveys to the presence of these fluids and to variations in temperature; these two techniques have been applied widely with satisfactory results. The magnetotelluric method, in particular, has been greatly improved over the last few years, and now offers a vast spectrum of possible applications, despite the fact that it requires sophisticated instrumentation and is sensitive to background noise in urbanized areas. The main advantage of the magnetotelluric method is that it can be used to define deeper structures than are attainable with the electric and the other electro-magnetic techniques. The thermal techniques (temperature measurements, determination of geothermal gradient and terrestrial heat flow) can often provide a good approximation of the temperature at the top of the reservoir (Dickson and Fanelli, 2004).

The Transient Electro Magnetic (TEM) method is one of the active geophysical methods used in the exploration of geothermal resources in Iceland. The popularity of TEM methods in geothermal exploration has increased in the last two decades. TEM methods demand considerably more sophistication than DC methods, both with respect to instrumentation and theoretical background. The rapid development in electronics and computers in the last decades has made the TEM methods more applicable as exploration tools (Árnason and Flóvenz, 1992).

In TEM soundings current is created in the subsurface rocks by a time varying electromagnetic field at the surface. This is done by injecting a time variant current, normally a step-function, into a grounded dipole or loop of wire at the surface. A transient response is measured during current-off time. The record response is usually the decay of the magnetic field. In TEM sounding, information on variation of resistivity with depth is obtained by observing the transient signal as time increases. Depth of exploration is also increased by increasing the source-receiver distance. Measuring the decay of the magnetic filed instead of electric field at the surface, makes the TEM method relatively free of local resistivity variation close to the receiver (Stemberg et al., 1988).

This method has many advantages as compared to other resistivity methods. No current has to be injected into the ground which makes the method applicable in areas of resistive surface. The central-loop configuration is more downwards focused than other resistivity methods. This implies that resistivity structures with relatively strong lateral variation of resistivity can be mapped with 1-D inversion of central-loop TEM sounding. The method has been widely used in geothermal exploration of Iceland since 1986 (Árnason and Flóvenz, 1992).

Exploration drilling
The final aim of all preliminary exploratory work is to select promising sites for exploratory drilling. Drilling of exploratory wells represents the final phase of any geothermal exploration program and is the only means of determining the real characteristics of the geothermal reservoir and thus of assessing its potential (Combs and Muffler, 1973). The data provided by exploratory wells should be capable of verifying all the hypotheses and models elaborated from the results of surface exploration and of confirming that the reservoir is productive and that it contains enough fluids of suitable characteristics for the utilization for which it is intended. Siting of the exploratory wells is therefore a very delicate operation.

3.4 Utilization

After the Second World War many countries were attracted by geothermal energy, considering it to be economically competitive with other forms of energy. It did not have to be imported, and, in some cases, it was the only energy source available locally. Generation of electricity and direct heat use of geothermal energy are the two main categories of geothermal energy utilization as described below:

3.4.1 Power generation

Utility-scale geothermal power production employs three main technologies. These are known as dry steam, flash steam and binary cycle systems. The technology employed depends on the temperature and pressure of the geothermal reservoir. Unlike solar, wind, and hydro-based renewable power, geothermal power plant operation is independent of fluctuations in daily and seasonal weather.

A dry steam power plant uses very hot (>235 °C) steam and little water from the geothermal reservoir. The steam goes directly through a pipe to a turbine to spin a generator that produces electricity. This type of geothermal power plant is the oldest, the first being demonstrated in Lardarello, Italy. In 1904 Italian engineers managed to light five bulbs with a generator running on geothermal steam. They went on to improve the technique and had a 250 kWe turbine running by 1913 (Shibaki, 2003).

Flash steam power plants use hot water (>182 ºC) from the geothermal reservoir. When the water is pumped to the generator, it is released from the pressure of the deep reservoir. The sudden drop in pressure causes some of the water to vaporize to steam, which spins a turbine to generate electricity. Both dry steam and flash steam power plants emit small amounts of carbon dioxide, and hydrogen sulphide, but generally 50 times less than traditional fossil-fuel power plants. Hot water not flashed into steam may be returned to the geothermal reservoir through injection wells.

Binary-cycle power plants employ moderate-temperature water (107-182 ºC) from the geothermal reservoir. In binary systems, hot geothermal fluids are passed through one side of a heat exchanger to heat a working fluid in a separate adjacent pipe. The working fluid, usually an organic compound with a low boiling point such as iso-butane or iso-pentane, is vaporized and passed through a turbine to generate electricity. An ammonia-water working fluid is also used in what is known as the Kalina Cycle. Makers claim that the Kalina Cycle system boosts geothermal plant efficiency by 20–40 percent and reduces plant construction costs by 20–30 percent, thereby lowering the cost of geothermal power generation. The advantages of binary cycle systems are that the working fluid boils at a lower temperature than water does, so electricity can be generated from reservoirs with lower temperature, and the binary cycle system is self-contained and therefore, produces virtually no emissions. For these reasons, some geothermal experts believe binary cycle systems could be the dominant geothermal power plants of the future.

Many countries utilise geothermal energy to generate electricity. The installed geothermal electric capacity in 1995 was 6833 MWe, in 2000, 7972 MWe and the increase between 1995 and the year 2000 (Huttrer, 2001) 1139 MWe. Also the total installed capacity at the end of 2003 was 8402 MWe. The geothermal power installed in the developing countries in 1995 and 2000 represents 38 and 47% of the world total, respectively. The utilization of geothermal energy in developing countries has exhibited an interesting trend over the years. In the five years between 1975 and 1979 the geothermal electric capacity installed in these countries increased from 75 to 462 MWe; by the end of the next five-year period (1984) this figure had reached 1495 MWe, showing a rate of increase during these two periods of 500% and 223%, respectively. In the next sixteen years, from 1984 to 2000, there was a further increase of almost 150%. Geothermal power plays a fairly significant role in the energy balance of some areas; for example, in 2001 the electric energy produced from geothermal resources represented 27% of the total electricity generated in the Philippines, 12.4% in Kenya, 11.4% in Costa Rica, and 4.3% in El Salvador (Dickson and Fanelli, 2004).

3.4.2 Direct use

Direct heat use is one of the oldest, most versatile and also the most common forms of utilization of geothermal energy. Space and district heating, agricultural applications, aquaculture and industrial uses are the best known and most widespread forms of utilization, but other forms are already in use or in the late planning stages.

Space and district heating, had high growth from 1995-2000 over 56% or 9.4% annually in 28 countries. About 75% of the 59,696 TJ/yr utilization is estimated for district heating, and the remainder for individual space heating. The majority of the district heating systems are in Europe where the leaders are France and Iceland, whereas the United States dominated the individual home heating systems use. Other countries which have extensive district heating systems are China, Japan and Turkey (Lund and Freeston, 2001).

District heating in Iceland had its beginning early in the 20^{th} century and in 1970 about 43% of the population was served by geothermal district heating systems. After the oil crisis in the 1970s, high priority was given to replacing imported oil with the indigenous energy sources hydro and geothermal. Today about 87% of the space heating is by geothermal energy, the rest is by electricity 11.5% and oil 1.5% (Ragnarsson, 2003).

The *agricultural applications* of geothermal fluids consist of open-field agriculture and greenhouse heating. Thermal water can be used in open-field agriculture to irrigate and/or heat the soil. The greatest drawback in irrigating with warm waters is that, to obtain any worthwhile variation in soil temperature, such large quantities of water are required at temperatures low enough to prevent damage to the plants that the fields would be flooded. One possible solution to this problem is to adopt a subsurface irrigation system coupled to a buried pipeline soil heating device. Heating the soil in buried pipelines without the irrigation system could decrease the heat conductivity of the soil because of the drop in humidity around the pipes and consequent thermal insulation. The best solution seems to be that of combining soil heating and irrigation. The chemical composition of the geothermal waters used in irrigation must be monitored carefully to avoid adverse effects on the plants. In some places in warm countries where the heat is not needed to heat the greenhouses the important use of the geothermal stream and water is for disinfection of soil. The main advantages of temperature control in open-field agriculture are (Barbier and Fanelli, 1977):

- It prevents any damage ensuing from low environmental temperatures,
- It extends the growing season, increases plant growth, and boosts production, and
- It sterilizes the soil.

The most common application of geothermal energy in agriculture is, however, in greenhouse heating, which has been developed on a large scale in many countries. The cultivation of vegetables and flowers out-of-season, or in an unnatural climate, can now draw on a well tried technology. Various solutions are available for achieving optimum growth conditions, based on the optimum growth temperature of each plant, and on the quantity of light, on the CO2 concentration in the greenhouse environment, on the humidity of the soil and air, and on air movement. The simplest greenhouses are made of single plastic films, but recently some greenhouses have been constructed with a double layer of film separated by an air space. This system reduces the heat loss through the walls by 30 - 40%, and thus greatly enhances the overall efficiency of the greenhouse. Greenhouse heating can be accomplished by forced circulation of air in heat exchangers, hot-water circulating pipes or ducts located in or on the floor, finned units located along the walls and under benches, or a combination of these methods. Exploitation of geothermal heat in greenhouse heating can considerably reduce their operating costs, which in some cases accounts for 35% of the product costs (vegetables, flowers, house-plants and tree seedlings).

Aquaculture, which is the controlled breeding of aquatic forms of life, is gaining worldwide importance nowadays, due to an increasing market demand. Control of the breeding temperatures for aquatic species is of much greater importance than for land species. By maintaining an optimum temperature artificially we can breed more exotic species, improve production and even, in some cases, double the reproductive cycle (Barbier and Fanelli, 1977). The species that are typically raised are carp, catfish, bass, tilapia, mullet, eels, salmon, sturgeon, shrimp, lobster, crayfish, crabs, oysters, clams, scallops, mussels and abalone. Aquaculture also includes alligator and crocodile breeding, which could prove an innovative and lucrative industry. Experiments in the United States have shown that, by maintaining its growth temperature at about 30 °C, an alligator can be grown to a length of about 2 m in 3 years, whereas alligators bred under natural conditions will reach a length of only 1.2 m over the same period. Another form of aquaculture is the cultivation of protein-rich microalgae, such as *Spirulina*.

The entire temperature range of geothermal fluids, whether steam or water, can be utilized for *industrial applications*. The different possible forms of utilization include process heating, evaporation, drying, distillation, sterilization, washing, de-icing, salt and chemical extraction, as well as oil recovery. Industrial process heat has applications in 19 countries, where the installations tend to be large and energy consumption high. Examples include: concrete curing, bottling of water and carbonated drinks, paper and vehicle parts production, oil recovery, milk pasteurization, leather industry, chemical extraction, CO_2 extraction, mushroom growing and laundry use, salt extraction and diatomaceous earth drying, pulp and paper processing, and borate and boric acid production (Lund and Freeston, 2001).

As regards *non-electric applications* of geothermal energy, The installed capacity in the world is 15,145 MWt and the energy use is 190,699 TJ/yr for the year 2000. During that year 58 countries reported direct uses, compared to 28 in 1995 and 24 in 1985. The number of countries with direct uses has very likely increased since then, as well as the total installed capacity and energy use. The most common non-electric use world-wide (in terms of installed capacity) is heat pumps 34.80%, followed by bathing 26.20%, space-heating 21.62%, greenhouses 8.22%, aquaculture 3.93%, and industrial processes 3.13% (Lund and Freeston, 2001).

3.5 Environmental effects of geothermal development

3.5.1 Overview

The environmental aspects of geothermal development are receiving increasing attention with the shift in attitudes towards the world's natural resources. Not only is there greater awareness of the effect of geothermal development on the surrounding ecosystems and landscape, but there is also a growing appreciation of the need for efficient and wise use of all natural resources. Geothermal power generation is often considered as a '*clean*' alternative to fossil fuel power plants, but it is necessary to survey the effect of geothermal contamination on the environment to minimize it.

Most countries have embodied their environmental concerns in legislation and regulations. These regulations are similar, and many countries have regulations that require an environmental analysis of a proposed geothermal project, as well as specific regulations that define the quantities of pollutants that may be emitted to the atmosphere or discharged to land and water. There is, however, significant variation in the number of agencies involved in the environmental review of a project, and the amount of time required from application through to project approval. The different types of geothermal fields and geothermal development have varying impacts and legislation needs to cover all possible development scenarios. In general, as development proceeds, the legislative requirements move from environmental impact reports during the pre-development stage, to gaining consent for development and finally a monitoring role during production.

Geothermal energy production generally has a well-deserved image of an environmentally friendly energy source when compared to fossil fuel and nuclear energy production. Continuing justification for this reputation will rely as much on the conscience of the developer as the underlying legislation. Most countries have developed or adopted criteria to protect their own environment. The criteria may be designed to specifically protect native species or ecosystems, or may be adopted from those of another country with similar biological characteristics.

The degree to which geothermal development affects the environment is, in most cases, proportional to the scale of such development. For example, the environmental impacts associated with direct geothermal use projects are often minimal. Those associated with large scale electrical generation projects may be large. The direct use projects are often designed as closed loop use systems where the low- or medium-temperature geothermal fluids are circulated through a heat exchanger or a heat pump (or flow naturally around downhole heat exchangers).

Natural features such as hot springs, mud pools, geysers, fumaroles and steaming ground are associated with most geothermal systems. Because of their unique nature, these are often tourist attractions or are used by local residents. Geothermal development that draws from the same reservoir has the potential to affect these features. These visible signs of geothermal activity are a part of a country's heritage and in any geothermal development they must be taken into account during an environmental impact assessment.

The thermal features may also hold significant cultural and spiritual importance for many indigenous peoples. The Waiotapu thermal area in New Zealand is classified as category A under New Zealand Resource Management Act 1991, (RMA): areas containing unique and outstanding hydrothermal features that must be completely preserved if a representative selection of features is to be retained. Therefore, geothermal development is under no circumstances allowed in this geothermal field. The potential impacts of large scale geothermal development are summarized in Table 2. Some typical and important effects of geothermal development and utilization, including impacts on geology and land, air, water, and that of noise, are described below in more detail.

3.5.2 Impacts on geology and land

Preliminary exploration is usually the least expensive exploration activity with the least environmental effect. There are usually no environmental effects of geological mapping as it only involves walking or aerial reconnaissance over the exploration area. Sampling procedures during this phase are also benign. Temperature gradient well drilling requires only small areas of surface disturbance to construct a levelled area for the drill rig.

In geothermal projects most land effects occur during construction and drilling. Each drill site is usually between 200 and 2500 m^2 in land and the soil in these areas is compacted and changed, and close to the drill site there is also some deposition of waste soil and drill mud. To transport the drill rig and other instruments road construction may be needed and this affects the land. Construction of roads, well pads, and power plant sites results in cut and fill slopes that reshape the topography of the areas, but the effect on the area’s topography is not significant. During installation there is some effect on the land from soil movement for construction of pipeline, power plant and other buildings (Brown, 1995).

During operation subsidence and induced seismicity are the main possible effects on the land of the power plant and surrounding areas. In areas of low rock strength the withdrawal of massive quantities of fluid from the ground may cause subsidence of the ground surface. Withdrawal of geothermal water from any type of reservoir will normally result in pressure reduction in the formation pore space and this can lead to subsidence. Subsidence has been observed in ground water reservoirs and geothermal reservoirs. Subsidence has a number of implications for geothermal development and also for the effect on the surrounding area as it can have serious consequences for the stability of the pipelines, drains and well casing in a geothermal field. If a field is close to a populated area it can lead to instability. In more remote areas, where there may be no habitation, the local surface watershed system may be affected.

Before exploration, a baseline levelling survey and gravity measurements with the installation of levelling stations need to be carried out at a number of separate survey stations to cover as long a time as possible before exploration so that the local tectonic change in level, if any, can be subtracted from those due to production.

While having a subsidence potential, hydrothermal reservoirs are not as greatly subject to subsidence as geopressured reservoirs where subsidence is almost a certainty. Geopressured zones have such a

TABLE 2: Potential impacts of large scale geothermal development
(after The World Bank Group, 2004)

Potential impact	Potential effect	Mitigation and remediation measures
Land requirement	• Vegetation loss • Soil erosion • Landslides • Land ownership issues • Surface disturbance	• Single drill pads – several wells • Re-vegetation programs • Adequate land compensation • Avoid well sites from steep area
Water withdrawal from streams and waterways for drilling purposes	• Impact on local watershed • Damming and diverting local streams • Impact on local farming • Effect on biological resource	• Withdrawal from streams with high flow rates • Coincide drilling with rainy season not dry season • Build temporary reservoirs • Liaise with local farmers to take their usage into account
Water withdrawal from reservoir	• Loss of natural features • Increase in steaming ground • Hydrothermal eruptions • Lowering of water table • Increase in steam zone • Subsidence • Saline intrusion • Effect on flow of other wells	• Avoid water withdrawal from outflows • Avoid areas where there is propensity for hydrothermal eruptions (which occur naturally also) • Careful sustainable management of resource, balancing recharge with take • Monitoring shallow ground water wells
Waste (brine and condensate) disposal into streams and waterways	• Thermal effects • Chemical effects • Biological effects	• Effluent treatment and removal of undesirable constituents • Reinject all waste fluids • Cascaded uses of waste fluids e.g. Fish farms, pools
Reinjection	• Cooling of reservoir • Induced seismicity • Scaling • Infiltration into shallow ground water and surface water	• Careful planning of reinjection wells outside main reservoir • Monitor flow patterns before reinjection eg. tracer tests • Anti-scale treatment of fluids • Reinject at suitable location and depth
Drilling effluent disposal into streams and waterways	• Biological effects • Chemical effects	• Contain in effluent ponds or in barrels for removal
Air emissions	• Biological effects • Chemical effects • Localized slight heating of atmosphere • Localized fogging	• Effluent treatment and removal of undesirable constituents • Minimize emissions by scrubbing H_2S and treating other Non Condensable Gases (NCGs)
Noise	• Disturbance to animals and humans • Impaired hearing	• Muffling of noise eg. silencers

high subsidence potential because the thick sedimentary sequences in which they are found are under-compacted and the water trapped in these sequences actually bears part of the lithostatic load. Withdrawing water from a geopressured reservoir leads to compaction of these rock units and results in subsidence. In geothermal fields the best known example is Wairakei, New Zealand, where subsidence rates of up to 40 cm/y have been reported (Allis, 1990).

Geothermal resources are generally located in areas of high natural heat flow along thinning crustal zones. Thus, areas that are geothermally active are also very likely to be seismically active.

3.5.3 Ground subsidence

In the early stages of a geothermal development, geothermal fluids are withdrawn from a reservoir at a rate greater than the natural inflow into the reservoir. This net outflow causes rock formations at the site to compact, particularly in the case of clays and sediments, leading to ground subsidence at the surface. 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 high-permeability paths between the reservoir and the compressible 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 for same amount of energy mass withdrawal from water-dominated field is greater than steam-dominated fields, however, the geological characteristics typically associated with geothermal field is very important. Ground subsidence can affect the stability of pipelines, drains, and well casings. It can also cause the formation of ponds and cracks in the ground and, if the site is close to a populated area, it can lead to instability of buildings.The largest recorded subsidence in a geothermal field was at Wairakei in New Zealand. Here the ground subsided as much as 18 metres in 30 years of geothermal fluid extraction. Monitoring has shown that a maximum subsidence rate of 45 cm/year occurred in a small region, outside the production area, with subsidence of at least 2 cm/year occurring all over the production field (Hunt and Brown, 1996).

Subsidence in other fields has been observed and was 1.7 m in Larderello between 1923 and 1986 (Dini and Rossi, 1990), about 10 cm in the Geysers between 1974 and 1977 (Allis, 1982) and up to 15 cm between 1982 and 1987 in Svartsengi geothermal field in Iceland (Björnsson, and Steingrímsson, 1992).

Fluid re-injection can help to reduce pressure drop and hence subsidence, but its effectiveness depends on where the fluid is re-injected and the permeability conditions in the field. Typically, re-injection is carried out at some distance from the production well to avoid the cooler rejected waste fluid from lowering the temperature of the production fluid and may not help prevent subsidence. Precise gravity measurements have been successfully used to confirm fluid withdrawal from reservoirs and to estimate fluid recharge to the geothermal reservoir.

3.5.4 Landscape and land use impacts

Geothermal power plants require relatively little land. Geothermal installations do not require damming of rivers or harvesting of forests, and there are no mineshafts, tunnels, open pits, waste heaps or oil spills. An entire geothermal field uses only 1–8 acres per MW versus 5–10 acres per MW for nuclear plants and 19 acres per MW for coal plants (Geothermal Energy Program, 2002). Table 3 compares acreage requirements by technology.

TABLE 3: Comparison of land requirement for base load power generation (Geothermal Energy Program, 2002)

Power source	Land requirement (Acre/MW)
Geothermal	1– 8
Nuclear	5 –10
Coal	19

Geothermal power plants are clean because they neither burn fossil fuels nor produce nuclear waste. Geothermal plants can be sited in farmland and forests and can share land with cattle and local wildlife. For example, the Hell's Gate National Park in Kenya was established around an existing 45 MWe geothermal power station, Olkaria I. Land uses in the park include livestock grazing, growing of foodstuffs and flowers, and conservation of wildlife and birds within the Park. After extensive environmental impact analysis, a second geothermal plant, Olkaria II, was approved for installation in the park in 1994, and an additional power station is under consideration (The World Bank Group, 2003).

Geothermal plants are also benign with respect to water pollution. Production and injection wells are lined with steel casing and cement to isolate fluids from the environment. Spent thermal waters are frequently injected back into the reservoirs from which the fluids were derived. This practice neatly solves the water-disposal problem while helping to bolster reservoir pressure and prolong the resource's productive existence.

3.5.5 Impacts on air

Surface exploration activity (geology, geochemistry and geophysical exploration) of geothermal projects does not affect atmospheric air.

During drilling air pollution can result from non-condensable gas emissions, exhaust smoke from generators, compressors and vehicles. Combustion of diesel fuel in the drilling rig produces NO_x, CO_2, SO_2 and hydrocarbons, but the amount of these gases is not significant and does not have an important effect on the atmosphere. During well testing, steam and spray can have an adverse effect on the local vegetation with trees and grass being scalded.

Some pollutant gases are emitted to the atmosphere during well testing from well pads, especially during multiple well flow tests in adverse meteorological conditions, but effects of gases are not likely. Although H_2S produces an unpleasant odour, eye irritation and respiratory damage, its concentration during drilling is not likely to be significant.

Fugitive dust is generated by several types of activities scheduled during construction, operation and decommissioning. The principal source is dust generated by travel on unpaved roads, dust generated by earthmoving activity during construction and reclamation on the power plant site and well pads, and dust carried by wind blowing across exposed surfaces. Most of the fugitive dust emissions occur as a part of construction and reclamation activities, and would result only in short-term fugitive particulate matter less than 10 microns in diameter ($PM_{(10)}$).

Geothermal power generation using a standard steam cycle plant will result in the release of non-condensable gases, and fine solid particles into the atmosphere. Various poisonous chemical components in geothermal steam escape into the atmosphere from power plants via ejector exhausts, cooling towers, silencers and drains and traps. Geothermal gases are carbon dioxide (CO_2), hydrogen sulphide (H_2S), arsenic (As), hydrogen (H_2), nitrogen (N), Argon (Ar) ammonia (NH_3), hydrocarbons such as methane (CH_4), and ethane (C_2H_6), trace amounts of carbon monoxide (CO), mercury (Hg), boron (B) vapour and helium (He), and radon (Rn). Of these compounds hydrogen sulphide, carbon monoxide, mercury, arsenic and radon are poisonous. Apparently, not much attention has been paid to airborne poisons in geothermal steam other than hydrogen sulphide. This noxious gas has an unpleasant smell when present in low and harmless concentrations. When more strongly concentrated and present in lethal quantities, it paralyzes the olfactory nerves and thus becomes odourless (Brown, 1995).

The most significant ongoing gas emission will be from the gas exhausters of the power station that discharge through a cooling tower. The main hazardous chemical substances that are possible airborne contaminants and are released during geothermal development are carbon dioxide and hydrogen sulphide, and the concentration of carbon dioxide is higher than that of hydrogen sulphide. Summary of geothermal project emission sources for some pollutants is shown in Table 4.

TABLE 4: Summary of geothermal project emission sources and pollutants (Hauck and Phillips, 1997)

Sources	H_2S	$PM_{(10)}$	NO_x	SO_x	CO	other
Construction						
Earth moving activities		●	●			●
Heavy equipment and vehicles		●	●	●	●	
Drill rig		●	●	●	●	
Emergency backup generator		●	●	●	●	
Well drilling and testing	●	●			●	●
Normal plant operation						
Plant vent silencer	●	●				
Cooling tower	●	●				
Drill rigs engines	●	●	●	●	●	●
Well flow testing	●	●				●
Vehicles and mobile equipment		●	●	●	●	●
Plant conditions						
Plant vent silencer	●					●
Emergency backup generator		●	●	●	●	●
Decommissioning						
Earth moving activities		●				●
Demolition activities		●				●
Vehicles and mobile equipment		●	●	●	●	●

3.5.6 Impacts on water

Unless all waste bore water and cooling water is re-injected, geothermal fluid discharge may have an impact on local and regional surface waters such as rivers, lakes and estuaries. The water phase in wet fields sometime contains toxic ingredients such as boron, arsenic, ammonia and mercury, which, if discharged into courses, could contaminate downstream waters used for farming, fisheries or human water supplies.

High concentrations of heavy metals are associated with high-temperature brines such as at Salton Sea in California and on the islands of Milos and Nisyros in Greece. High boron and arsenic concentrations are found in many geothermal systems associated with andesitic volcanism. Examples include Mt. Apo in the Philippines and Ahuachapan in El Salvador. Boron rich waters occur in geothermal waters which have reacted with marine sediments, such as at Ngwaha in New Zealand. Waters of geothermal systems hosted by basaltic rock are low in boron and arsenic and heavy metals but relatively high in both hydrogen sulphide and aluminum. This is exemplified by Krafla, Iceland (Arnórsson, 2004).

The construction and drilling operation phases of geothermal development are not expected to have much adverse effect on water quality. Drilling fluids including drilling mud and many chemicals are used to lubricate the drill bit, stabilize the hole, and remove drill cuttings. When the drill bit hits permeable rocks drilling fluids may be lost into the rock formations. Excessive loss of fluids could result in localized changes in water quality. These changes could be adverse, but the proposed drilling fluids should be composed of non-toxic constituents that would cause minimal water quality degradation.

Also during drilling, liquid wastes that are returned from the drill column include water, non-toxic drilling additives, rock cuttings, and once the geothermal reservoir is intercepted – geothermal fluid. These liquid wastes are directed to the well pad sump and could potentially leak from the sumps, infiltrate the shallow groundwater and degrade the quality of the local ground water. The sumps are constructed and maintained to have a permeability of less than 6 to 10 cm/sec. Each liquid-holding sump has a capacity adequate to hold the expected volumes of fluids to be produced during short-term flow tests and well start-up and work-over operation.

Bentonite is a common drilling mud additive which provides additional clay to the liner of the sumps and further reduces the potential for leakage from the sumps. For these reasons, it is unlikely that substantial leakage occurs from the well pad sumps to the shallow aquifers.

During the operation phase, impacts on the water quality of surface water or ground water in the shallow aquifer are not expected during normal production and injection practices. The injected fluid is released to the geothermal reservoir, which is not connected to the shallow groundwater system. However, impacts could occur during the operation phase due to mixing of the geothermal fluid in the shallow groundwater aquifer waters through damaged well casings or accidental discharge of geothermal fluids to the surface. The local water quality could be affected if the well casing failed. Accidental discharge of geothermal liquids to surface drainage could occur due to blowouts during drilling, leaking pipes or wellheads, and overflow from well sumps of greatest concern is the protection of public drinking water supplies. Spent geothermal liquids in the amounts expected to be discharged, could affect ground water supplies in a disastrous way, because such contamination might well be impossible to correct.

3.5.7 Noise impacts

Noise is a sound which is unwanted or not desired and which may disrupt or degrade human activities. The air pressure variations are measured as the change in sound pressure exerted on the diaphragm of a microphone attached to a sound level meter. During surface exploration for geothermal resources no environmentally significant noise is created.

Noise is one of the most ubiquitous disturbances to the environment from geothermal development, particularly during the construction and operation phases. Many geothermal developments are in remote areas where the natural level of noise is low and any additional noise very noticeable. Residents in such areas will probably regard any noise as an intrusion into their otherwise quiet environment. Animal behaviour is also affected by noise with reports of changes in size, weight, reproductive activity and behaviour. Instant noise is usually measured in decibels, denoted dB(A). The human ear is a remarkably sensitive device, which can detect sound intensities as low as 10^{-12} W/m^2 with the threshold of pain occurring at 10 W/m^2 (Brown, 1995).

Development of a geothermal field creates considerable noise, particularly at the drilling and well-testing stages. Drilling operations, with noise from diesel engines and other heavy equipment, can create localized noise levels of 80 to 90 dB for 24 hours a day.

The noise from the first discharge of wells is intense and can create annoyance at a distance of several kilometres. It may affect birds and animals in the district as well as be of concern to local residents. Unsilenced geothermal wells may create noise levels of up to 120 decibels overall in their near vicinity, and to prevent damage to hearing, workers must wear ear protectors. Using cylindrical type silencers the noise can be brought down to about 85 dB. Thus, even with good designs for noise reduction workers have to be recommended to use ear protectors both during drilling and discharge tests.

Most of the noise from power plant operations results from the three power plant components: the cooling tower, the transformer, and the turbine-generator building. Once the plant has started operation, noise mufflers can be made effective enough to keep the environmental noise below even the 65 dB limit set by the U.S. Geological survey (D'Alessio and Hartly, 1978). TABLETable 5 summarizes noise level during construction and operation of a geothermal plant.

TABLE 5: Drilling and testing noise levels (After Brown, 1995)

Activities	**Noise level (dBa)**
Air drilling	85–120
Mud drilling	80
Discharging wells after drilling	Up to 120
Well testing	70–110
Diesel engines (provide electricity)	45–55
Heavy machinery (earth moving during construction)	Up to 90

3.5.8 Visual impacts

Surface manifestations in geothermal areas are often valued as beauty spots and act as tourist attractions. Development of such areas needs to be balanced against the value of preservation for national heritage and tourism. Withdrawal of reservoir fluid through drillholes leads to a pressure decline in the reservoir and may cause hot springs to dry out. Reservoir depressurization may also enhance boiling at shallow depth and in this way enhance fumarolic activity. It is difficult to predict these changes before production. For that reason nature is often given the benefit of the doubt when deciding whether or not to develop a geothermal area of scenic beauty. Many geothermal power plants including the steam supply system have not been constructed in such a way as to minimize visual pollution although others have been well camouflaged into the surroundings.

Some direct use installations have no visual impact. Geothermal heating plants can be integrated into the urban landscape since all equipment including the pipes of large district heating systems can be concealed underground. Other uses of geothermal energy such as horticulture and fish farming tend to have relatively minor visual impact, depending on the scale of development and the nature of the terrain in which these activities take place (The World Bank Group, 2004).

Two main types of visual effect accompany electrical power generation using geothermal resources, i.e. decline in surface manifestations and the scenery effect of a power house. Decline of geothermal manifestations is particularly relevant in liquid-dominated geothermal systems. The scenery effects of a power house are important if the power plant is located in a tourist area. Such effects can be reduced by an appropriate power plant site selection. A electricity generation plant can have a relatively minor visual impact and certainly no greater than that of conventional fossil fuel burning plants; moreover these plants are located outside urban areas and require little land, taking up only a fraction of that needed to develop other energy sources.

3.5.9 Social and economic effects

The use of geothermal energy for power generation in developing countries and rural electrification results in improved quality of life through better illumination, better air quality, improved access to information and telecommunications as well as being a stimulus to business development. The low marginal cost of the fuel source may mean that the off-peak capacity of geothermal power plants can be used cheaply for regional development projects such as pumping irrigation water.

If geothermal resource ownership and control is vested, at least partly, with local communities or land owners, then there is an opportunity for partnerships between local interests and private power developers to develop geothermal projects with feedbacks of benefits to the local community. This is the common model for all recent geothermal projects in New Zealand where the indigenous Maori resource owners have formed partnerships with power developers for plant financing, construction and operation, leading to increased economic autonomy of the rural communities (The World Bank Group, 2004).

The Olkaria geothermal project has to some extent improved the living standards of the Maasai community. The project can become a good example of a large-scale power project impacting positively on the welfare of the local community. To a large extent the project has opened up this community "to the outside world" by the construction of an infrastructure such as roads and telecommunications, making access to markets and other facilities possible. It was noted that a good number of visitors to the power plant do call at the Maasai Cultural Centre to admire and possibly buy Maasai artifacts and watch traditional dances, and thus bring in revenue (Bw'Obuya, 2002)

A well designed geothermal project includes the following socially related aspects:

- A process that helps to manage change (social and physical environment) to intended and current policies and projects
- Focus on individuals, groups, communities and ecosystems affected by change which employs analysis, research, monitoring and management which incorporates methods of public involvement and consultation.
- An impact assessment procedure used to examine the social and environmental consequences, both beneficial and adverse, of a proposed development project and to ensure that these consequences are taken into account in project design.

An all too frequent failing of projects is the non-execution of environmental and sociological guidelines and recommendations established in the early phases of the project. A policy requiring that guidelines and recommendations be established (Environmental and Sociological Impact Assessment Studies) often, however, a policy requiring implementation of the recommendations often seems to be lacking, and most often the requirement for budgetary provision for implementation of such recommendations are totally ignored. Solutions are required which give priority to the identified development needs of the people. In order to get the support of the communities there must be consultation, information, education and evidence that the lives of the rural poor are to be improved as a result of the geothermal development. The steps in a social assessment process in geothermal projects are described in Table 6.

TABLE 6: Steps in a social assessment process in geothermal projects
(Hunt and Brown, 1996)

Phase	Main efforts
Scoping	Identification of issues, variables to be described/measured, likely areas of impact, study boundaries
Profiling	Overview and analysis of current social context and historical trends
Formulation of alternatives	Examination and comparison of options for change
Projection and estimation of effects	Detailed examination of impacts of one or more options against decision criteria
Monitoring, mitigation and management	Collection of information about actual effects, and the application of this information by the different participants in the process to mitigate negative effects and manage change in general
Evaluation	Systematic, retrospective review of the social change being assessed, including the social assessment process that was employed

Nearly half of the developing countries have rich geothermal resources, which could prove to be an important source of power and revenue (Geothermal Energy Program, 2002). Geothermal projects can reduce the economic pressure of a developing country is fuel imports and can offer local infrastructure development and employment. For example, the Philippines have utilized local geothermal resources to reduce dependence on imported oil, with installed geothermal capacity and power generation second in the world after the United States. In the late 1970s, the Philippine government instituted a comprehensive energy plan, under which hydropower, geothermal energy, coal, and other indigenous resources were developed and substituted for fuel oil, reducing their petroleum dependence from 95% in the early 1970s to 50% by the mid-1980s (International Association for Energy Economics, 1998). Developing countries will likely require increasing amounts of power in the coming years. Through technology transfer programs, some industrialized countries are helping developing countries make use of their local sustainable and reliable geothermal energy resources.

3.6 Risks and limitations in geothermal development

3.6.1 Exploration risk

Reconnaissance surveys of geothermal areas are frequently undertaken by national research institutions as part of national indigenous resource investigations. Prioritization of resources for development at this reconnaissance stage will significantly increase the certainty of success. A survey of geothermal fields in active volcanic regions in the Pacific rim indicate that at the reconnaissance stage the probability that a productive geothermal field exists in the area is 50% if even a single hot spring is present. If the spring is boiling, or fumaroles (steam vents) are present, then the probability increases to 70% (The World Bank Group, 2004).

However the more detailed surface exploration studies leading to the pre-feasibility stage may result in expenditure of up to US$1 M, which is at risk (30% probability of failure) through not identifying a useable heat resource. The expenditure of exploration drilling (frequently 3 wells) is an order of magnitude greater (US$1.5-2 M per well) and this is similarly at risk if the wells do not result in useful production (commonly through low reservoir temperatures or low permeability). Fewer or less costly shallower wells may be applicable for smaller developments. On the other hand deep exploration drilling risk will increase with decreasing reservoir temperature as below about 200°C (The World Bank Group, 2004). The outcome of the drilling of a geothermal well is frecuently defined somewhere in the range from success to failure. Succesful drilling means usually that the energy output of the well is large and that the production charechteristic of the well is suitable for the intended utilization of the geothermal energy. For a well, intended to be used for electricity generation, a success would in general include (Stefánsson, 1992:

- High mass flow from the well
- High enthalpy of the geothermal fluid
- Low concentration of non-condensable gasses
- Low level of scaling from the geothermal fluid
- Low level of corrosion by the geothermal fluid).

Resource prioritization to target the most promising areas and good exploration surveys have proven to deliver high success rates for exploration drilling of high temperature geothermal systems. A 1987 study in Indonesia identified 214 geothermal fields which were prioritized for development on a least cost of development basis. Of the top 20 fields, 11 have been drilled into and exploitable reservoirs confirmed (currently 707.5 MW installed), a single well has been drilled into one and it abandoned due to poor results, feasibility studies have been completed for two and these await exploration drilling, and surface exploration is underway in the remaining 6 fields. The low exploration risk is emphasized in Indonesia as geothermal reservoirs (temperatures > 220°C) have been found in 89% of the prospects where exploration drilling to more than 1000 m depth has been undertaken. East African countries (Djibouti, Ethiopia and Kenya) have a similar success rate or 83% for deep exploration drilling while in New Zealand the exploration success rate is 100%. The Philippines have also had a very high success rate in developing geothermal resources through the Philippines National Oil

Company accepting the risk of geothermal resource development in the belief that they had a good understanding of Philippine geothermal resources.

The higher risks associated with low temperature geothermal resources can be illustrated by the experiences in Thailand. Three main areas have been explored by drilling but wells deeper than 1000 m have only been drilled at San Kampaeng. Here the maximum well output was 11 kg/s of 125°C water, equivalent to about 170 kWe, which is uneconomic to exploit due to the cost of drilling to these depths. In contrast at Fang, 17 kg/s of 120°C water is produced from 150 m deep wells and is used in a 300 kWe binary turbine. This electricity is reported to cost about US 7 cents / kWh and illustrates that if relatively high temperatures with moderate flows can be encountered at relatively shallow depths cost effective power can be generated (The World Bank Group, 2004).

3.6.2 Size of development and reservoir exhaustion

The size, and therefore production capacity of a geothermal reservoir provides another significant risk in geothermal development. A complete understanding of the reservoir can only be obtained by withdrawing fluids from the reservoir over a sustained period, with subsequent computer modelling to assess the performance in the future. It can take several years of production from a field before the reservoir performance can be gauged with confidence since the reservoir rate of decline is often approximately exponential in nature with initial high rates of decline (The World Bank Group, 2004).

Assessment of resource size and production capacity (resource assessment) is a critical part of any geothermal development. At the feasibility stage, resource assessments rely on the extent of the reservoir, as defined by drilling and geophysical anomalies, and knowledge of reservoir fluid temperatures without long term production data. Such assessments can have large errors thus increasing the risk of plant size incompatibility.

Once long term reservoir performance has been established the production capacity will be estimated in terms of MW of energy over a particular time period (frequently taken as 30 years, the approximate life of steam turbines). Such estimates reduce the likelihood of excessive withdrawal of fluids from reservoirs which leads to reservoir pressure decline and reduced well (energy) outputs. Reservoir pressure decline may in turn allow low temperature groundwater to flood the system and cool the reservoir even further. The risk of pressure decline can be mitigated by conservatively sizing the rate of heat extraction (power station size) in comparison to the estimated resource capacity.

In several geothermal fields there are oversized power stations compared to the exploited reservoir size, the most well known being The Geysers in California. The Momotombo field in Nicaragua is another example. It was initially utilized with a 35 MWe power station in 1983 but with the addition of a second 35 MWe plant in 1989 the reservoir was overproduced, resulting in reservoir decline, to the extent that in 1998 the field was only producing 20 MWe (The World Bank Group, 2004).

Once a resource has been developed, regular monitoring of production data (engineering and scientific data) is undertaken accompanied by simulation studies to better predict the future behaviour of the reservoir in order to maximize production and minimize premature reservoir failure.

3.6.3 Economic and political risk

Rural electrification projects suffer less from changes in national policies and economics than private energy developments. For example the 1997 Asian economic downturn put many geothermal developments on hold with subsequent loss of income revenue. The financing for the power station at the Ulumbu rural electrification geothermal project on the island of Flores in Indonesia was diverted to alternative uses in late 1998 due to the Asian economic crisis. The late 1990's global economic weakness has also left many geothermal projects in Central and South America on hold due to lack of funding.

Changes in government policies which might impact on rural geothermal energy developments include (The World Bank Group, 2004):

- Changes in environmental policy
- Changes in land use policy
- Changes in incentives for such energy developments
- Changes in resource consents processes.

3.7 Sustainable geothermal resource exploration

3.7.1 Definition of sustainable development

The term sustainable development has been defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987). In other words, sustainable development, demands that we seek ways of living, working and being that enables all people of the world to lead healthy, fulfilling, and economically secure lives without destroying the environment and without endangering the future welfare of people and the planet.

Activist groups involved in promoting sustainable practices use this description to resolve environmental, economic and social development. Since development applies to everyone at all times, the concepts and practices of sustainability can also apply to all generations of people in every natural and man-made environment. Sustainability provides a framework for economic opportunities in the form of new businesses and jobs, rebuilding communities to incorporate environmentally friendly behaviour, and revitalizing democracy by making better choices for everyone. Five criteria exist for development decisions to be considered sustainable. Decisions must consider:

- *Long-term impacts and consequences*; have to look at the long-term perspective and see what opportunities will exist rather than reacting immediately with a best solution.
- *Interdependence;* have to "promote actions that expand economic opportunity, improve environmental quality and increase social well-being at the same time."
- *Participation and transparency;* The opinions of people that are affected by the decisions should be considered and the process of development should be open for public access and participation.
- *Equity;* sustainable decisions will help every person equally.
- *Proactive prevention;* sustainable development should not only look to the future but also look at what we are doing now. Changes we can make today will prevent environmentally negative consequences (Steer and Wade-Gery, 1993).

Some definitions of sustainability are mainly focused on sustaining economic development. However other authors think that ecological considerations shall be involved in the total developments, not just economic development. Barbier (1987) argues that sustainable development depends upon interaction among three systems, the biological system, the economic system, and the social system. The goals of sustainable development for the three systems are:

- For the biological system, maintenance of genetic diversity, resilience, and biological productivity;
- For the economic system, the satisfaction of the basic needs (reduction of poverty), equity enhancement, increasing useful goods and services;
- For the social system, ensuring cultural diversity, institutional sustainability, social justice, and participation.

While sustainability has become a widely acknowledged concept, in the recent development thinking, there are considerable arguments on how to implement the concept. Pearce and Turner (1990) propose a working definition, which involves maximization of the net benefits of economic development, subject to maintenance of the services and quality of natural resources over time. In this definition the maintenance of services and quality of the stock of resources over time implies, as far as practicable, the adherence to the following rules:

- Utilize renewable resources at a rate less than or equal to the natural rate at which they are regenerated.
- Create minimum environment pollution and damage and keep waste flows to the environment at or below the assimilating capacity of environment.
- Optimize the efficiency with which non-renewable resources are used, subject to sustainability between resources and technical progress.

3.7.2 Project planning process and environmental sustainability

Essentially, sustainable development is a model of development which aims to pursue, in a mutually compatible way, economic growth, social inclusion and improvement and environmental protection and enhancement, for both current and future generations.

The pursuit of sustainable development is much more than merely minimizing the environmental impact of economic development. It involves a move away from compartmentalized decision-making to a broader perspective of those economic, social and environmental elements which together comprise quality of life for all citizens. It calls upon a new approach to development planning whereby the full costs and benefits of these three elements are taken into account and fully integrated into the planning process from the start. For better understanding of the planning process, planning environment is described in a systems perspective with four major systems including (Brundtland, 1987):

- The ecological system (the natural resources and environmental quality);
- The economic system (the production and consumption of services, investment and technological development);
- The socio-cultural system (norms and values);
- The government;
-
- These systems are interrelated, and many economic activities result from interactions between them.

Planning in a system perspective at the regional level, a policy maker is trying to decide how best to allocate resources or lead the renewable resources development process to the desired direction through a planning system, in the face of uncertainty about the impact of the allocation process on the surrounding environment.

In the process of producing energy from geothermal resources, in most cases extensive use of resources or emission of the pollutants to the surrounding environment has led to negative impact on the environment. To avoid that, information about the adverse effect on the health and economy of people and physio-chemical and biological environment should be incorporated in the related decision making processes for project development. Unfortunately the problem of adverse effect is often not incorporated in the development decision process and this leads to imbalances between the economic and environmental systems. To protect environmental and public health as well as to stimulate sounder environmental behaviour, balancing the economic, environmental and soci-cultural systems in particular when considering development possibilities for future generations, relates to the concept of "sustainable development" (Brundtland, 1987). To tackle the imbalances, responsible agencies for environmental management and protection can intervene in the economic system (e.g., through regulations or levies), the ecological system (e.g., through rehabilitation of ground water) or address the economic system in more direct ways via the socio-cultural system (by stimulating more environmental consciousness in the economic decision making process). These interventions may take place at different spatial scales e.g., local, regional, national, and international. The United Nations Conference on Environment and Development (UNCED, 1992) and the resulting Agenda 21 have bestowed worldwide respectability on the concept of sustainable development. Given the development in management and planning, sustainability concepts, the growing number of disciplinary qualitative and quantitative models, and the advances in information technology, which have led to large amounts of data sets, the main question is how to integrate and make use of all these opportunities. How to achieve sustainable ways of making use of resources and how to implement adaptive co-management concept? According to Hallding (2001) sustainable solutions can build on:

- Through understanding of the sources of conflicts, including their natural, technical, institutional, social and cultural aspects.
- Participation of all related stakeholders in the process vital, first they arrive at a common understanding of the problem and to share as far as possible a vision of the future and ideas about the path to sustainable solutions.
- Examining the social, environmental and economic constituents of the conflict, in order to assess different policy options to make the best use of resources. This may include regulations, financial sanctions and economic incentives and to increase public awareness and participation, information dissemination and support for possible institutional change.
- Finally an organization to pursue the co-operation, a means of monitoring achievement, and implementation plans.

Implementation of these activities requires proper decisions and analytical tools to help stakeholders to gain a greater understanding of the way planning decisions affect our environment over time. Tools to help identifying the most relevant issues for a given region are a trade-off between achieving energy production from geothermal resources and its environmental costs (pollution cost). A tool that can assist in the appraisal of an alternative plan of action, to identify its effects in terms of magnitude, location in space and time, the losses and gains, and the efficiency of the resources deployed. The sustainable program in geothermal resource development increases commitment to actions which are necessary to meet environmental goals, and ultimately, improve the likelihood of success for sustainable development programs.

3.7.3 Sustainable geothermal resource development

For many years humans have used natural resources to develop a better, if not an easier way of life. During last century we realized that these resources could not be reproduced for our never-ending needs. To manage this problem we turned to renewable resources and technologies. We have developed ways to harness the power of the sun, which we hope will be around for a long time. We can also use the wind and geothermal resources for power generation and the latter for industrial purposes. Besides adapting our energy sources to clean and safe consumption we have also begun to change the way we live. Today we know that it is important "*to meet the needs of the present without compromising the ability of future generations to meet their own needs*". Developing sustainable communities accomplishes this goal.

Geothermal energy is usually classified as *renewable* and *sustainable*. Renewable describes a property of the energy source, whereas sustainable describes how the resource is developed and utilized. The most critical aspect for the classification of geothermal energy as a renewable energy source is the rate of energy recharge. In the utilization of natural geothermal systems, the recharge of energy takes place by advection of thermal water on the same time scale as production from the resource. This justifies our classification of geothermal energy as a renewable energy resource. In the case of Hot Dry Rock (HDR) systems, and some of the hot water aquifers in sedimentary basins, energy recharge is only by thermal conduction; Due to the slowness of the latter process, however, HDR systems and some sedimentary reservoirs should be considered as finite energy resources (Stefánsson, 2000).

The sustainability of a geothermal resource is implied in two main concepts; sustainable construction and development and sustainable utilization or resources extraction;

- The sustainability of development involves carrying out a geothermal project with minimum environmental impacts and maximizing the social benefits during exploration construction and utilization phase of the project.
- Sustainable production of geothermal energy from an individual geothermal system can be defined as: "For each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, E_0, below which it will be possible to maintain constant energy production from the system for a very long time (100- 300 years). If the production rate is greater than E_0 it cannot be maintained for this length of time. Geothermal energy production below, or equal to E_0, is termed sustainable production, while production greater than E_0 is termed excessive production" (Axelsson et al., 2001).

This work is going to describe methods to develop and conduct a geothermal project with minimum environmental impacts and maximum social benefit. Sustainable development of geothermal projects is the way to carry out project activities by targeting the right numbers of wells in the optimum locations in the reservoir for maximizing geothermal fluid extraction with minimum environmental changes. Sustainability takes into account all exploration and construction phases of geothermal project development. During exploration and construction phases sustainability involves implementing the investigations and constructions causing minimum environmental effects and in the utilization to manage the activities with minimum effect on the surrounding environment and adequate extraction of geothermal fluid from the reservoir.

In this context, sustainable development does not imply that any given energy resource needs to be used in a totally sustainable fashion, but merely that a replacement for the resource can be found that will allow future generations to provide for themselves despite the fact that the particular resource has been depleted. Thus, it may not be necessary for a specific geothermal field to be exploited in sustainable fashion. Perhaps we should direct our geothermal sustainability studies towards reaching and then sustaining a certain overall level of geothermal production at a national or regional level, both for electrical power generation and direct heat applications, for a certain period, say 300 years, by bringing new geothermal systems on line as others are depleted (Wright, 1999).

4.0 DESCRIPTION OF THE PROPOSED PROJECT AND STUDY AREA

4.1 Proposed project for development

The Námafjall high-temperature geothermal area has been utilized for steam production since the early 1970s. At Námafjall the steam has been utilized for operating a 3 MW back-pressure turbine unit, drying of diatomaceous earth and heating of fresh water for space heating. A total of 12 wells have been drilled at Námafjall but only three are used for production. In 1986 the National Power Company of Iceland purchased and took over the management of the Námafjall geothermal field and in the 1990s the company initialled plan to build a larger power plant. Before a decision is taken on the first phase, information from exploration drilling is required to confirm that the fields are suitable for development, where the production wells should be drilled, at least for the first development phase and to determine the physical and chemical properties of the geothermal fluid. According to the implementation schedule for the first phase, approval for drilling is needed for exploration wells drilled over a two year period, and one further year is required after the decision on development is taken to acquire approval for the power plant construction. It is also assumed that plant is started up 30 months after the final decision is made (Landsvirkjun, 2003).

The plan for developing a larger power plant has involved employing four companies in different fields to carry out the project phases. These are:

ICELANDIC GEOSURVEY (ISOR) has been contracted to carry out all the geoscientitic work such as geological, geochemical, geophysical and reservoir engineering studies. The studies started in 1992 and most of the work has been carried out. The temperature of the reservoir has been determined using geochemical techniques and a reservoir conceptual model has been put forward on the basis of geophysical logging and reservoir engineering studies. Detailed information about these investigations is presented in the next section.

HÖNNUN has been in charge of the environmental studies leading to the Environmental Impact Assessment (EIA). The environmental studies were carried out for finding out the key impacts of each phase of development on the surrounding environment including exploration, drilling and operation phases. The main EIA for the proposed project included effects on geology and soil, hydrological effects (ground water and surface waters), biological effects (flora and fauna), socio-economical effects (Tourism, land uses, job and traffic) and noise. The EIA process is finished and the project for a 90 MWe plant approved by the Ministry of Environment.

VGK is the third company that has been contracted and is responsible for the mechanical engineering part. The main tasks of VGK are design and implementation of well sites, steel fabrication for well testing, power plant and other mechanical engineering equipment.

KEMIA, the fourth company carries out yearly sampling from wells and other geothermal manifestations for monitoring chemical composition of fluids in the area.

In the light of successful long-term production and recent updates in surface field evaluation, a new power plant is scheduled south of the current production zone. The total production capacity will be 80-90 MWe, developed in two 40 MWe or three 30 MWe phases with conventional condenser-type turbines with cooling towers.

4.1.1 Main elements of proposed power project

Simplified process diagram for the power plant

For the last decade, all new geothermal power generation projects have been planned in relatively small (20-40 MWe) phases, rather than harvesting the geothermal field in one large phase as previous plans assumed. By building up the steam supply system and the power plant in relatively small phases, it is possible to start the power production early and then build further phases with added confidence as knowledge and experience of the geothermal system builds up. The previous methodology, however, required extensive research before a decision on a power project could be made and the risk of failure was high.

The condenser-type generation process is most commonly applied to geothermal power projects, extracting energy from hot (300 ºC) hydrothermal system. This generation method was used for the present Krafla power plant and is the most likely option for the planned projects in Krafla, Bjarnarflag, Gjástykki and Theistareykir. Figure 3 is a diagram of a conventional condenser-type power production process for a final phase of 90 MWe (Landsvirkjun, 2003).

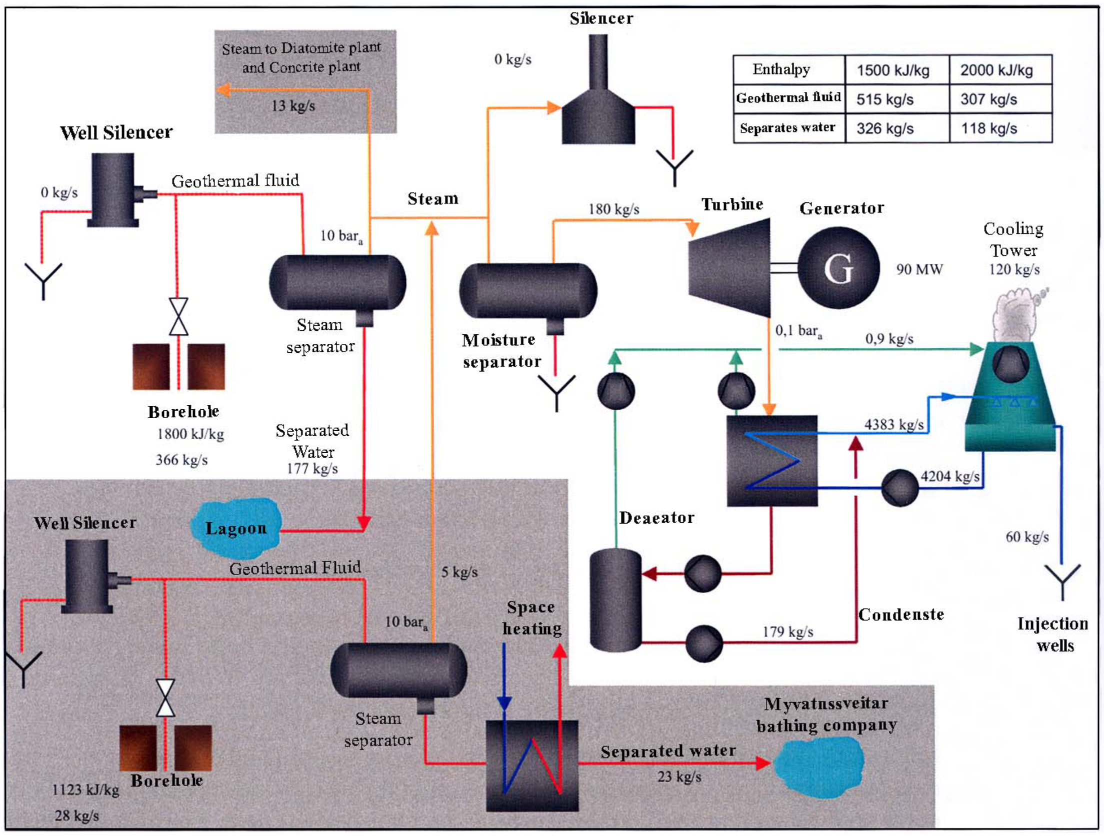

FIGURE 3: Production flow diagram for proposed 90 MWe Bjarnarflag power plant (Landsvirkjun, 2003)

Wells
Wells are drilled through the geothermal reservoir and produce geothermal fluids at the surface. The wells are generally 2000 m deep, the top 800-1000 m are cased and cemented but the production zone is completed with a slotted liner to allow flow. The wells are either drilled vertically or directionally. Directional wells increase the chance of intersecting highly productive fractures and fewer well pads are needed for directional drilling which is an environmental and economical advantage. Surface structures associated with the wells include the drill site template, wellhead equipment, wellhead shed and blow-out silencers.

Steam supply system
The steam supply system gathers the two-phase geothermal fluid and transports it in insulated pipes to the separation station where the steam phase is separated from the brine phase. In some cases, as in the Krafla power plant, the brine phase is re-flashed at a lower pressure where secondary steam is separated from the remaining brine. The steam (both high-pressure and low-pressure) is carried to the power house, whereas the brine phase is directed to the disposal system.

Disposal system
A disposal system accepts and disposes of both the brine from the separation station and the condensed water from the cooling towers. In Iceland, surface disposal is the most common option as the water quickly disappears into surface fractures and is diluted in the groundwater system. An experiment in which part of the brine is re-injected into the reservoir has recently started in the Krafla power plant but deep re-injection carries high uncertainty associated with reservoir cooling, pressure decline and geochemical effects such as possible scaling. Shallow re-injection into delineated disposal zones (300-500 m deep) is the third alternative that can be applied if the other two options fail.

Turbine and auxiliary systems
The turbine generating system comprises turbine, generator, intake valves, condenser, cooling system, and operating instruments. The effluent steam from the turbine is condensed in a condenser located immediately next to the turbine or below it, to improve the turbine efficiency. Normally the cooling medium is condensed water that has been cooled in cooling towers but in special cases, such as in the Nesjavellir power plant, surface water can be used. The cooling towers are normally the most prominent features of the power plant. Among other auxiliary systems is the gas removal system (ejectors or pumps) that removes non-condensable gasses from the condenser.

Electrical equipment
The electrical equipment includes control and protection systems, a power transformer and both high and low voltage systems. The substation and the transmission lines from the substation are not considered a part of the power plant.

Structures
In Iceland all the key elements of geothermal power plants are housed, from the small wellhead sheds to the powerhouse itself. Normally the powerhouses are steel buildings whereas service compartments are concrete structures.

4.2 Study area

The Námafjall high temperature geothermal field is located in North Iceland and has been located at the location in Lambert Conformal Conic projection system Datum: ISN93 between 594100 and 578000 N and 601700 and 568300 W. The field is located near to the well known Lake Mývatn tourist area. The Námafjall high-temperature geothermal area is in a very active volcanic area. South of Krafla, this volcanic activity diminishes over a distance of a few km, but continues again with active volcanic fissures in the area of Bjarnarflag and in the western part of Námafjall.

The Námafjall geothermal area lies within the fissure swarm of the Krafla volcanic system, 4 km south of the Krafla caldera. Surface manifestations extend over a 4 km^2 area, characterized by continuous light-coloured geothermal alteration, as well as vents and steaming ground. The Námafjall geothermal field is characterized by steaming ground with numerous pools and fumaroles precipitating native sulphur around them in unusual quantity. The surface extension of the field is somewhat obscured by recent lava fields filled with ground water, but as judged from surface alteration, steaming ground etc., it is at least some 4-5 km^2 in size (Landsvirkjun, 2003). A number of faults extend through the Námafjall area, often just 200-300 m between them. This distance becomes even shorter within the most active part of the fissure swarm, which lies through Bjarnarflag. There, one can see a clear relationship between geothermal vents and fault lines. Though this relationship does also exist on Mt. Námafjall, it is more varied and the same applies to HveraröND east of Námafjall.

East of Námafjall are the clay pits and the old steam drill holes in the Hveraröndarea. A popular walking track extends from Hveraröndup to the top of Námafjall by the magnificent sulphur deposits of Námakolla. Figure 4 is a general map of the area in which the study area has been defined.

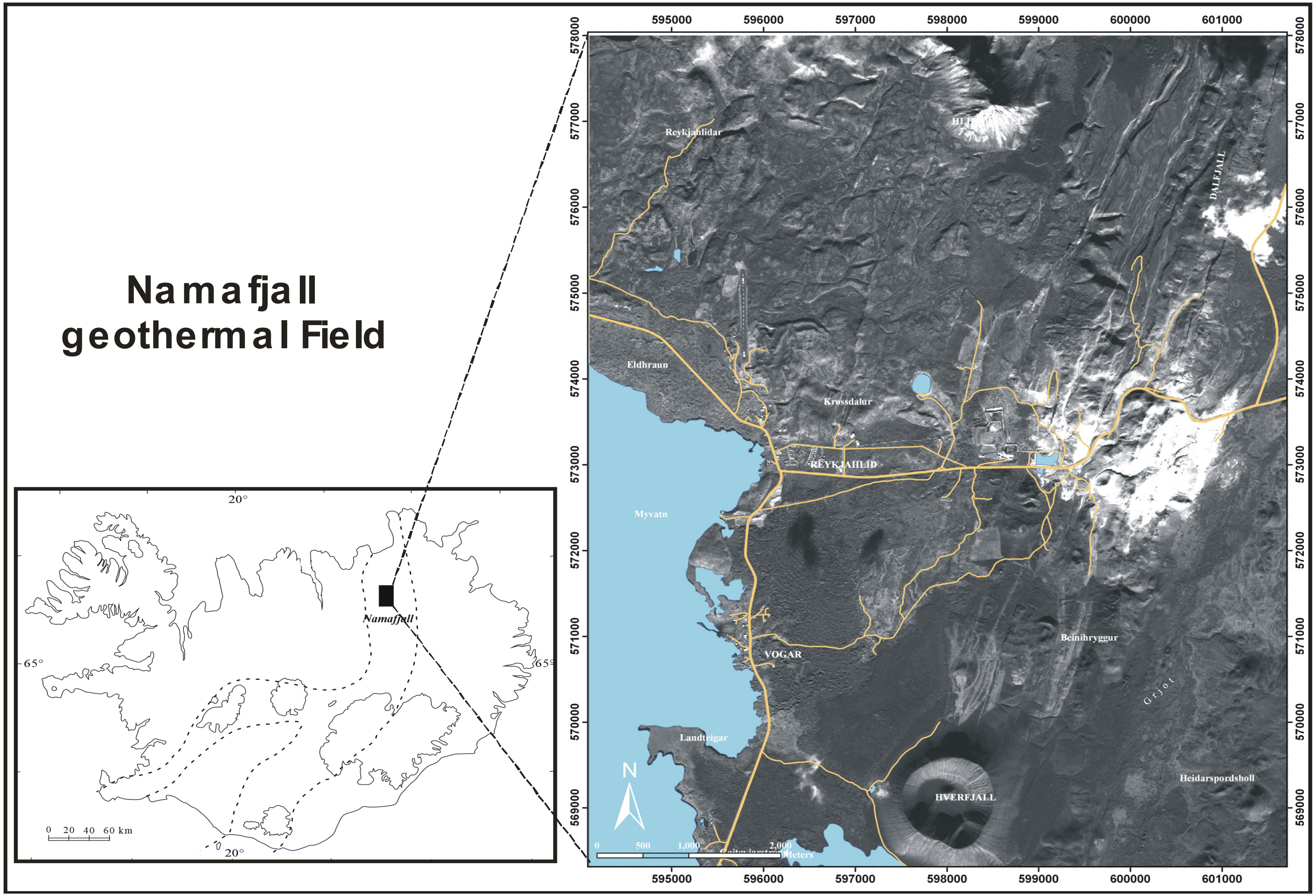

FIGURE 4: General map of the study area in Námafjall

4.2.1 Geology

The Krafla central volcano, within which the Krafla geothermal area is located, lies astride one of five en echelon arranged NNE-trending fissure swarms within the zone of active volcanism and tectonism in N-Iceland. The fissure swarm that intersects the Krafla caldera, which was formed about 100 thousand years ago, is 5–8 km wide and about 100 km long. Two other fracture systems have been identified in the Krafla area. Near Hvíthólar, curved caldera rim fractures are exposed and NW–SE trending fissures are found in the Sudurhlídar wellfield that have been related to intrusive activity into the roots of the central volcano (Gudmundsson and Arnórsson, 2002).

Námafjall area is close to Krafla volcano and postglacial volcanism in the area has been divided into two main periods. The first period was in early postglacial times and ended about 8000 years ago. The second period started about 3000 years ago and is still ongoing (Saemundsson, 1984). Postglacial eruption products from the two main eruption periods can be found on the Námafjall ridge and in its vicinity. The Námafjall ridge is a part of a larger hyaloclastite ridge called the Námafjall–Dalfjall–Leirhnúkur ridge, formed during the last glacial period through subglacial fissure eruptions. The ridge is about 15 km long and 1 km wide, rising approximately 150 m above its surroundings, trending NNE, i.e. in about the same direction as the presently active fissure swarm (Gudmundsson et al., 1971). The Námafjall ridge itself is about 2.5 km long and 0.5 km wide (Gudmundsson, and et al., 1965). Postglacial basaltic flows cover the low ground on either side of the ridge, derived from volcanic fissures within, or in the vicinity of, the area (Landsvirkjun, 2003).

At Námafjall the drilled area has been divided into an upper and a lower stratigraphic succession (Gudmundsson, 1993a). Subsurface geology and hydrothermal alteration studies have shown that the upper succession, which extends from the surface to about 1100 m, is largely composed of hyaloclastites (70%) but intercalated with lava flows. In the lower succession lavas from shield volcanoes, with inter-beds of hyaloclastites, are dominant. The abundance of intrusives increases with depth, being about half of the succession by volume below 1700 m. The oldest rocks penetrated by the deepest wells are considered to be less than 0.5 million years old, i.e. from the Brunhes magnetic epoch (Gudmundsson, 1993a). The basaltic hyaloclastites and lavas range in composition from olivine- to quartz-normative.

Hydrothermal alteration at depth has been studied by Kristmannsdóttir (1978), Ármannsson et al. (1987) and Gudmundsson (1993b). Some of the hydrothermal minerals at Námafjall, such as quartz, calcite and pyrite, are distributed over a large temperature interval. Others display a depth zonal variation which is the consequence of their temperature stability. The degree of alteration is very variable. Hyaloclastites are more susceptible to alteration than basalt and some of them have been almost completely transformed mineralogically. On the other hand, many of the smaller intrusives are quite fresh (Gudmundsson and Arnórsson 2002). Map 1 (Appendix I) is a geological map of the Námafjall area.

4.2.2 Hydrology

Ground water
Different basaltic lava flows are exposed in the area and as indicated on the geological map in Map 4.1 they are all of postglacial age. The lava flows are bounded in the north by glacial moraines and in the east by older lava flows and by the Pleistocene hyaloclastites of the Námafjall ridge (Thórarinsson, 1979).

The postglacial lava flows act as very good aquifers; because of the numerous open fissures and large active faults with a NNE/SSW strike like Grjótagjá and Stóragjá. The faults are related to a large north-south fissure swarm, that the lavas are derived from North-south fissures dominate near the Námafjall ridge but they are transformed to a western to southeastern direction into lake Mývatn. Only the young Laxá-lavas have flowed in the northwestern direction. From this it can be concluded that fissures which have developed in the lava flows during cooling have preferential E-W to SW-NE directions. The lava layers can also be expected to have a general dip toward the southwest (De Zeeuw and Gislason, 1988). The postglacial lava flows consist of lava and scoria layers. From the profiles of the boreholes that have been drilled in the area it can be concluded that the uppermost layer consists mainly of lava to a depth of 20 to 25 m. This layer is underlain by a sequence of scoria layers interbedded with lavas. The fissured lavas to a depth of 25 m can be expected to act as very good aquifers. Ground water will flow preferentially from north to south through the north-south faults and from east to west according to the directions of the lava flows. The scoria layers probably act as more a homogeneous aquifer (De Zeeuw and Gislason, 1988)

At Bjarnarflag flashed geothermal water enters the shallow groundwater system through active open faults and fissures. The aquifers of that system consist of lavas and scoria layers. From Bjarnarflag the groundwater flows in a southwesterly direction and reaches Lake Mývatn in three main tongues. There seems to be a relation between the direction of the lava flows and the direction of groundwater flow. This is probably caused by the fact that fissures, which developed during the cooling of the lava, are mostly parallel to the direction of the lava flow. It might also be caused by the general dip of the lava and scoria layers toward the southwest. The large N-S faults like Stóragjá and Grjótagjá do not form a barrier to groundwater flow (De Zeeuw and Gislason, 1988). As mentioned already groundwater from the area has been discharged into lake Mývatn through different flow pattern from north to south. Figure 5 shows the basic trends of the flow pattern in Námafjall (Ármannsson, 2005).

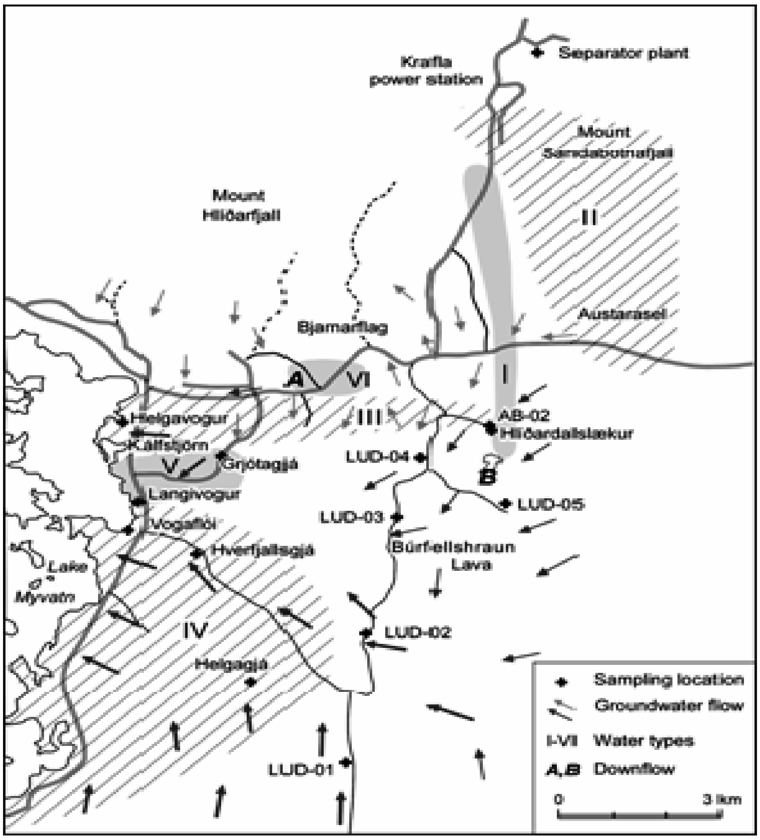

FIGURE 5: Suggested flow pattern for the groundwater flow in Námafjall area (Ármannsson, 2005).

Temperature in fissures seems to vary seasonally. Temperature variation is about 1°C in Grjótagjá and 0.5 °C in Stóragjá with the lowest values in late winter and early spring and the highest ones in late summer, probably reflecting the effect of melt-water. For a detailed interpretation of seasonal variations in the chemical composition of groundwater, data are somewhat limited but both seasonal changes and possibly long-term (temporal) changes are evident.

Measurements of the flow velocity in Grjótagjá fissure suggest that the surface flow in the top layer of the groundwater in the fissures is very fast, up to 3.5 m/s, but at a depth of 2-4 m the flow becomes disturbed and obvious mixing occurs (Thoroddsson and Sigbjarnarson, 1983). The groundwater chemistry studies by De Zeeuw and Gislason (1988) show that mixing of hot and cold groundwater is only important near the hot and cold water boundary zones. The amount of infiltrated rain water and snow is small compared to the amount of hot groundwater flow.

Surface water

The surface water of the area consists of cold and hot springs and surface runoff and Lake Bjarnarflagslón. The study area is located in highly permeable bedrocks, such as recently formed lava fields that present a special case where surface runoff is negligible. There is hardly any surface water in the area because it is covered by young and porous lava fields and transacted by numerous faults. Almost no creeks and rivers exist and nearly all the precipitation within the area seeps underground. The water is only exposed in depressions where the land surface intersects the groundwater table or where aquifers are interrupted by tectonic faults and fissures (Kristmannsdóttir and Ármannsson, 2004).

Part of Lake Mývatn is located in the study area. Lake Mývatn is a well known fresh water lake that was protected by law in 1974, and in 1978 designated to the Ramsar list of wetlands of international importance. Lake Mývatn covers about 37 km^2. Numerous bays and creeks line its coastline and in the lake there are some fifty islands and islets. The lake is not very deep, its average depth being 2.5 metres, and the maximum depth is 4 metres. Moreover there area several small lakes and pools in area those are important for social and environmental reason.

4.2.3 Geochemistry

Geochemical surveys are a useful means of determining whether the geothermal system is water or vapour-dominated, of estimating the minimum temperature expected at depth, of estimating the homogeneity of the water supply, of inferring the chemical characteristics of the deep fluid and of determining the source of recharge water (Combs and Muffler, 1973).

The geochemical survey consists of sampling and chemical and/or isotope analysis of the water and gas from geothermal manifestations (hot springs, fumaroles, etc.) in the study area. As the geochemical survey provides useful data for planning its cost is relatively low compared to other more sophisticated methods, such as geophysical surveys. Therefore the geochemical techniques should be utilized as much as possible before proceeding with other more expensive methodologies.

Various geochemical studies have been carried out during exploration for a new development phase of the Námafjall high temperature geothermal area. In order to evaluate reservoir temperatures and their distribution geochemical studies including sampling of fumaroles and mud pools have been carried out and using several geothermo-meters such as CO_2, H_2S, H_2 and CO_2/H_2 average temperatures have been calculated and used for modelling reservoir temperature from 1952 – 1993 by the geothermal division of the Icelandic National Energy Authority (Ármannsson, 1993). Table 7 shows the details of the samples and calculated temperatures. Figure 6 shows the distribution of average results for different geothermometers plotted as geothermal reservoir temperature distribution.

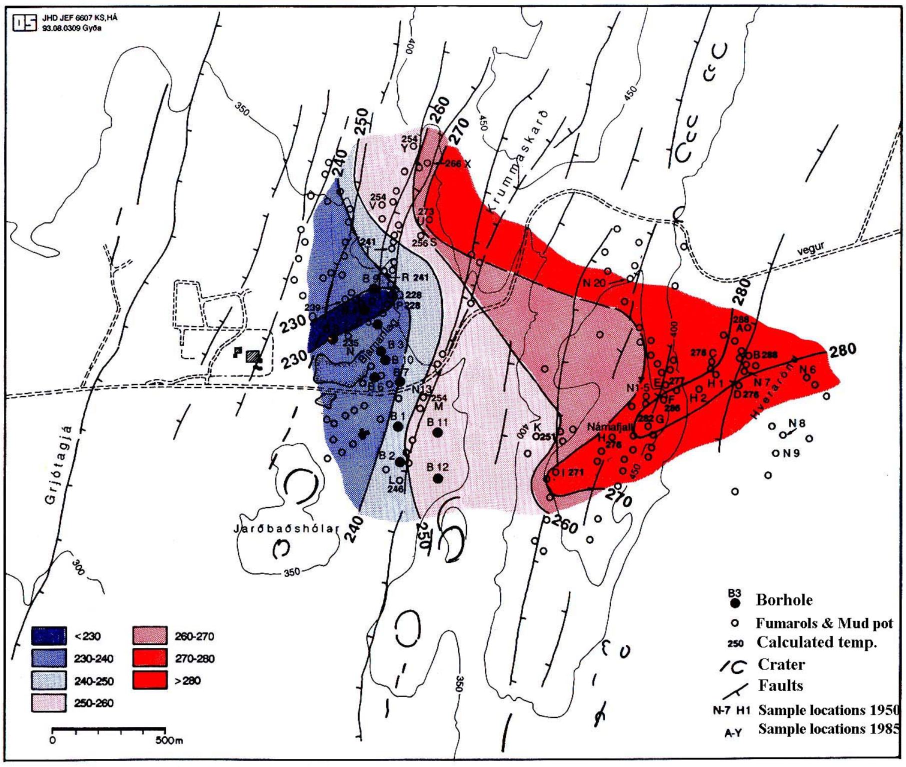

FIGURE 6: Distribution of calculated temperatures from geochemical studies in Námafjall geothermal area (Ármannsson, 1993)

TABLE 7: Calculated temperatures by different geothermometers in Námafjall area, the geothermometers are from Arnórsson, and Gunnlaugsson (1985) (Ármannsson, 1993)

Samples	Geothermometers (ºC)				Average temp. (ºC)
	CO_2	H_2S	H_2	CO_2/H_2	
A	276	284	290	301	288±24
B	291	293	288	282	288±5
C	279	295	268	260	276±15
D	282	289	270	261	176±12
E	256	274	279	300	277±18
F	267	290	285	301	286±14
G	264	280	284	301	282±15
H	255	270	278	299	276±18
I	267	269	271	278	271±5
J	245	100	224	213	196±65
K	246	263	245	249	251±8
L	249	256	241	240	246±8
M	242	266	249	259	254±11
N	241	231	234	234	235±4
O	251	232	239	235	239±8
P	248	215	230	221	228±14
Q	247	181	241	241	228±31
R	249	221	246	248	241±13
S	247	242	260	275	256±15
T	230	244	241	254	241±10
U	260	269	274	289	273±12
V	252	252	253	258	254±3
X	250	258	269	288	266±16
Y	254	253	253	257	254±2

4.2.4 Geophysical studies

Geophysical surveys are directed at obtaining indirectly, from the surface or from depth intervals close to the surface, the physical parameters of deep geological formations. These physical parameters include temperature (thermal survey), electrical conductivity (electrical and electromagnetic methods), propagation velocity of elastic waves (seismic survey), density (gravity survey) and magnetic susceptibility (magnetic survey). These methodologies are, therefore, suited to defining details during the final stages of exploration, before exploratory wells are sited. Information on the existence of geothermal fluids in the geological structures can be obtained with electrical and electromagnetic prospecting methods, which are more sensitive than the others to the presence of these fluids and to variations in temperature; these two techniques have been applied widely with satisfactory results. The thermal techniques (temperature measurements, determination of geothermal gradient and terrestrial heat flow) can often provide a good approximation of the temperature at the top of the reservoir (Dickson and Fanelli, 2004).

Resistivity methods have been used in geothermal surveying for decades in Iceland. From the mid sixties, DC-methods, mostly Schlumberger soundings, were used to identify and delineate high-temperature systems. In the mid eighties the DC methods were succeeded by central-loop TEM-soundings (Transient Electro-Magnetic). The TEM-soundings have proven to be more downward focused and have better resolution at depth than the DC-methods.

All high-temperature systems, within the basaltic crust in Iceland, have a similar resistivity structure. The fields have a distinctive low resistivity zone at their outer margins which is underlain by higher resistivity towards the interior of the reservoir. This resistivity structure was found to contradict the conceptual model that the resistivity should generally decrease with increasing temperature

Comparison of this resistivity structure with data from wells in Icelandic geothermal fields show a good correlation with alteration mineralogy. The low resistivity in the low-resistivity cap is dominated by conductive minerals in the smectite-zeolite zone in the temperature range 100-220ºC. At temperatures 220-240ºC zeolites disappear and smectite is gradually replaced by the resistant chlorite. At temperatures exceeding 250ºC chlorite and epidote are the dominant minerals and the resistivity is probably dominated by the pore fluid conduction in the high-resistivity core. The important consequence of this is that the observed resistivity structure can be interpreted in terms of temperature distribution. A similar resistivity structure is to be expected in acidic rocks. Due to different alteration mineralogy, however, the transition from the conductive cap to the more resistive core presumably occurs at temperatures lower than 200°C (Árnason et al., 2000).

A TEM-survey was carried out in the Námafjall high-temperature geothermal field in 2002 by the National Energy Authority of Iceland. The resistivity structure of a high temperature field reflects the thermal alteration of the rock. It is defined by a low-resistivity cap underlain by a high-resistivity core (Karlsdóttir, 2002).

The surface: Fresh unaltered and dry rocks show high-resistivity as often seen on the surface of a high-temperature field covered by recent lavas.

The low-resistivity cap: In the temperature range 100–230 ºC in the high-temperature field the dominating minerals are zeolites and smectite. Smectite is a layered clay-silicate with abundant free ions to carry electric current easily. That causes the low resistivity in the low-resistivity cap.

The high-resistivity core: Deeper in the high temperature field where the temperature exceeds 230–240 ºC the smectite is converted into chlorite with a fixed lattice, causing and increase in the resistivity. This means that, provided that the resistivity structure is in equilibrium at the temperature in the field, the high-resistivity core indicates the part of the field with temperatures exceeding 240 ºC.

The results of the TEM measurements in the Námafjall area are presented in Figure 7, which shows a resistivity map at 600 m b.s.l. (Karlsdóttir, 2002):

- Námafjall is a separate high-temperature field with a connection to the high-temperature field in Krafla.
- The most active part of the high-temperature field lies under, and just south of Namaskard, where the high-resistivity core almost reaches the surface, indicating the upflow zone in that area. The resistivity values in the low-resistivity cap are lowest in this area, lying in the range 4-6 Ωm whereas the resistivity value in the low-resistivity cap on the outskirts of the temperature field are 6-10 Ωm.
- The resistivity map at 1000 m depth (600 m b.s.l.) shows the low-resistivity cap surrounding the high-resistivity core in an area close to km^2. This horizontal section through the geothermal field is used as an indication of its size.
- The resistivity soundings in the connecting zone between the two geothermal fields of Námafjall and Krafla show characteristics that could indicate inflow of cold fluid or cooling of that area.

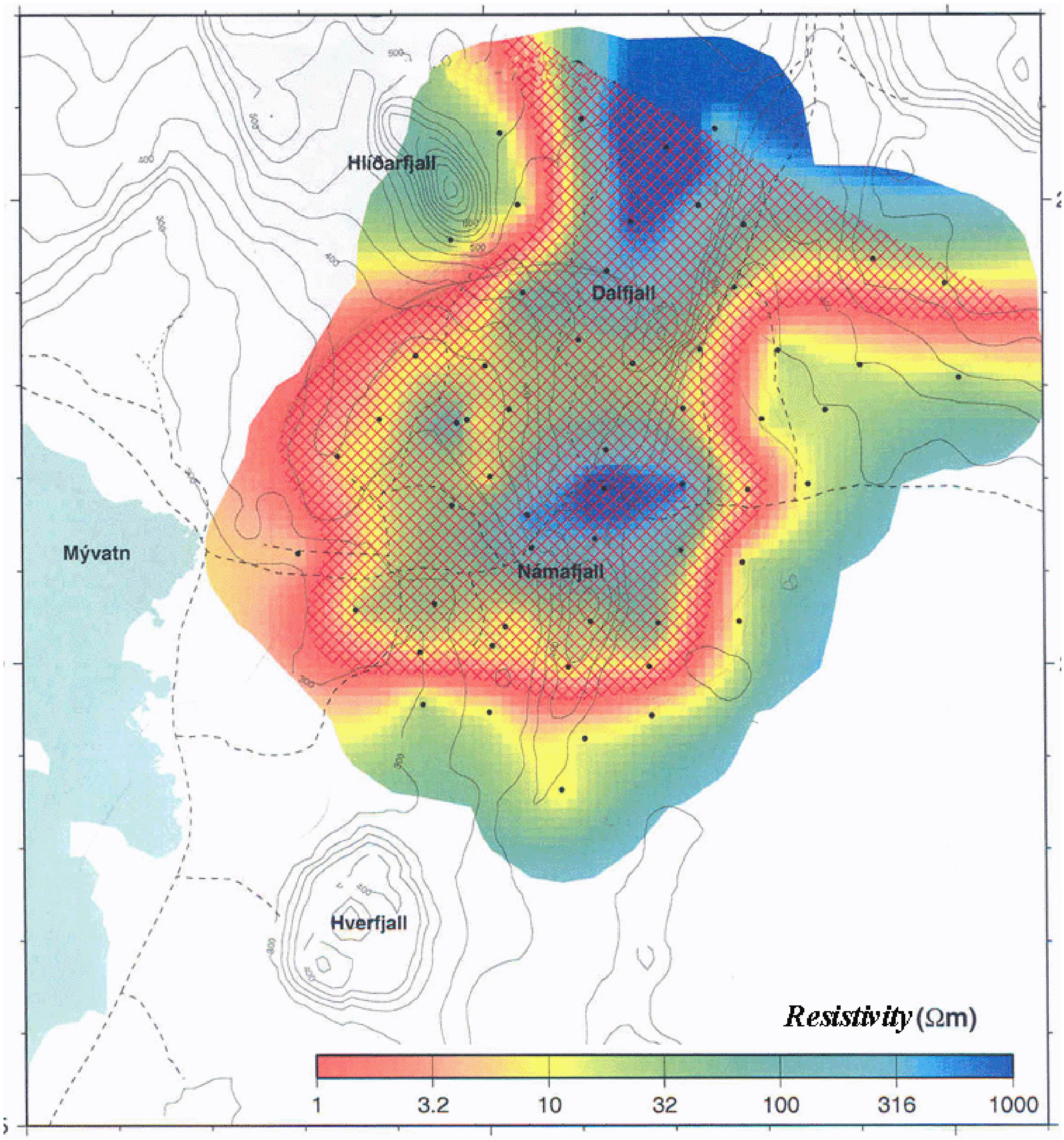

FIGURE 7: TEM-resistivity map of Námafjall area in 600 m b.s.l.
(Karlsdóttir, 2002)

5.0 GEOTHERMAL WELL SITE SELECTION

The final aim of all exploratory work in geothermal exploration is to select promising sites for exploratory drilling. From the combined evidence provided by all the different steps in the exploration works the promising well sites for exploratory drilling are selected. The purpose of this work is to provide a method by using the GIS-based decision support system to combine all exploration and environmental data and information to select optimum geothermal well sites for exploration drilling in order to reach to the deep geothermal resources. In order to develop a decision support model for sustainable development of geothermal resources, the exploration work including geological, geochemical and geophysical investigations have to be carried out. Lastly to account for the environmental considerations in site selection process the environmental impacts of exploration, construction and operation of geothermal resources have to be understood and modelled.

The decision support model should maximize the productivity of the field and the lifetime of the reservoir and predict environmental changes during exploration, construction and utilization phases, such as air pollution, ground water and surface water pollution, subsidence, noise pollution, biological changes, and socio-economic effects and prevent the degradation of any other natural resources.

Deciding which area is suitable for well targeting can often be a daunting task for exploration project managers and decision makers. However, the decision process can be made less cumbersome if it is broken down into general steps:

- Assessment and characterization of geothermal potential in the study area
- Assessment and characterization of the study area from the environmental point of view
- Development of site selection criteria,
- Prioritization of potential sites.

GIS-based decision support system is a new technology and method now being used by planners, resource managers, and permit applicants in the site selection and ranking process to make optimal choices for locating, conducting, and sustaining restoration project sites.

The diagram of the Decision Support System (Figure 8) is used for implementing decision making for geothermal well site selection in this work. For finding the optimum area for well sites, the first decision-making process is used on all exploration survey results to find out the suitability. Secondly the study area is classified based on environmental suitability. Finally by combining exploration suitability and environmental suitability with special assigned weighting for each layer the promising area for exploration drilling is selected.

5.1 Exploration decision-making

5.1.1 Overview

Evaluations of geothermal prospects are based mainly on the results of geological, geophysical and geochemical surveys and investigations in the early stages of exploration. The geo-scientific data available are examined to infer the nature, characteristics and the probable size of the geothermal resource and construct a conceptual model of the field. The exploration model usually represents the probable origin and source temperature of fluids used in deciding whether to conduct exploration drilling and/or additional geo-scientific investigations.

The final stage for successful development is the delineation phase, during which production wells are targeted to define the boundaries of the reservoir and to provide information on possible areas for injection. Knowledge of the subsurface conditions is gained as development begins then it is also possible to refine the initial conceptual model of the system and improve the quality of the resource assessment.

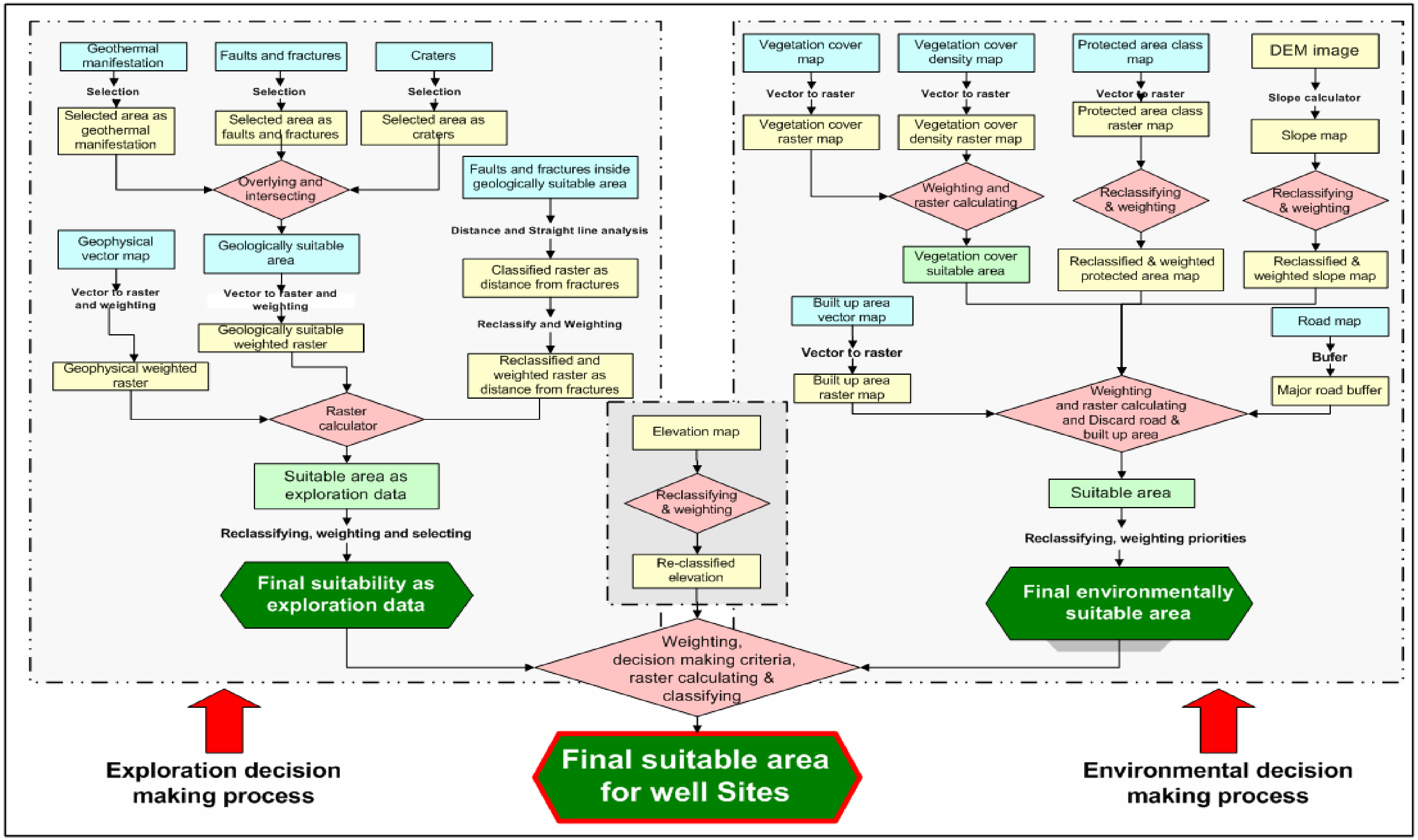

FIGURE 8: Flow diagram of a decision making process for geothermal exploration and environmental management

The current work involves describing a GIS-based decision support system model by using available data from most of the investigation methods mentioned as a digital data layer in GIS for supporting decision makers in targeting the exploration wells' appropriate location with respect to the reservoir. The flow diagram of the analysis for exploration decision-making process and applied data layers for analysis is shown in Figure 9.

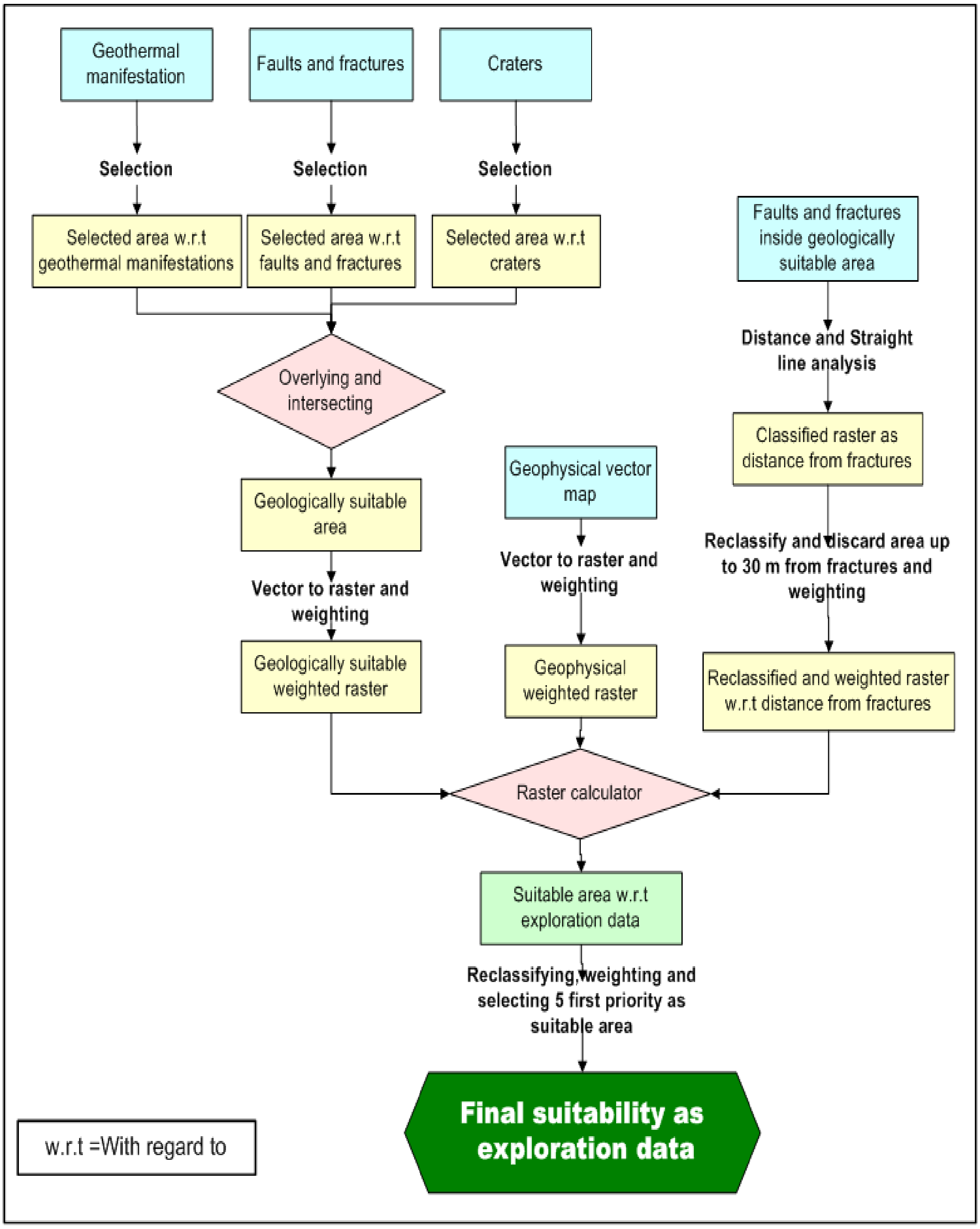

FIGURE 9: Flow diagram of the analysis, decision making process and applied data layers for analysis of exploration data

5.1.2 Geological exploration

In geothermal exploration, geological studies should emphasize the mapping of young igneous rocks that could act as heat sources, potential reservoir rocks, distribution and nature of hydrothermal alteration, and the distribution, orientation and nature of fractures and faults. In these studies, field work should be supplemented where possible by satellite imagery and aerial photography. Three main concepts in geological exploration are described and examined for the Námafjall area in following sections.

Geothermal manifestations

Manifestations including hot springs, fumaroles, mud spots, steaming ground and hydrothermal alteration are sign of an area of a deep geothermal reservoir and are called geothermal manifestations. The geothermal manifestations in the study area are mapped by the Geological Division of National Energy Authority of Iceland (Saemundsson*, in* www.os.is*, access Nov. 2004)*.

Thermal surface signatures in this area are marked by active and extinct geothermal manifestations. The active manifestations occur in the form of fumaroles, hot springs, mud pots, altered ground, warm ground, and sulphur deposition. Extinct manifestations are indicated by the presence of altered ground and brick red/grey clay deposition. These manifestations are mainly structurally controlled, occurring along faults and fractures. Fumaroles and mud pots are distributed widely in the central part of the study area. The physical nature and geochemical environment of the fumaroles, hot springs and pools at these sites strongly suggest that the waters consist of mixtures of condensate of fumarolic steam mixed with cooler, shallow groundwater. These manifestations are mainly structurally controlled, occurring along faults and fractures.

The part of the study area whose surface area is dominated by geothermal manifestations is defined as the prospect area for geothermal resources because it assumed that the manifestations have been created by the presence of geothermal resources. Using GIS/ArcInfo a 500 m buffer is generated around surface manifestations assuming that the area is a prospect area for continuation to the next step of geothermal exploration for further exploration. This prospect area based on surface manifestations is shown in Map 2. It shows that most of the geothermal manifestations are located in the central west part of the study area.

Faults and fractures

One of the keys to targeting regions for geothermal potential is to understand the role of faults in controlling fluid flow in the crust. Prior evidence suggests that critically stressed fractures and faults can play an important role in geothermal fields (Barton et al., 1995; Hickman et al., 1997).

In geothermal systems the fluid flows mostly through fractures in source rocks. Permeability of geothermal reservoirs is caused by fractures of various lengths and widths (e.g. Grant et al., 1982). Therefore the importance of fractures in geothermal development has been well recognized. Hanano, (2000), pointed out that there are two different roles of fractures in geothermal development;

- Contribution to occurrence of natural convection in geothermal systems to form convective geothermal resources,
- Contribution to high degree of permeability around wells which enables in-flow around the wells with low enough flow resistance at a very high flow rate.

Since the ascending velocity of natural convection in geothermal reservoirs is of the order of 10^{-9}m/s, fractures of very small to very large permeability contribute to the first role. However, the inflow velocity of a single phase liquid within fractures in the vicinity of the well ranges from 10^{-1} to 10 m/s for example. Thus, only fractures of very high permeability can contribute to the second role (Hanano, 2000).

The faults and fractures creating a secondary permeability in source rock, plays great roles in transporting geothermal fluid into the drilled wells, thus they have important roles in geothermal exploration and have to taken in account in the exploration process. Significant correlation was observed between geothermal manifestations and the regional tendency of fault orientations. The more altered areas have been located in the most fractured part of the field.

The Námafjall geothermal area is a part of Krafla fissure swarm. During the past decades, a major volcano-tectonic episode tool placed in the Krafla fissure swarm at the divergent plate boundary in north-east Iceland. This swarm is an 80-km-long and as much as 10-km-wide zone of tension fractures, normal faults, and volcanic fissures. The average length of 1,083 measured tectonic fractures is about 350 m, the maximum length being 3.5 km, and the average estimated depth is of the order of 102 m. Most fractures strike north to north-northeast, with widths as great 40 m and throws of as much as 42 m. Pure tension fractures are most common, but as they grow they commonly change into normal faults. Most fractures gradually thin out at their ends, but several exceptionally wide tension fractures end in tectonic caves, several tens of metres long, only a few metres beneath the surface. The total dilation measured in 5 profiles across the Krafla swarm reaches a maximum of at least 80 m and decreases from south to north along the swarm. New lavas covered many old fractures, but several new fractures were also formed and many old ones increased in size. New lava flowed into some of the major fractures in the area, presumably forming pseudo-dikes. The long fractures are normally composed of shorter segments, some of which are composed of still smaller segments down to the scale of columnar joints (Ophieim and Gudmundsson, 1989).

A number of faults extend through the Námafjall area, often just 200-300 m between them. This distance becomes even shorter within the most active part of the fissure swarm, which lies through Bjarnarflag. There, one can see a clear relationship between geothermal vents and fault lines. Though this relationship does also exist on Mount Námafjall, it is more varied. The Námafjall high-temperature geothermal area is a very active volcanic area. This volcanic activity diminishes over a distance of a few km, but continues again with active volcanic fissures in the area of Bjarnarflag and in the western part of Námafjall (Saemundsson, 2004).

A fractures and faults map of the study area is digitized and compiled from a geological map of the area and proved by a SPOT panchromatic image. There are 2 main types of faults and fractures in the area, the fractures are located in the active part of the main Krafla fissures swarm, and the fractures are located outside of the active zone. The whole study area has been classified according to faults and fractures in two main parts by using the Buffer technique of the GIS system. A 500 meter buffer has been created around faults and fractures. This assumes that the area located inside this buffer is more suitable than other areas for carrying out further exploration, because as it is already argued and assumed the most fractured area is best suited to geothermal exploration. Well sites inside this buffer area are preferred because the fractures have a great role in generating an upflow zone and creating secondary permeability to increase the permeability of the reservoir and the flow rate of wells. If the wells are located in the nearby fractures where the permeability of the reservoir is less, directional drilling will be a way to increase the permeability and flow rate by intersecting faults and fractures close to wells. The fault and fracture map with a 1000 meter buffer is presented in Map 3. Finally with regards to faults and fractures only, the central part of area from north east to south is more suitable to well targeting than others but for the final selection all other related data and information from the next steps have to be considered.

Craters

A crater is a steep, bowl-shaped depression surrounding a vent. A volcanic crater forms when the walls of a vent collapse inward following an eruption. Volcanic craters can constitute one of the elements in geological exploration of geothermal resources and presence of more craters in an area leads geologists to assume that the area has had or has a great deal of volcanic activity and this can be one of the reasons for the concentration of additional exploration work in the area to locate geothermal resources.

Most of the craters in the study area have been located in the central to south east part of the study area. The craters in the study area have been extracted from a geological map and proved by a SPOT satellite image. For finding a suitable area based on craters a buffer of 1000 metres has been made by the ArcInfo of its surrounding. Map 4 shows the craters and prospecting area based on craters.

Geological suitability
On the bases of geological considerations, taking into account geothermal manifestations, fault and fractures, and crater layers the suitable area was selected by the overlaying and intersecting technique of GIS/ArcInfo. It is assumed that the area located in the part common to all three geological types is the best area to continue exploration activities such as geochemical and geophysical investigation in. Map 5 shows the area that has been extracted from overlying and intersecting of the three layers mentioned and it is the prospect area based on geological considerations.

5.1.3 Geochemical classification

Various geochemical studies have been carried out during the exploration for a new development phase of the Námafjall high temperature geothermal area. In order to evaluate reservoir temperatures and find the distribution of reservoir temperatures in a prospect area, geochemical studies including the sampling of fumaroles and mud pools and reservoir temperature estimation have been averaged by using several geothermometers such as CO_2, H_2S, H_2 and CO_2/H_2. The average calculated temperatures have been used for modelling the reservoir temperature in 1993 by the Geothermal Division of Icelandic National Energy Authority (Orkustofnun) and Icelandic Geosurvey (ISOR) companies (Ármannsson, 1993). The geothermometer and the resulting calculated temperatures are presented in Table 7. Several geothermometers were used for each sample and the averages are defined as the reservoir temperature of each sample point. Distribution of the calculated reservoir temperature by geochemical geothermometers was plotted using the spatial analyst of ArcInfo and the result in the form of a raster map is shown in Map 6. The study area has been classified according to calculated temperatures by geochemical methods in the GIS system and it shows that the reservoir temperature increases from the east to the west part of the geological prospect area. The temperature range is from 230 to 280 ºC or more and there exists a suitable temperature for development in most of the prospect area but the most highly ranked area is in the western part of the prospect area.

5.1.4 Geophysical classification

As mentioned and described in an earlier chapter, TEM-resistivity measurements have been carried out by the Geothermal Division of the Icelandic National Energy Authority (Orkustofnun) in 2002 (Karlsdóttir, 2002). The results indicate a prospecting geothermal reservoir which, is targeted around 1000 m depth (600 m b.s.l.) and the low-resistivity cap surrounding the high-resistivity core is located in an area covering close to 20 km^2 (Figure 7). The correlation between the resistivity structure of the high-temperature geothermal system in basaltic rocks and alteration mineralogy in the Námafjall geothermal field can be summarized as follows:

- The resistivity is relatively high in cold unaltered rocks outside the reservoir.
- The smectite-zeolite zone forms a low resistivity cap on the outer margins of the reservoir.
- The resistivity increases again towards the interior of the reservoir at the top of, or within, the mixed layer clay zone (Karlsdóttir, 2002).

In Map 7 according to geophysical investigations the area has been ranked as 5 different levels of importance and evaluated. The first priority is the resistivity core area and is predicted to have the highest temperature in the reservoir and in the current modelling study this area has highest weight, but the area outside of the low-resistivity cap has the lowest weight. Table 8 shows the resistivity, priority and importance of each part of the area in decision-making process. Based on Table 8 the resistivity map has been classified to 6 different levels.

5.1.5 Site selection based on exploration data

Weighted overlay is a technique for applying a common scale of values to diverse and dissimilar input in order to create an integrated analysis.

TABLE 8: Resistivity values obtained by TEM method
with evaluation and relative value

Resistivity (Ωm)	Evaluation	Relative value
1 – 3.2	Not so good	1
3.2 – 10	Good -	2
10 – 32	Good	3
32 – 100	Good +	6
100 – 316	Very good	8
316 – 1000	Ideal	9

The three input rasters, i.e. a geologically suitable area (Map 5), distance to fractures and a reordered geophysical data layer, are used in this modelling. The three rasters are assigned theirs own percentage of influence such as described later in this section. The cell values are multiplied by their influence percentages, then the weighted overlay is run in spatial analysis and a raster of overall suitability is created. The raster created is reclassified again in to 10 different classes and the five first classes have been used as five priority areas for the next step. A short description and assigned weighting for each layer are:

- From the geological layers and information, including fractures, craters and surface manifestations Map 5 has been used in the final exploration model with equal weighting in the whole area covered and its importance in the final decision is 10 % used for raster calculation.
- The factures and faults are not only important in a large scale selection of the geological section of the prospect area. They are accounted for in the selection of detailed locations of well sites in inside suitable area selected in geological investigations. For finding best targets for well sites, all fractures and faults located in the geologically suitable area are selected, first a 30 m buffer generated on both sides of them to avoid well sites exactly on top of the faults and fractures. Secondly by using the Spatial analyst of ArcInfo a distance model has been carried out from fracture buffers (30 buffers). In this model, it is preferable that the well sites be selected as near as possible to the faults and fractures buffer but not less than 30 metres or over top of them. A 500 m "straight-line distance" analysis was conducted on a 30 m buffer and a raster map has been generated. The raster map reclassified base distances to 10 classes with highest value, 9, given to nearest class (30-100 m distance) and lowest value, 0, for distance class (450 – 500 m distance) and the reclassified map is Map 8. The weighting of this layer is 25 % in the final raster calculation criteria.
- The reclassified TEM-resistivity map (Map 7) is used for the final raster calculation. The weighting of this layer has been assigned 65 % in final raster calculation criteria.

The final calculated map based on the layers mentioned with a specified weighting is presented in Map 9. In this map the most suitable area is shown in dark red and the areas with less suitability presented in light colour. In the next section of this chapter the study area is evaluated according to environmental suitability and the final selection of well sites conducted by calculation of these two data layers.

5.2 Environmental suitability analysis (decision-making)

A growing emphasis on environmental quality has prompted many countries to adopt legislation and guidelines that will ensure the consideration of the natural environment in land-use planning and site selection processes. This has resulted in considerable research and development of models that can support the location planning and decision-making processes.

This approach usually considers a comprehensive set of factors in determining vulnerability of land for various development activities and vice versa. Therefore, its effective use requires not only a flexible system capable of storing, manipulating and transforming a large volume of spatially oriented data into usable information, but also a mechanism for analyzing relations and applying criteria related to environmental quality in land use planning and site selection process.

Geographic Information System has emerged as a valuable computer-based tool in supporting a variety of spatial problem tasks and selecting the most appropriate sites from the environmental point of view for geothermal wells. To select well sites with minimum environmental effects, environmentally important factors such as "land slope", "3D elevation model", "vegetation cover" "vegetation cover density", "protected area", "tourist attraction", socio-economical and residential (Built up) area", and "historical and cultural places" have been assigned specific weighting as per their relative importance.

The following section describes how information and data layers were generated and taken into account in the site selection process. A flow diagram with relative digital data layers is used in the decision-making process for determining (the appropriate) area for future development in the Námafjall geothermal field (Figure 10).

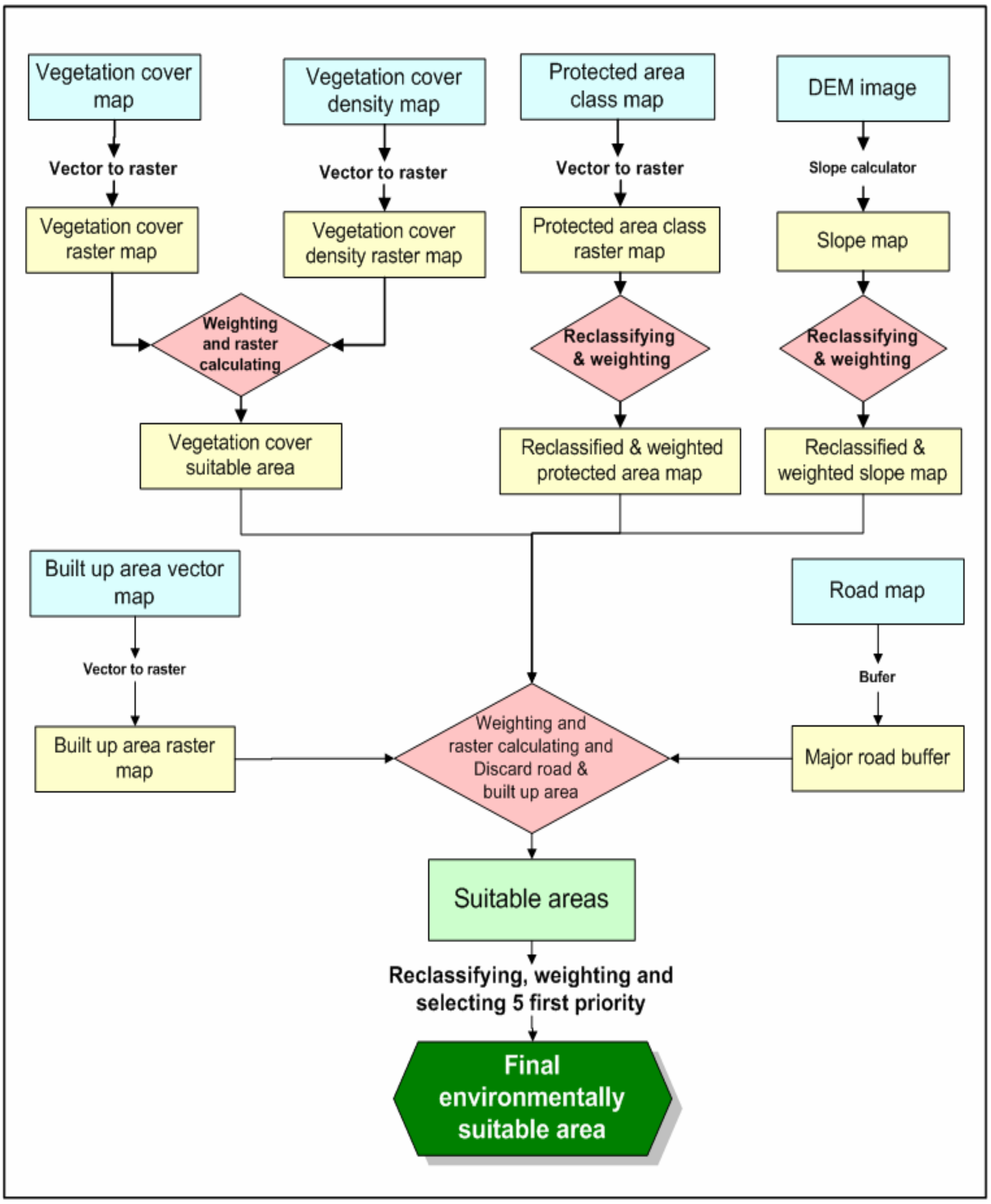

FIGURE 10: Flow diagram of the analysis, the decision making process and the data layers applied to the analysis an environmental suitability

5.2.1 Digital elevation model and topography

Any digital representation of the continuous variation of relief over space is known as a digital elevation model (DEM). A digital elevation model is an ordered array of numbers that represent spatial distribution of elevations above some arbitrary datum in the landscape. A DEM is a matrix where every cell value represents the elevation at the centre point in the corresponding area on the earth's surface. Normally the DEM is interpolated from line or point data, but nowadays it is constructed by the use of satellite information.

The DEM files may be used in the generation of graphics such as isometric projections displaying slope, direction of slope (aspect), and terrain profiles between designated points. They may also be combined with other data types such as stream location data and weather data to assist in evaluating power plant air pollution or they may be combined with remote sensing data to aid in the classification of vegetation. Some applications include:

- Generating a topographical map
- Generating 3D view of the terrain surface
- Modelling terrain gravity data for use in locating energy resources,
- Determining the volume of proposed reservoirs,
- Calculating the amount of material removed during extraction of natural resources,
- Determining landslide probability,
- Developing parameters for hydrologic models (U.S. Geological Survey, 1993).

GIS-based land elevation can be enhanced by the use of digital elevation data. For producing the topographic map of the study area the digital elevation map of the area has been used and DEMs are efficient and convenient sources of this information. ArcMap – 3D analyst has a capability to generate the topographical contour map from a DEM satellite data. The digital elevation map of the study area has been applied in the 3D analyst and the spatial analyst of ArcInfo to produce the topographic map but the generated topographic map has some distortion and uncertainty because of the existence of wide fissures and fractures and harsh structure of lava filed in the study area. Contour lines were serrated and there were also some unwanted and uncertain contour lines in parts of the area because of the existence of wide fractures where insides have been defined inaccurately by satellite as elevation. For correcting this uncertainty a "Neighbourhoods Statistics Analysis" has been performed. The Neighbourhoods Statistics Analysis uses the value of neighbourhood cells for to calculate new value for defined cell and the number of the neighbourhoods and the methods of neighbourhood selection (radius, blocks, line and point) are defined by analyser depending to the work.

In this work the first attempt to calculate a neighbourhood statistic's "mean value" by circular neighbourhood methods involved 3 cells in around by radius. The results were still not adequate and the lines were not smooth. The second attempts to calculate the neighbourhood statistic's mean value by circular neighbourhood methods involved 5 cells in radius, the result was acceptable and the topographical map with line intervals of 10 metres is created.

The Triangulated Irregular Network (TIN) is a system designed by Peuker and Douglas, (1986) for surface digital elevation modelling. The TIN model is a vector topological structure similar in concept to the fully topologically defined structures for representing polygon networks with the exception that the TIN does not have to make provisions for islands or holes. The TIN model regards the nodes of the network as primary entities in the database. The topological relations are built into the database by constructing pointers from each node to each of its neighbouring nodes. TIN datasets can be used to display and analyze surfaces such as slope and aspect. They contain irregularly spaced points that have x, y coordinates describing their location and a z-value that describes the surface at that point. A series of edges join the points to form triangles. The resulting triangular mosaic forms a continuous faceted surface, where each triangle face has a specific slope and aspect.

TINs can be created from several types of data including raster, point, line, and polygon feature classes that have z-coordinate values. Features used to create TINs ensure that known z-values are maintained in the surface. They may also interrupt the smoothness of the surface to more appropriately represent features such as streams, dams, building footprints, etc. where there is an abrupt change in the surface's slope around the feature.

The TIN elevation map of the study area is constructed by ArcInfo by using DEM data. The elevation can be one of the important factors in selecting the well sites. Other factors being equal if the well sites are at a low elevation, it will decrease the cost of drilling because reaching a defined reservoir at a particular depth needs drilling wells to a shallower depth. The topographical map and the 3D model (TIN model) of the study area that have been generated from DEM data are shown in Map 10. The study area, according to elevation, is classified to 8 different levels. Therefore, the study area based on elevation is scaled in Table 9 with elevation, relative evaluation and relative value.

TABLE 9: Different classes of elevation with relative value and evaluation

Elevation (m)	Evaluation	Relative value
< 300	Ideal +	9
301 – 350	Ideal	8
351 – 400	Very good	7
401 – 450	Good	6
451 – 500	Poor	4
501 – 550	Very poor	2
551 – 600	Bad	1
601 – 760	Unacceptable	0

5.2.2 3D elevation model

A 3D elevation model of the study area has been made by the overlaying of the TIN map of the area which has been made from DEM data of the area (Map 10) and a multispectral SPOT satellite image. In ArcScene, the TIN map has been used as a base height structure and satellite image overlain for producing a natural view of the study area. This model is very important for planners and decision makers, because there is no opportunity for all involved in projects to visit the area and this type of model gives them the opportunity to have a real view of the area especially when making an artificial flight across the area by ArcScene and recording the flight view as a movie. Thus a natural view of the area is actually presented. A 3D view of the study area in which the view point is located on Hverfjall crater facing the north is shown in Figure 11.

5.2.3 Slope

Slope and aspect are important terrain parameters from the land utilisation point of view and also in assessing environmental impacts. Among the three parameters of the terrain (slope, aspect and altitude), slope is very important for assessing land capability, erodibility, stability and irrigability for environmental management purposes.

Slope is expressed as the change in elevation over a certain distance. In the case of DEM data the certain distance is the size of its pixel. Slope identifies the steepest downhill slope for a location on a surface. Slope is calculated for each cell in a raster DEM image. It is the maximum rate of change in elevation over each cell and its eight neighbours.

There are several techniques for generating maps that identify the bumps (convex features), the dips (concave features) and the tilt (slope) of a terrain surface. A terrain surface is organized as a rectangular "analysis grid" with each cell containing an elevation value. Grid-based processing involves retrieving values from one or more of these "input data layers" and performing a

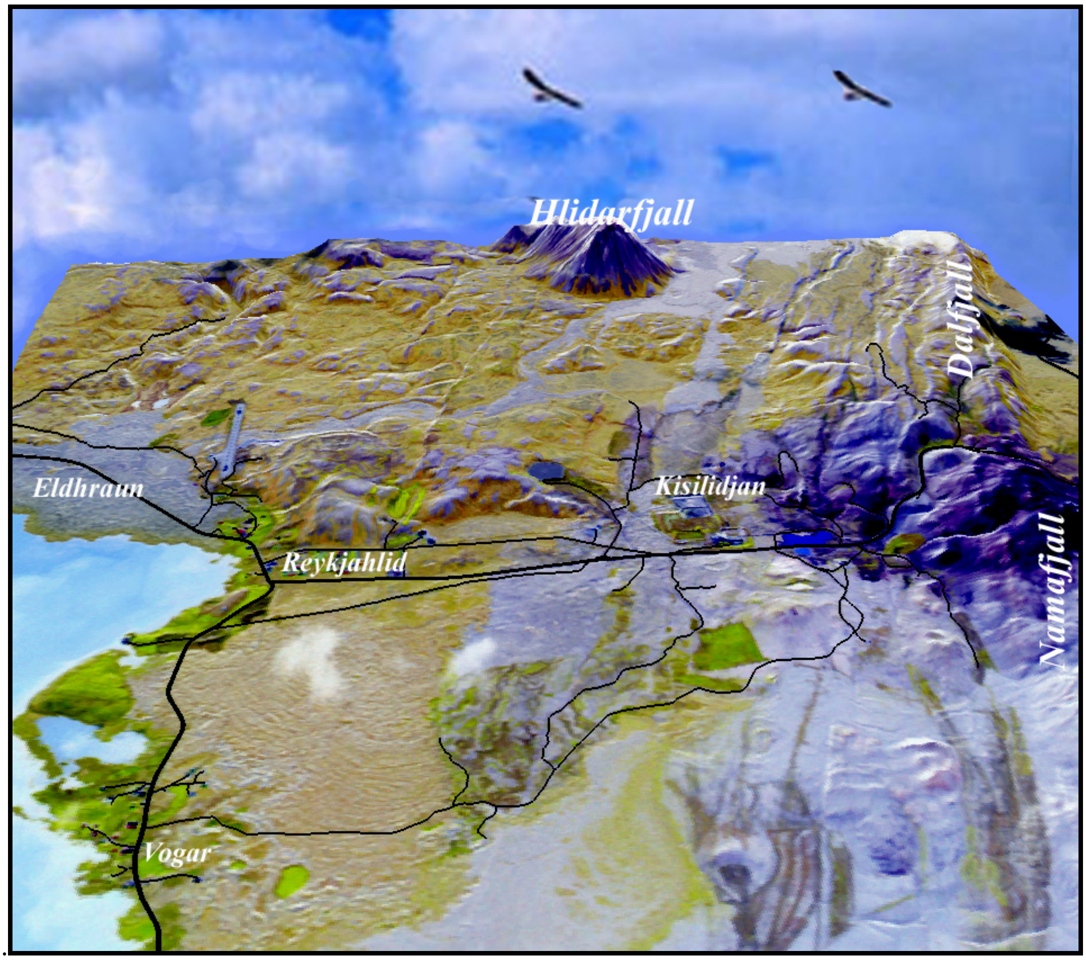

FIGURE 11: 3D elevation model overlain by satellite multispectral images

mathematical or statistical operation on the subset of data to produce a new set of numbers. While computer mapping or spatial data base management often operate with the numbers defining a map, these types of processing simply repackage the existing information and map analysis operations, on the other hand, they create entirely new spatial information.

The slope command in ArcMap takes an input surface raster and calculates an output raster containing the slope at each cell. The lower the slope value is the flatter the terrain and the higher slope value is the steeper the terrain. The output slope raster can be calculated as percent slope or degree of slope.

The slope map of the study area has been created by using a DEM image and the spatial analyst of ArcInfo is employed for calculation. A 3 × 3 pixel window is used to calculate the slope at each pixel. For a pixel at the location X, Y, the elevation around it are used to calculate the slope as shown in Figure 12.

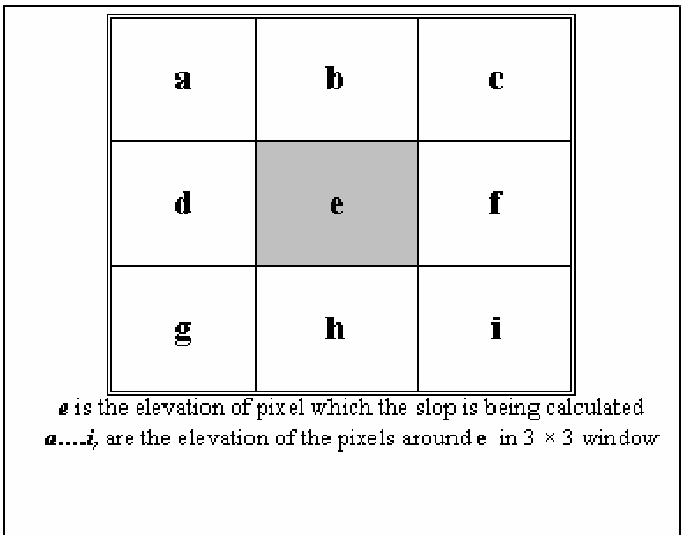

FIGURE 12: A 3×3 pixel windows is used to calculate the slope at each pixel

First the average elevation change per unit of distance in the x and y direction (Δx and Δy) are calculated as (ESRI, 2002):

$\Delta x_1 = c - a$ $\Delta y_1 = a - g$

$\Delta x_2 = f - d$ $\Delta y_2 = b - h$

$\Delta x_3 = I - g$ $\Delta y_3 = c - I$

$$\Delta x = (\Delta x_1 + \Delta x_2 + \Delta x_3) / 3 \times x_s$$
$$\Delta y = (\Delta y_1 + \Delta y_2 + \Delta y_3) / 3 \times y_s$$

where *a....i* = elevation value of pixels in a 3 × 3 windows, as shown above
x_s = x pixel size = 30 m
y_s = y pixel size = 30 m

The slope at the pixel *x, y* is calculated as:

$$S = \frac{\sqrt{(\Delta x)^2 + (\Delta y)^2}}{2}$$

If $s \leq 1$ *Percent slope* = $s \times 100$
If $s > 1$ *Percent slope* = $200 - (100/s)$

The output raster map was asked to generate the percent of slope by the spatial analyst of ArcInfo. There are several classifications of slope category but in this study the classification of slope which is used is shown in Table 10.

Natural slope of a site is important for construction of well sites and accompanying structures. The land with a greater slope may pose difficulty in the construction and may need levelling up and cause more surface disturbance. Therefore, the scales in Table 10 have been developed for evaluating the slope percent of the site on which the slope map classification has been based. The slope map run from DEM data has been symbolized using the 7 different classes of Table 10 and the final slope map is shown in Map 11. For defining the environmental sensitivity, the slope map has been taken into account. Based on slope classification the suitable area for a well site construction is an area with relatively little surface disturbance during the construction of the well pad and accompanying structures. For avoiding surface disturbances the geothermal drill site is better installed in a "Nearly level" to "Very gently" sloping (0 – 3 %) area.

TABLE 10: Slope classification of study area with evaluation and relative value

Slope categories	Slope (%)	Evaluation	Relative value	Covered area (m^2)	Proportion (%)
Nearly level	0 - 1	Ideal	9	32656500	44.4
Very gently sloping	1 - 3	Very good	8	12744900	17.3
Gently sloping	3 - 5	Good	7	6944400	9.4
Moderately sloping	5 - 10	Poor	6	9732600	13.2
Strongly sloping	10 - 15	Very poor	5	4562100	6.2
Moderately steep to steep sloping	15 - 35	Bad	1	6645600	9.0
Very steeply sloping	> 35	Unacceptable	0	261000	0.4

5.2.4 Vegetation

Vegetation mapping from satellite imagery has been dominated by the use of data from the reflective wavelengths of the solar spectrum, primarily the visible, near-infrared and mid-infrared. Landsat TM and SPOT HRV have been the most commonly used sensors for vegetation mapping and monitoring.

The first and common approach is to map vegetation from satellite imagery using multispectral data in image classification. In this approach patterns of spectral reflectance or "spectral signature" are associated with different vegetation types. In the image classification step, each pixel in the image data is assigned to a particular vegetation type, resulting in a map. This paradigm has primarily used data from the solar reflective wavelengths, but other kinds of data were later included, such as texture data and other kinds of map data such as topographic variables (Skidmore, 2002).

Image classification algorithms can be stored into those which are "supervised" or "unsupervised". The supervised classification approaches require training site as input prior to the image classification steps which are used to characterize the spectral signatures of the vegetation types. Initially, parametric statistical classifiers such as maximum likelihood, dominated (Swain and Davis, 1978).

Many factors influence the reflectance from vegetation canopies, some diagnostic of the vegetation type of interest in the mapping process and others unrelated. The vegetation factors known to influence the spectral reflectance of vegetation canopies include the overall life of the vegetation, leaf properties (leaf area and leaf angle distribution and spectral reflectance properties), vegetation height or tree size, the fractional cover of vegetation, and the health and water content of leaves. One issue that confronts the use of digital satellite images for mapping vegetation concerns scale, or the relationship between the size of individual pixels and the desired scale of the resulting map. Frequently, the pixels in the satellite images are too small to be classified individually in the final map. For example, on the map scale commonly used in local environmental modelling, such as 1: 25,000 minimum mapping units are typically of the order of 1-2 hectares, or 25-50 pixels in a SPOT HRV image or 11-22 pixels in a Landsat TM image. This issue remains one of active research, and several approaches exist for this situation, including: filtering of the image resulting from per-pixel classifiers (Kim, 1996); using spatial or contextual information in the classification process (Ketting and Landgrebe, 1976); and the segmentation of images into polygons in a step independent of image classification (Woodcock and Harward, 1992).

Vegetation mapping based solely on image classification of multispectral data is limited with respect to the vegetation attributes that can be provided in a reliable manner. Particularly apparent in this regard is the difficulty of mapping vegetation at the level of detail of individual plant species. This problem arises because many species often have overlapping spectral signatures which make their identification impossible or of poor accuracy. The relationship between vegetation mapping and GIS is mutually beneficial, vegetation maps are used extensively within GIS for the purpose of environmental modelling. However, the integration of other kinds of map data with remote sensing images through the use of GIS has greatly improved the vegetation mapping process (Skidmore, 2002).

The vegetation map of the study area has been digitized and simplified from the vegetation Map of Iceland, sheets 304 (Gaesafjöll) and 305 (Reynihlíd) in the scale of 1:40.000 which was published by the Agricultural Research Institute of Iceland (Agricultural Research Institute, 1982). The digitized vegetation map was overlapped with SPOT satellite images and the major plant communities rectified by pixel signatures in the image and proved by it. Map 12 shows the rectified vegetation cover type map of the study area. The vegetation in the study area consists of four main types of vegetation communities and each community consists of some species and subgroups including:

- The Dry moss-dominated vegetation including Rhacomitrium heath, and Kobresia mysuroides spesices;
- The Dwarf-shrub heathland community consists of Empetrum hermafroditum, Betula nana, Vaccinium uliginosum, Loiseleuria procumbens, Salix Caluna vulgaris, Arctostaphlus uva uris, and Dryas octopetsls;
- Scrub heath willows and dwarf birch dominated species are Betula nana, Vaccinium uliginosum, Empetrum hermafroditum, Kobresia myosuroides, Gramineae, Betula pubescens, Salix callicarpea, Salix lanata and Salix phylicifolia;
- In the Kobresia community, Kobresia myosuroides species is dominant.

Parts of the area are not covered by vegetation and are mostly dominated by gravelly and sandy flats, and lava. Also a part of Lake Mývatn is located in the study area and there are some bogs and fens in the western part of the area where Carex nigra and Carex chordorrhiza plant species grew. Table 11 shows the major plant communities and the area covered by each vegetation cover type.

TABLE 11: Plant species in study area with relative covered area and proportion

Major classes	**Vegetation cover type**	**Covered area (m^2)**	**Cover (%)**
Dry moss heath	Dry moss-dominated vegetation	4486205	6.02
Heath land	Dwarf-shrub heathland	8914665	11.96
	Scrub heath willows and dwarf birch	17917481	24.04
	Kobresia	1448529	1.94
Grassland	Grassland	1877550	2.52
Complex vegetation	Complex vegetation	2698159	3.62
Gramineae	Gramineae regrowthed on eroded land	3522265	4.73
Cultivated area	Cultivated area	773749	1.04
Wetland	Bogs and fens with Carex	449461	0.60
Water	Lake and lagoons	7782949	10.44
Land without vegetation	Gravelly and sandy flats	15519407	20.82
	Bare Soil	83124	0.11
	Lava	7303774	9.80
	Constructed land	209230	0.28
	Other land types	1539070	2.07

Vegetated parts of the study area are mostly covered by heath land, followed by dry moss vegetation and most land without vegetation is principally covered by gravelly and sandy flats, followed by the lava and bare soil land cover type. Figure 13 shows the land cover type of the study area proportionally. Therefore, the vegetation cover map has been simplified in area and 10 different land cover types (vegetated and not vegetated) are scaled in Table 12 which has been developed to evaluate the vegetation cover of the study area.

TABLE 12: Ten different land cover types (vegetated and not vegetated) for evaluating the land cover of the study area with relative value and evaluation

Land cover	**Area (m^2)**	**Proportion %**	**Evaluation**	**Relative value**
Land without vegetation	24444389	32.90	Ideal	9
Dry moss heath	4486206	6.04	Very good	8
Heath land	28047659	37.75	Good +	7
Complex vegetation	2698159	3.63	Good -	6
Revegetated area	3522266	4.74	Poor +	5
Grassland	1877549	2.53	Poor -	4
Cultivated area	773749	1.04	Poor	2
Bogs and fens with Carex	449461	0.60	Unacceptable	0
Inhabited land	209230	0.28	Unacceptable	0
Lake and lagoons	7782949	10.48	Unacceptable	0
Total	**74291616**	**100**		

Moreover, a vegetation cover density map has also been produced for the study area from the already mentioned Icelandic vegetation map. Vegetation cover density is a very important factor for environmental studies because environmental decision makers take it into account when they decide to start any construction projects involving major surface disturbance which it is appropriate to locate in less vegetated area. The plant cover density map of the study area is Map 13. There are six different vegetation density classes including, land without vegetation, less than 30 % cover, 30 to 65 % cover, more than 65 %, 100 % cover and cultivated lands. Also as mentioned before, a part of the area is covered by Lake Mývatn, lagoons, bogs and fens. Figure 14 shows the proportion of each cover density. Thus, there are six vegetation cover density types in the area and those are scaled in Table 13 with relative covered area, evaluation and relative value.

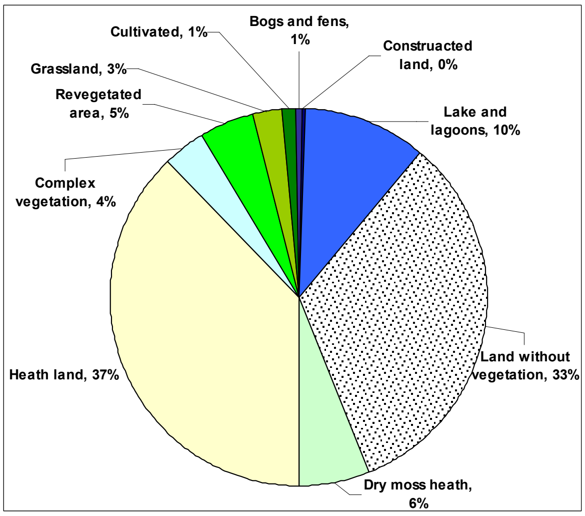

FIGURE 13: Covered portion of each vegetation type

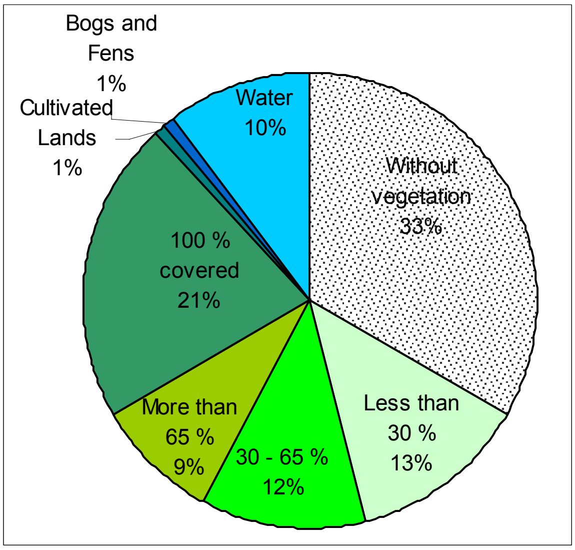

FIGURE 14: Different vegetation cover density proportion

TABLE 13: Vegetation cover density types of the study area with evaluation and relative value

Vegetation cover density	Covered area (m^2)	Proportion (%)	Evaluation	Relative value
Without vegetation	24,656,805	33.27	Ideal	9
Less than 30 %	9,474,990	12.79	Very good	8
30 - 65 %	8,679,795	11.71	Good	7
More than 65 %	6,658,362	8.99	Poor	5
100 % covered	15,702,041	21.19	Poor	3
Cultivated lands	773,749	1.04	Very poor	1
Bogs and fens	451,316	0.61	Unacceptable	0
Water	7,707,185	10.40	Unacceptable	0
Total area	**74291616**	**100**		

Vegetation suitability selection
Weighted overlay is used to find the vegetation suitability in the study area. It is a technique for applying a common scale of values to diverse and dissimilar input in order to create an integrated analysis.

Geographic problems often require the analysis of many different factors, and of course the factors in the analysis may not be equally important. It may be noticed that being a protected area is more important when choosing a site than land cover density, but how much is important? It is related to the decision of analysts and decision makers. Even within a single raster, the values have to be prioritized. Some values in a particular raster may be ideal for selection purposes (for example, slopes of 0 to 3 percent), while others may be good, others poor, and still others unacceptable.

The Weighted Overlay process allows all these issues to be taken into consideration. It reclassifies values in the input rasters onto a common evaluation scale of suitability. The input rasters are weighted by importance and added to produce an output raster. The steps are summarized below:

- A numeric evaluation scale is chosen. This may be 0 to 5, 0 to 9, or any other scale. The highest value represents high suitability and the lowest value represents low suitability.
- The cell values for each input raster in the analysis are assigned values from the evaluation scale and reclassified to these values. This makes it possible to perform arithmetic operations on the rasters that originally held dissimilar types of values.
- Each input raster is weighted - assigned a percent influence based on its importance to the model. The total influence for all rasters equals 100 percent.
- The cell values of each input raster are multiplied by the rasters weighting.
- The resulting cell values are added up to produce the output raster.

The suitable area in terms of land cover and vegetation cover density data found by overlaying the vegetation cover and the vegetation density map, first the vegetation cover map converted to a raster map and reclassified and ranked as socially, economically, and environmentally important to them and the ability of an area for further development and a value of suitability for project development assigned the same relative value as is presented in Table 12, it means that an area that is highly important in vegetation cover has less weight in this ranking. The area has been classified into 8 different classes with a particular weighting or relative value for each one. Secondly the vegetation density map is also converted to a raster map and reclassified and ranked by the cover density. The area with a high vegetation density got a lower reclassification value and the area with a lower vegetation density or without vegetation got a higher relative value. The area has been classified into 7 different classes with special weighting or relative value for each.

Finally to find out a suitable location for development with minimum damage to vegetation, a raster map is calculated by overlaying of the two already reclassified maps using the spatial analyst of ArcInfo, two layers are overlain and a raster has been calculated and a new raster map has been generated. The new map shows, which parts of the area are best (vegetation least affected) and which parts are worse (more impacts on vegetation) according to the vegetation cover type and the vegetation cover density data layers. Map 14 is the suitability map of the area its respect to vegetation cover and vegetation density information.

5.2.5 Protected areas

Protected areas are widely held to be among the most effective means of conserving biological diversity in situ. A protected area is defined by the International Union for Conservation of Nature and Natural Resources (IUCN, 1994) as: *"An area of land or sea especially dedicated to the protection and maintenance of biological diversity, and of natural and associated cultural resources, and managed though legal or other effective means"*. In practice, protected areas are managed for a wide variety of purposes which may include:

- Scientific research and education
- Wilderness protection
- Preservation of species and ecosystems
- Maintenance of environmental services
- Protection of specific natural and cultural features
- Tourism and recreation
- Sustainable use of resources from natural ecosystems
- Maintenance of cultural and traditional attributes

The IUCN has defined a series of protected area categories, based on a management objective, which are summarized in Table 14.

TABLE 14: The IUCN protected area management categories (IUCN, 1994)

Category	Name	Purpose of protection	Definition
Ia	*Strict Nature Reserve*	Protected area managed mainly for science	Area of land and/or sea possessing some outstanding or representative ecosystems, geological or physiological features and/or species, available primarily for scientific research and/or environmental monitoring
Ib	*Wilderness Area*	Protected area managed mainly for wilderness protection	Large area of unmodified or slightly modified land, and/or sea, retaining its natural character and influence, without permanent or significant habitation, which is protected and managed so as to preserve its natural condition
II	*National Park*	Protected area managed mainly for ecosystem protection and recreation	Natural area of land and/or sea, designated to: protect the ecological integrity of ecosystems for present and future generations exclude exploitation or occupation inimical to the purposes of designation provide a foundation for spiritual, scientific, educational, recreational and visitor opportunities, all of which must be environmentally and culturally compatible.
III	*Natural Monument*	Protected area managed mainly for conservation of specific natural features	Area containing one, or more, specific natural or natural/cultural feature which is of outstanding or unique value because of its inherent rarity, representative or aesthetic qualities or cultural significance.
IV	*Habitat/Species Management Area*	Protected area managed mainly for conservation through management intervention	Area of land and/or sea subject to active intervention for management purposes so as to ensure the maintenance of habitats and/or to meet the requirements of specific species.
V	*Protected Landscape/Seascape*	Managed mainly for landscape/seascape conservation and recreation	Area of land, with coast and sea as appropriate, where the interaction of people and nature over time has produced an area of distinct character with significant aesthetic, ecological and/or cultural value, and often with high biological diversity. Safeguarding the integrity of this traditional interaction is vital to the protection, maintenance and evolution of such an area.
VI	*Managed Resource Protected Area*	Managed mainly for the sustainable use of natural ecosystems	Area containing predominantly unmodified natural systems, managed to ensure long term protection and maintenance of biological diversity, while providing at the same time a sustainable flow of natural products and services to meet community needs.

In Iceland, according to *The Nature Conservation Act,* published in 1999, the protected sites of natural interest are divided into the following classes (Environment and Food Agency of Iceland, 1999):

National parks: Its landscape or biosphere is so unique, or because it has a historical significance, which gives grounds for preserving it and its natural characteristics and allow public access to it in accordance with specific rules.

Nature reserves: Areas which it is important to preserve because of their special landscape or biosphere. Protected areas are called nature reserves.

Natural monuments on land: Natural formations, such as waterfalls, volcanoes, caves or rock outcrops, as well as locations of fossil beds, rare rocks and minerals, which are important to preserve for their scientific value, beauty or uniqueness. Areas surrounding natural formations shall also be protected as necessary for them to be enjoyed to best advantage; such shall be clearly stated in the declaration of protection. Protected natural formations shall be called natural monuments.

Protected organisms, habitats and ecosystems: Organisms, their habitats and ecosystems which is important, from a scientific, natural historic or other cultural perspective, not to disturb, decrease in number or eradicate.

Country parks: A specific area for outdoor leisure and public access.

The Námafjall geothermal field is located in the Mývatn protected area. Lake Mývatn, the river Laxá and the surrounding area have been protected by law since 1974. The objective of the law is to protect the landscape, geological formations and wildlife of Lake Mývatn and the river Laxá and promoting research for this purpose. The protected area covers the entire district of Skútustadahreppur and the river Laxá, as well as the islets and tributaries of the river and a 200-metre wide stretch of riverbank along the river reaching all the way to Skjálfandi Bay.

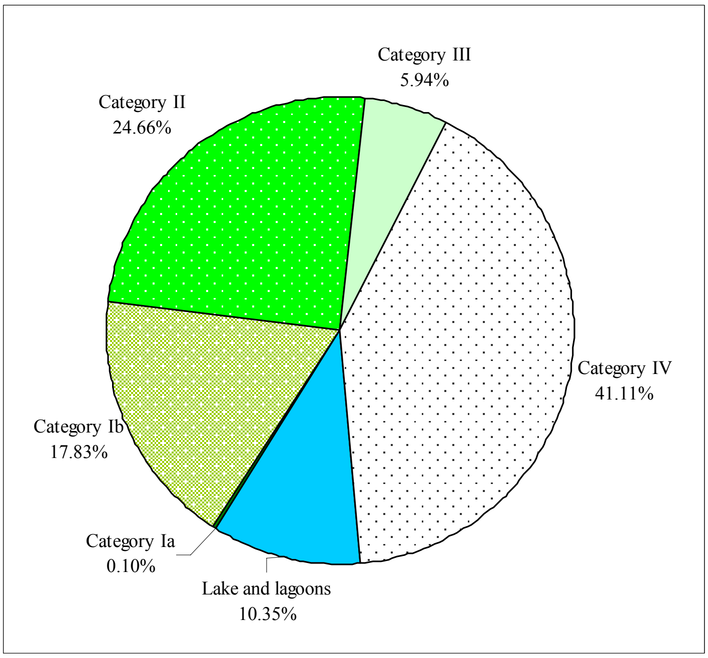

FIGURE 15: Proportion of each protected category in the Námafjall area

The study area includes protected categories Ia, Ib, II, III, IV according to the IUCN definition of protected areas. Any development activity in the area has to be carried out with particular consideration of each category of protection. Map 15, the protected area map of this study area is based on the Icelandic protected area map of Mývatnssveit, sheet No 19. As the map shows most of the area is covered by categories II and IV, category Ia only appears in the central east part of the area in south Reykjahlíd and covers only 0.1 %. Category Ib is fund in most parts of the area, covering about 18 %. The area and the proportion covered by each category are shown in Table 15 and results are plotted in Figure 15.

According to IUCN definitions for each category, any construction activities and surface disturbance in the area of categories Ia and Ib are avoided because both have been classified for high environmental protection goals and developers are not able to make any disturbance in areas in these categories. In the reclassification of the protected area map to a raster map, zero weighting is given to these categories. Categories II, III and IV have been weighted as 6, 8 and 10 respectively. It means that categories Ia and Ib will not be disturbed, in category IV there is more possibility of disturbance and in category II a lower one. In the raster map generated, there are five protection categories and these are scaled in Table 15 with relative covered area, evaluation and relative value given to each. This classified raster map shows specific relative value for which a higher value means greater ability of the area for development and it is used in the site selection criteria for well targeting (Nature Conservation Council of Iceland, 1987).

TABLE 15: Area and cover percentage of each protected category in Námafjall

Category (IUCN base)	Area (m^2)	Cover proportion (%)	Evaluation	Relative value
Lake and lagoons	7,644,088	10.3	Unacceptable	0
Category Ia	74,713	0.1	Unacceptable	0
Category Ib	13,168,082	17.8	Very poor	1
Category II	18,215,947	24.7	Good	6
Category III	4,388,850	5.9	Very good	8
Category IV	30,366,337	41.1	Ideal	9

5.2.6 Built up area

Some part of the study area has been developed already and several residential, industrial and farming sites are active in area. These occupy about one square kilometre and their proportion is 1.35 percent. The most important ones are described briefly.

Kísilidjan diatomite plant has been in central part of study area in Námafjall high-temperature field, is among the largest industrial users of geothermal steam in the world. The plant has been in operation since 1967, and the annual production has been between 20,000-30,000 tons of diatomite filter aid which is exported. The raw material is diatomaceous earth taken from deposits on the bottom of Lake Mývatn. After a period of decreasing production, the productivity of the factory has been increased considerably 1992 - 1995. This resulted in a production of 28,100 tons in 1995, which is close to the capacity of the factory. The process requires about 220,000 tons annually of geothermal steam at 10 bar absolute (180°C). This corresponds to an energy use of 515 TJ per year. Kísilidjan covers an area of 625,000 m^2 according to the land use map (Gudmannsson and Jóhannsson, 1997) including the diatomite plant, storage pool, access road and other facilities. The Icelandic government decided to close this plant mostly because of the environmental impacts on Lake Mývatn, and actually it closed November 30, 2004.

Léttsteypan is a factory for producing concrete using of the geothermal heat. It is located in the central part of the area.

The main residential area is Reykjahlíd in the eastern part of the area near to Lake Mývatn. Also there are some other small villages like Vogar, Grímsstadir and Geiteyjarströnd. Most economical activity of the residents in area is centred on farming and sheep keeping. About 470 people live in the district of Skútustadir in the Lake Mývatn area, of whom more than 200 live in the settlement of Reykjahlíd. In earlier years the inhabitants earned their living mainly from agriculture and trout fishing. More recently there have been huge changes, beginning when the Kísilidjan diatomite plant started operation in the 1960s. It was the largest employer until it closed production, but there is still work at the power plants at Bjarnarflag and Krafla. Tourism has long been a mainstay in the Mývatn area, with several hotels, restaurants, campgrounds and other firms offering tourist services.

A new bathing pool with sauna has been built up in the area and is one of the tourist attractions.

The built up area including residential and industrial areas have been extracted from a SPOT satellite image by digitizing the relevant area in a vector map in ArcInfo and some of them have also been digitised from the land use map of the area that was available only for a small area in the central part (Gudmannsson and Jóhannsson, 1997). Map 16 shows the major built up parts of the study area.

5.2.7 Environmental suitability analysis

GIS offers a better way to find the right and minimum environmental effects of geothermal well targeting. In this analysis through GIS, integration of various layers became easy and it provides flexibility to change and add new layers.

As described already weighted overlay is a technique for applying a common scale of values to diverse and dissimilar inputs in order to create an integrated analysis and it has been used in this work.

The three input rasters including slope, vegetation cover suitability (generated from vegetation cover and cover density layers) and protected area have been reclassified to an evaluation scale of 9 to 0 and all three rasters are assigned the same percentage of influence (33.33%). The cell values are multiplied by their influence percentages, then the weighted overlay is run in spatial analysis and a raster of overall suitability is created.

Some parts of the area have been built up already as residential, industrial, tourist stop and farming areas, also there are some small lagoons; analysis is going to exclude these areas from the final selections. The built up data layer is used as a mask in the spatial analyst to exclude this area from any further calculations.

The raster map created was reclassified again into 10 different classes and the first five classes have been used as five priority areas in the next step. The last five classes and the built up areas have been discarded and are shown in the map in white. The most suitable classes are shown in dark green, the less suitable areas are lighter and white areas are excluded from the final calculation in the next step. Map 17 shows the classified environmental suitability in study area.

5.3 Final wells site selection (Decision-making)

Developing final selection criteria is the final task in the well site selection process. Criteria can be developed before, after, or concurrently with the site assessments and characterizations, because the development of the selection criteria is an independent process. Criteria should never be based on the availability of information about the sites.

The select criteria will vary and are usually very much dependent upon the goals of the project and on the conditions of the study area. The most successful selection criteria are scientifically and quantitatively based. Developing measurable criteria helps ensure the accuracy of the prioritization process and the likelihood of success.

To selecting well sites with minimum environmental effects, 30 % weighting has been given to "Environmental suitability" as this pertains to the key features of the sites. The 3D model elevation layer is also used in the final selection criteria with a 10 % weighting and the final exploration layer has a 60 % influence weighting.

The raster calculator of the spatial analyst is employed for the final site selection and the final raster map generated and the first three priorities are converted into a vector map. From the areas has been classified as priority one, two areas have been selected for targeting the wells in first phase of the project development. Map 18 shows the final selected area with suitable sites for exploration drilling.

6.0 POWER PLANT SITE SELECTION

6.1 Introduction

The size and arrangement of the power plant main building depend on the plant equipment and facilities selected including steam separators, generators, cooling tower, potential for future expansion, and aesthetic and environmental considerations. Generally, the main building will consist of a turbine bay with a travelling crane, pumps, and switchgear; a steam generator bay, and general spaces as may be required for machine shop, locker room, laboratory and office facilities. The general spaces will be located in an area that will not interfere with future plant expansion and isolated from main plant facilities to control noise.

As the selection of a plant site has a significant influence on the design, construction and operating costs of a power plant. The purpose of this work is to evaluate each potential plant site to determine which is the most environmentally suitable and economically feasible for the type of power plant being considered. Selection of the site will be based on the availability of usable land for the plant, including yard structures, fluid handling facilities, and any future expansion. Other considerations that will be taken into account in site selection are; air pollution, visual impact, vegetation cover and cover density, surface disturbance, noise impact, geological and natural risk, site drainage, distance to power transmission line, wind data, and so on. For economic purposes and operational efficiency, the plant site will be located as close to the well field as environmental conditions permit.

According to the Environmental Impact Assessment report (Landsvirkjun, 2003) three different power plant sites designated as sites A, B, and C, have been chosen for the Námafjall geothermal power plant with regard to topographical and geological conditions. Then, in this work the three power plant sites have been compared with regard to environmental impact, associated risk and economical evaluation and finally one of them suggested as a future site for plant construction. Figure 16 shows the proposed power plant sites and other related features of the Námafjall geothermal project.

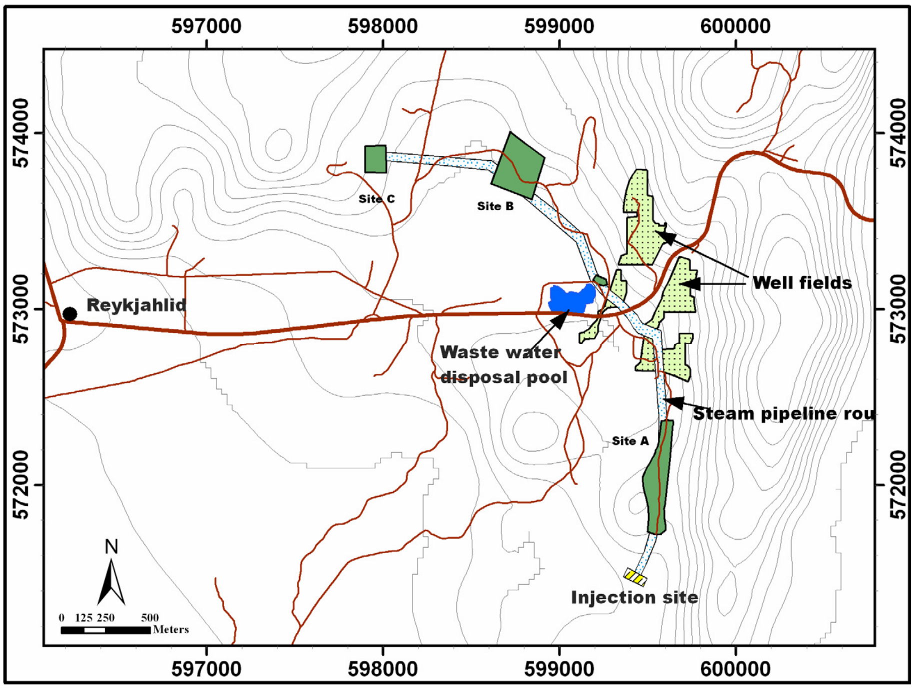

FIGURE 16: Proposed power plant sites and other related features (Based on Landsvirkjun, 2003)

6.2 Methodology of site evaluation

For evaluating the proposed power plant sites several components are taken in account and Matrix analysis is employed for the final selection process. Thirteen different factors including air pollution, visual quality, vegetation, waste water, noise, land stability and subsidence risk, slope and surface disturbance, geology and natural risk, faults and natural risk of pipelines, land use or operation area, distance to production field, required access road and transmission line, which are important environmentally and economically are selected. The percentage importance of those 13 factors with respect to other factors is also defined in the final matrix analysis. Every factor for each site is also analyzed by GIS, compared with other sites, weighted and finally the aggregated weighting are used for decision making on the suitability and ranking of sites. Totally the site selection processes are used sitting criteria to:

- Comparison of every factor in each site.
- Determination of which factors of importance were considered
- Understand why particular sites were chosen.
- Comparison of sites with best available site in the study area

6.3 Environmental considerations

All power plant design, regardless of the type of power plant, must be in accordance with the rules and regulations which have been established by national and local governments. To meet various environmental regulations, it is often necessary to utilize design features that will greatly increase the cost of the power plant without increasing its efficiency. For example, the cost of the pollution control equipment that will be required for each site under consideration is one such item which must be carefully evaluated.

The environmental considerations are important in power plant site selection, because the wrong power plant site will have great environmental effects on surrounding ecology and human communities and compensation for future impacts would need a large amount of investment and time. Several environmentally important factors are considered in power plant site selection; important ones including air pollution, visual quality, vegetation cover, soil investigation, waste water disposal, noise impact, land suitability and subsidence risk, and slope are taken in account in this work. Every factor is analyzed in a defined area and then weighted.

6.3.1 Air pollution

Geothermal power generation is often considered as a clean alternative to fossil fuel or nuclear power plants. But it is necessary to survey the effect of geothermal air pollutants on the atmosphere. Geothermal power generation using a standard steam cycle plant will result in the release of non-condensable gases, and fine solid particles into the atmosphere. Air pollution is dispersed by the wind in the area and thus the wind patterns define the directional of pattern pollutant dispersal. In the current study the background concentration of H_2S in the area has been measured and modelled and meteorological data has been obtained from the Meteorological Office of Iceland for predicting future pollution pathways.

In the proposed 90 MWe Námafjall power plant spent geothermal fluid will be partly discharged to the environment after use and partly injected into injection wells, but most part of the gas will be released to the environment from a cooling tower. The yearly emission of each gas from the power plant can be calculated from total fluid flow rate, gas fraction of the fluid and the concentration of each gas in the fluid. For the proposed Námafjall power plant the total volume of gases has been estimated from the total flow rate of fluid and predicted gas fraction. Table 16 shows the annual estimated gas discharge from power plant.

TABLE 16: Annual estimated gas emission from Námafjall power plant

Gas	Current 3 MWe power plant (Tonnes/year)	Proposed 90 MWe plant (Tonnes/year)
CO_2	2000	19200
H_2S	500	8700

Background H_2S model

The atmospheric H_2S concentrations in the area have been measured using the hydrogen sulphide analyzer, Jerome 631-X portable instrument with the analysis range of 0.003 – 50 ppm in area in Mid-November, 2004 in calm weather conditions at 34 points distributed over the whole study area. For each point the measurement was carried out 3 times and average values used for the concentration of the gas at each point. The locations, the exact measured and average concentrations at each measured point are shown in Table 17. To establish the surface dispersion, Surfer, version 8.0, has been used to make a dispersion model using the Krigeing method. Figure 17 shows the H_2S dispersion model for the Námafjall area. It is clear that most of the naturally emitted H_2S is dispersed in the western part of the area, which is not inhabited. It shows that the naturally emitted H_2S is not problematic in the area but care should be taken that it does not suffer from air pollution after the new power plant installation.

TABLE 17: Atmospheric concentration of H_2S in Námafjall area, November 2004

Point ID	X	Y	Concen. (ppb)	Point ID	X	Y	Concen. (ppb)
1	416818	7281140	0	**18**	414677	7281207	14
2	416763	7281170	17	**19**	414881	7281147	1
3	416674	7281129	247	**20**	415038	7281150	7
4	416595	7281095	137	**21**	415143	7281176	9
5	416576	7281029	450	**22**	415157	7281266	50
6	416557	7280964	108	**23**	415067	7281405	2
7	416645	7280948	10	**24**	415105	7280951	21
8	416749	7280944	2	**25**	414749	7280990	2
9	417301	7281547	2	**26**	415400	7280551	11
10	416147	7281781	0	**27**	415385	7280753	59
11	415650	7281263	33	**28**	415097	7280746	48
12	414662	7281512	4	**29**	414960	7280043	1
13	414902	7281586	7	**30**	414530	7281004	44
14	414788	7281499	1	**31**	414186	7281014	23
15	414625	7281452	3	**32**	412085	7281105	27
16	414518	7281405	6	**33**	412748	7281006	19
17	414549	7281296	11	**34**	413866	7281007	17

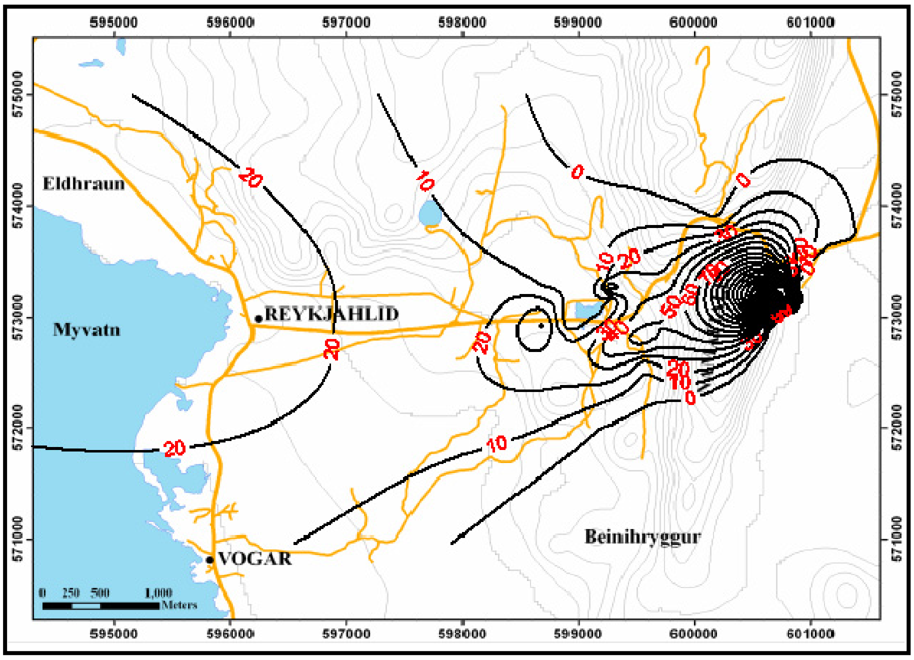

FIGURE 17: Background H_2S distribution model in the Námafjall area

Wind pattern and direction of pollution distribution
Wind pattern has a major role in the dispersion of air pollution from the power plant to its vicinity and most of the pollution is distributed over the area according to the wind pattern. In this study meteorological data for 5 years from 1999 to 2003 have been obtained from the Icelandic meteorological office for the Mývatn station (station no 4300) which is the nearest one.

A wind rose diagram was drawn for each year separately by Grapher, version 4.0, to establish the major wind pattern in the area. Figure 18 shows the wind rose diagram, for five years, from 1999 – 2003. This figure clearly shows that the major wind patterns are similar during the last years with avoidable difference and the wind direction is mostly from north to south. As is mentioned earlier, pollution distribution follows the wind pattern. Thus most of the pollution from each proposed power plant site will travel south, northwest and northeast. Figure 19 shows the probability of pollution dispersion from each proposed power plant site. If it is assumed that the power plant characteristics are same in all three sites. More pollution from site C would reach the Reykjahlíd area than from the others due to the shorter distance and dominate wind direction. With regard to air pollution proposed site A is best with a relative value 9, site B comes second with the relative value 8 and site C, is assigned the relative value 6.

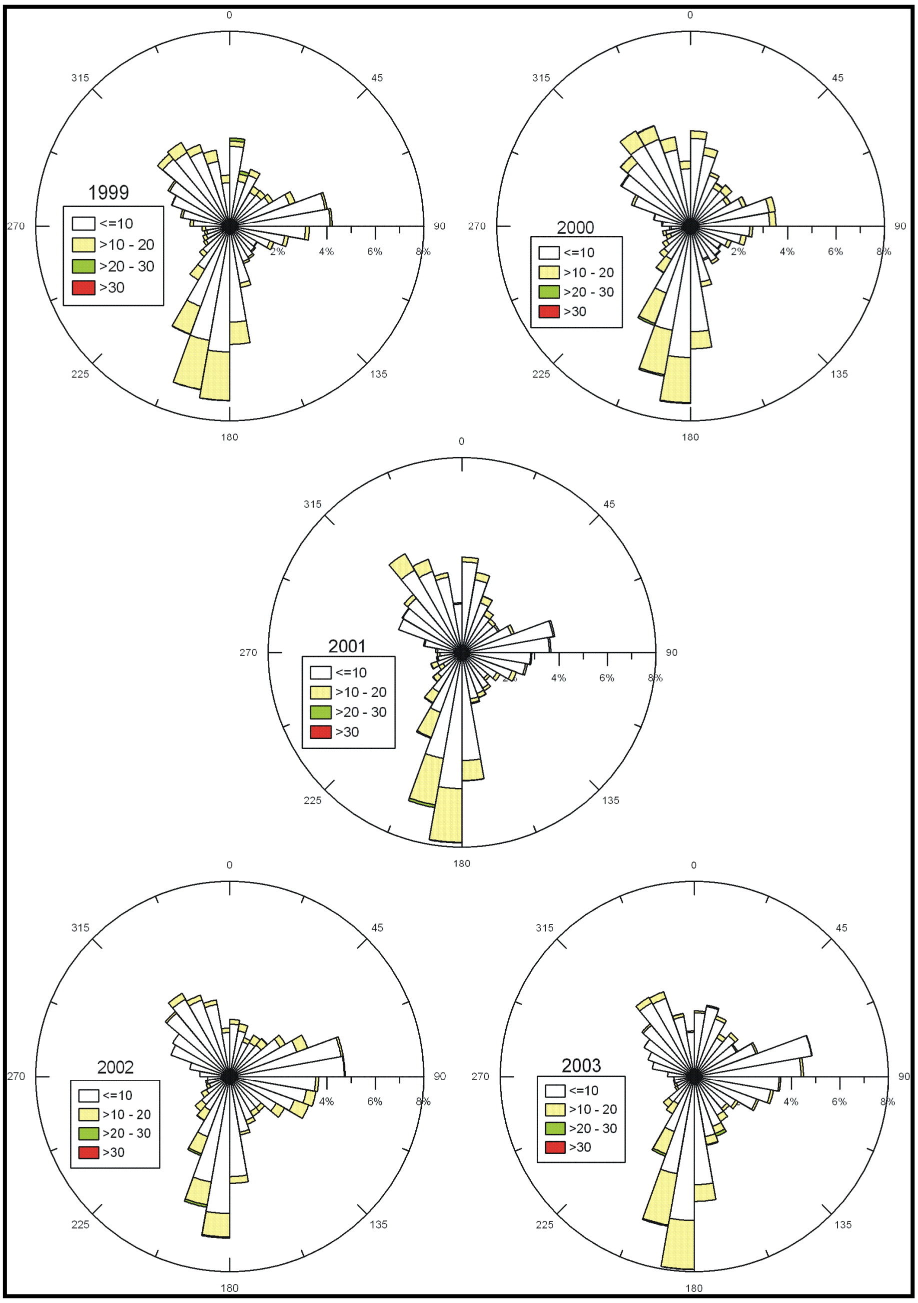

FIGURE 18: Wind rose diagram, for five years, 1999-2003

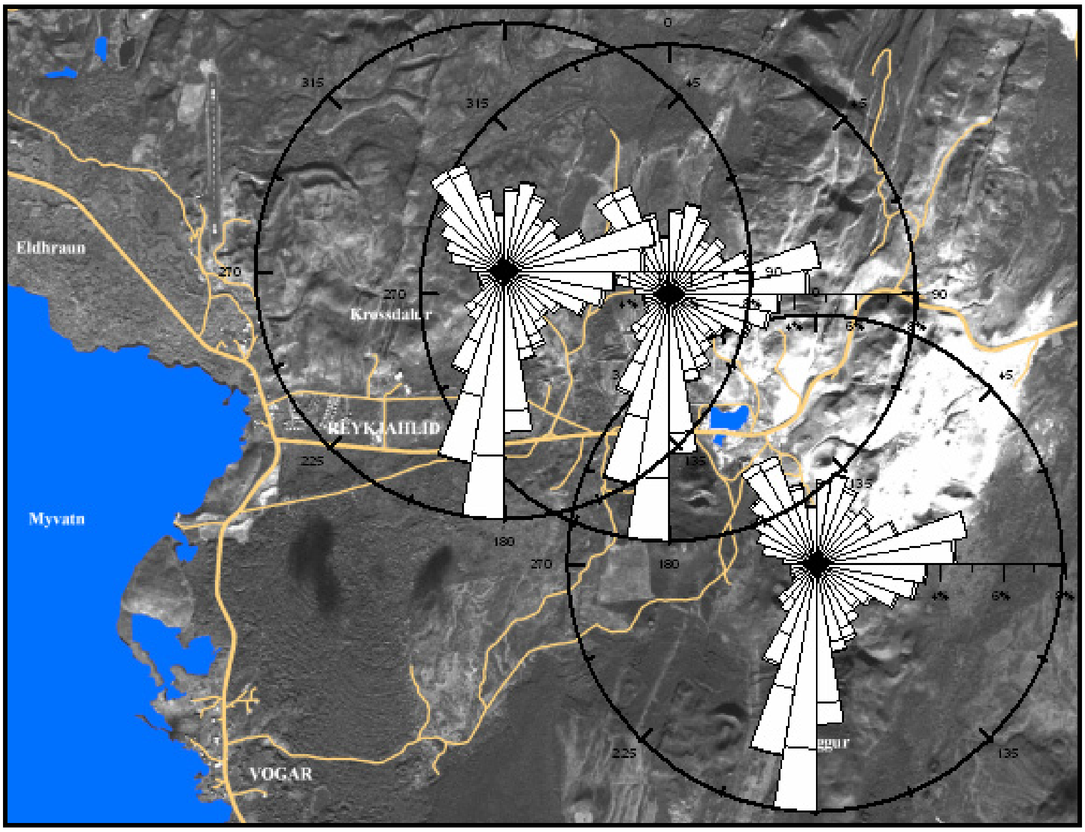

FIGURE 19: Probability of pollution dispersion from each proposed power plant site

6.3.2 Visual quality

Visual perception is an important component of environmental quality that can be affected by construction projects. The location, design, and/or maintenance of power plant facilities may adversely affect visual features of the landscape, and concern over adverse visual impacts can be a source of opposition to a project. In geothermal projects the visual quality may be diminished by loss of naturalness and the imposition of man-made structures like drill sites, drilling rig, and accessories creating artificial landscape elements in the project area, but all these are temporary and disappear when drilling is completed. The power house and related facilities are the main man-made structures which will be present in the area for the whole project lifetime and consideration of its visual impacts is very important, because natural geothermal manifestations such as hot springs, fumaroles, mud pools and boiling pools are attractions for tourists. Geothermal areas are much visited by tourists in any country and for protecting the attraction of the area particular attention to the visual effects of a geothermal power plant is necessary.

The visual impact assessment of a proposed development addresses three types of issues: spatial, quantitative and qualitative. Spatial issues include from where the development is visible or, more specifically, to whom it is visible quantitative issues include what part of the development is visible, what part of the surrounding area is affected and to what degree; and qualitative issues include the visual character of the development and its compatibility with its surroundings.

The principle of indivisibility states that visibility is determined in two ways either from the site or to the site. It includes both being viewed from outside the development area and the outside view from the site developed to adjacent areas. In GIS's 3D analysis extension, they are both calculated with respect to Viewshed. Viewshed includes all visible or invisible area in the sites from given viewpoints or view corridors (ESRI, 2002).

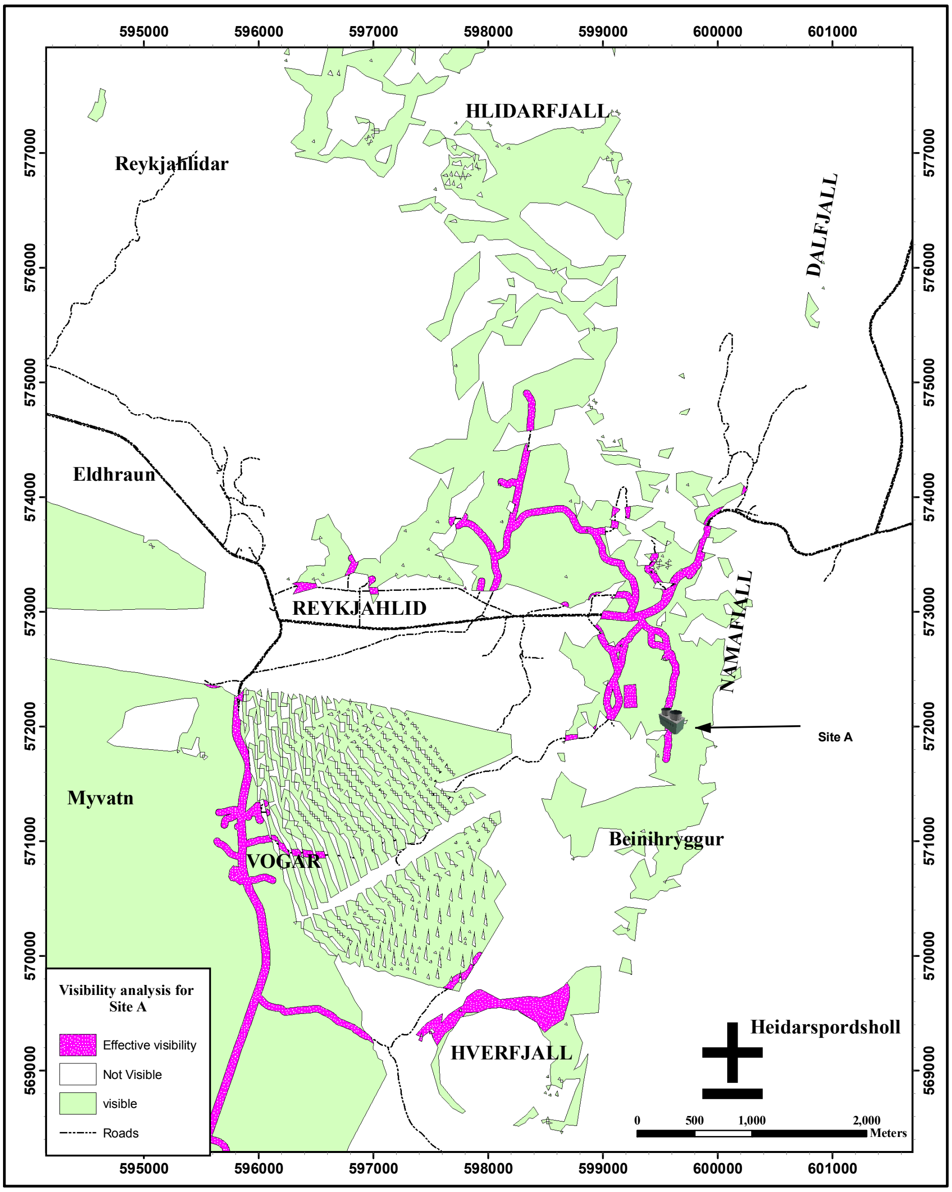

FIGURE 20: Visibility and effective visibility map for site A

The viewshed identifies the cells in an input raster that can be seen from any observation points in defined area. Each cell in the output raster receives a value that indicates whether the given location can be seen from the observation points or not. If you only have one observation point, each cell that can be seen from the observation point is given a value of 1. All cells that cannot be seen from the observation point are given a value of 0.

The viewshed is useful when it is necessary to know how visible objects might be - for example, it may be necessary to know "From which locations in the landscape the power plant will be visible if it is placed in a certain location". Displaying a hillshade underneath an elevation layer the output from the Viewshed function gives a very realistic impression of the landscape and clearly indicates what locations an observer can see from the observation point (ESRI 2002).

To find the best site of visual quality among the three proposed power plant sites detailed modelling has been carried out by ArcInfo-3D Analyst. The shape of the surface terrain dramatically affects what parts of the surface someone standing at a given point can see. 3D Analyst allows the determination of visibility on a surface from point to point long a given line of sight, or across the entire surface in a

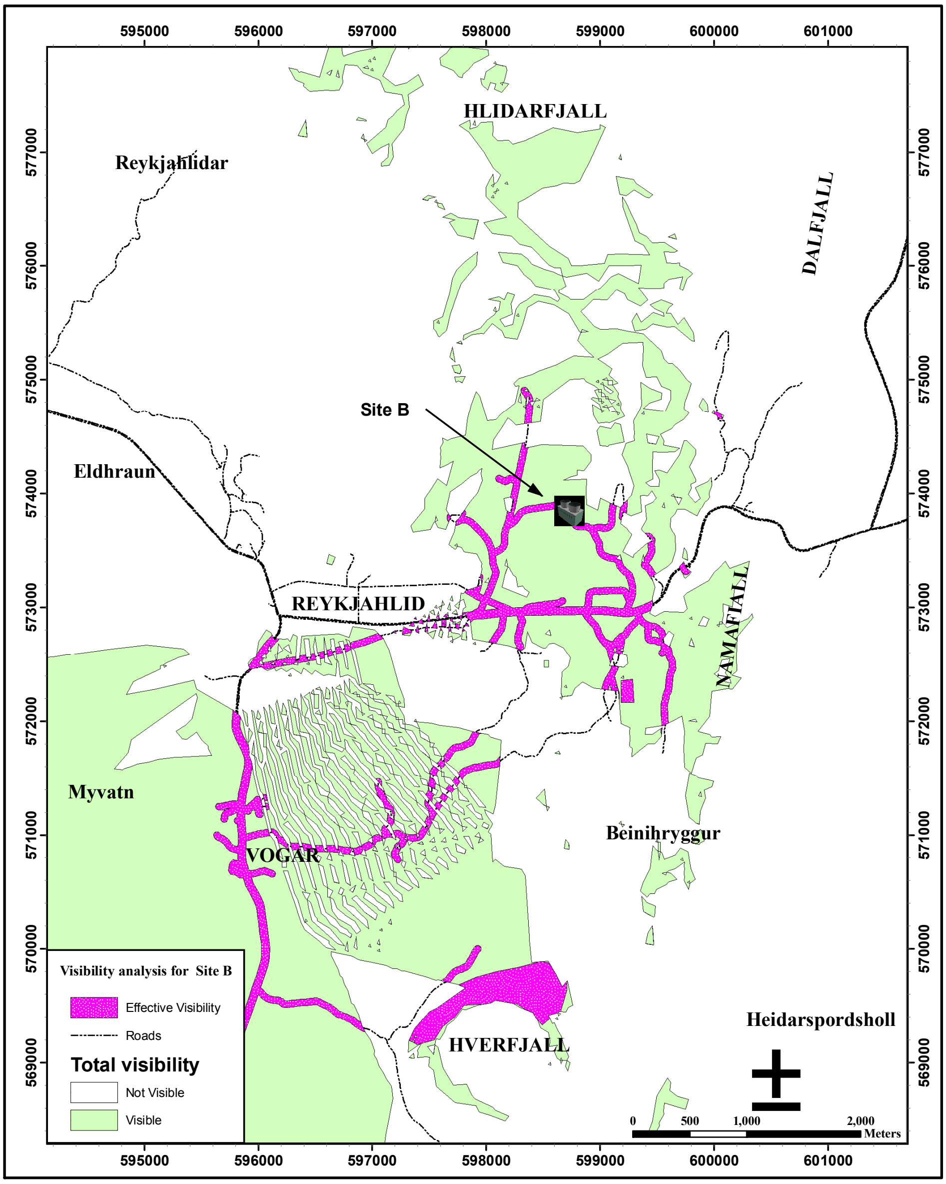

FIGURE 21: Visibility and effective visibility map for site B

viewshed. It is assumed that the whole site area defined has been occupied by the power plant facilities and a 15 m height defined for the power plant and 1.6 m height for the viewer. The viewshed analysis has been carried out and the visible areas are coded 1 and non-visible areas got code 0. The raster map generated was converted to a vector map to calculate the whole area covered by each category. This map shows completely from which part of the area the given power plant is visible.

It is also important to find out how visible the power plant is from the areas that are frequented by tourists and from residential areas. This is called "effective visibility" in this study, because the importance of all areas is not the same and some parts are more important than others. The area close to the main roads (visitors passing by road), tourist stop areas, and residential areas are the most important for effective visibility analysis. Thus, to calculate the effective visibility, a 30 m buffer is generated on both sides of main roads and tourist stop areas and a residential area are added to the generated buffer area and is called the area more important for visibility analysis. The part of the total visible area this defined area constitutes has been calculated in the last step for each site separately and the new defined area called effective visibility. The visibility map of the study area for the three proposed sites is shown in Figures 20-22. Table 18 shows the total visibility and effective visibility area for each power plant site. The evaluation and given relative value for each site are also shown in

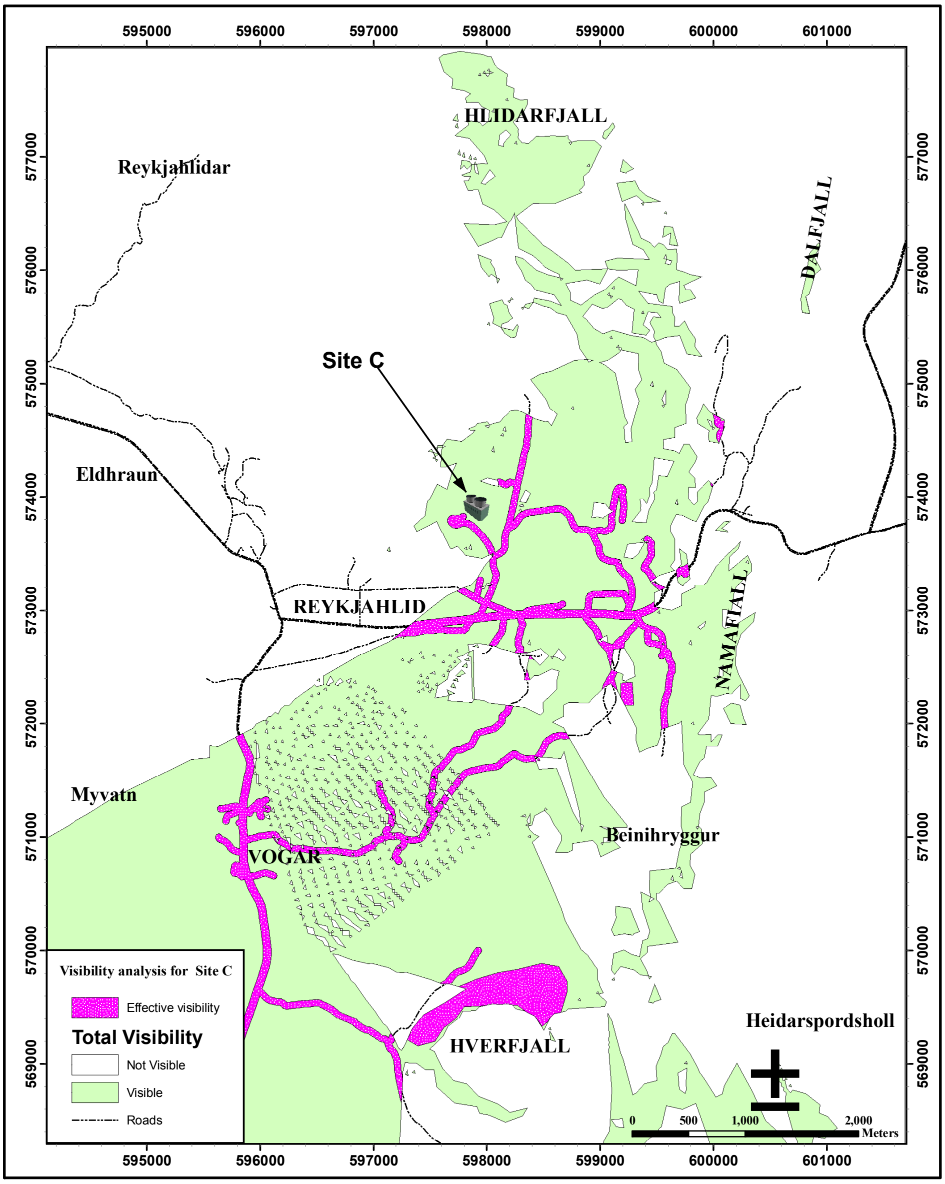

FIGURE 22: Visibility and effective visibility map for site C

table. Figure 23 shows the comparison histogram of visibility analysis for the three proposed power plant sites. According to visibility analysis site A is best and site C worst. Though, the total visible area for site A is larger than that for site B the effective visibility for site A is smaller than that of sites B and C.

TABLE 18: Area of total visibility and effective visibility with evaluation and relative values

Sites	Total visibility (km^2)	Effective visibility (km^2)	Evaluation	Relative value
Site A	21.95	1.42	Ideal	9
Site B	20.9	1.89	Good	6
Site C	24.4	2.10	Poor	3

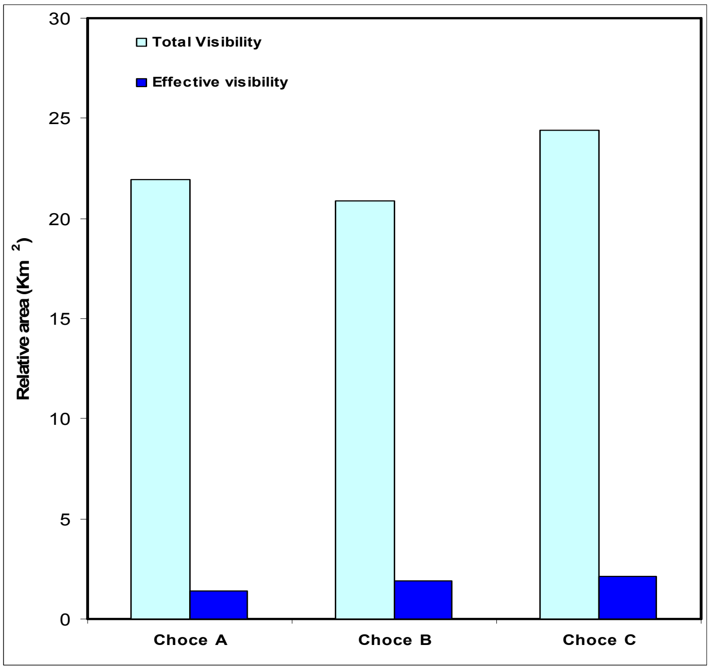

FIGURE 23: Visibility analysis for the three proposed power plant sites

6.3.3 Vegetation cover

The vegetation cover will be damaged during power plant construction in the proposed sites For reducing the environmental impacts of geothermal power plant construction, it is important to install the power plant in an area with plant species of relatively small importance from cultural, economical and scientific points of view, and it is better to locate the power plant in an area with minimum vegetation cover density. For addressing the prospect conditions, the plant cover and cover density of each of the three sites are extracted by clip analysis of ArcInfo from the main vegetation cover and the cover density map which was presented in the last chapter. The plant cover for those sites is shown in Figure 24 and a vegetation comparison histogram is shown in Figure 25. The types of plant in each area with relative cover area, evaluation and relative value for each site as plant cover and cover density are presented in Table 19. Site B is the best location and site C is the worst according to vegetation cover.

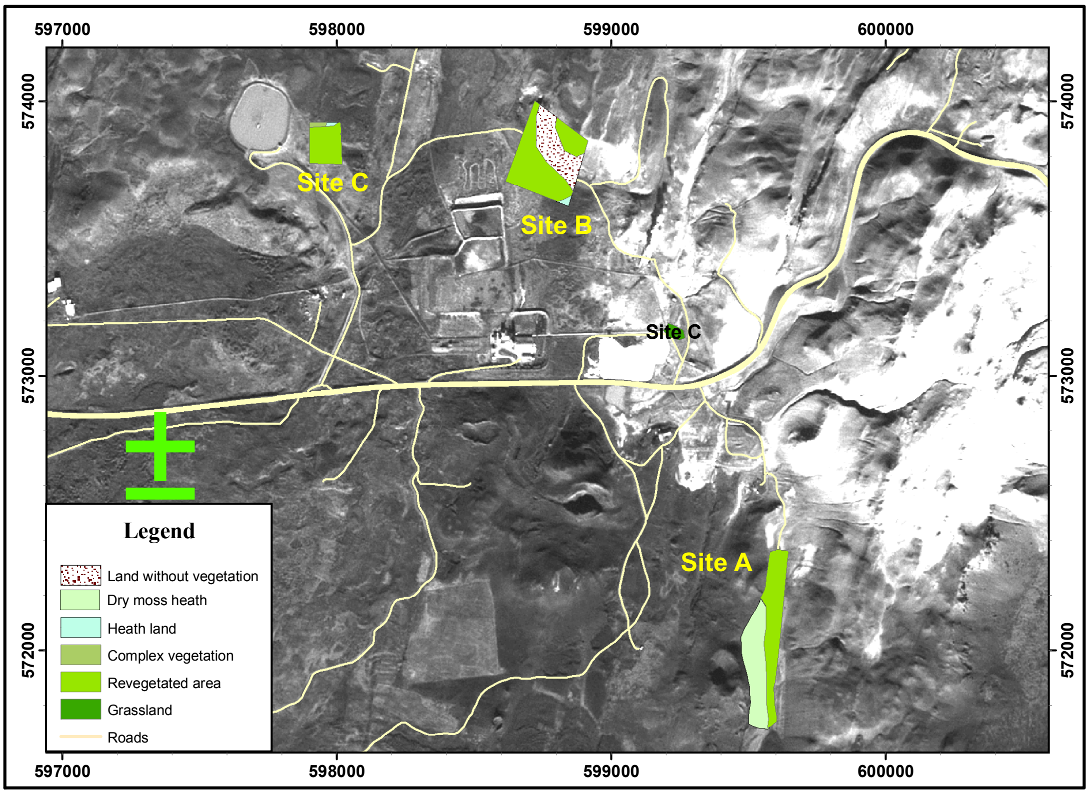

FIGURE 24: Vegetation cover map of the three proposed power plant sites

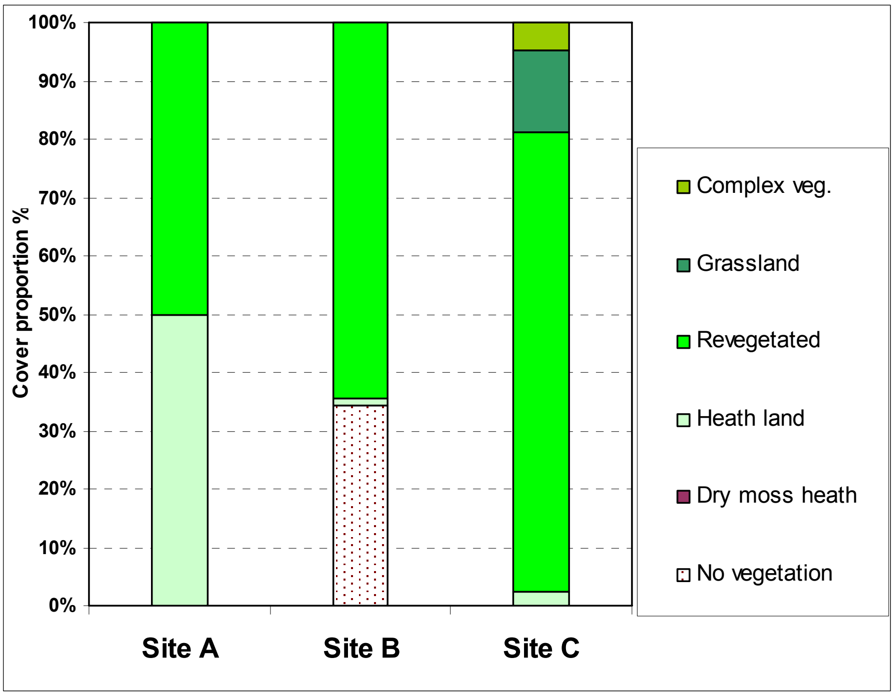

FIGURE 25: Vegetation cover comparison histogram for the three proposed power plant sites

TABLE 19: Type of vegetation cover in each site with relative covered area (m^2), evaluation and relative value for each site

Power plant Sites	No vegetation	Dry moss heath	Heath land	Re-vegetated	Grassland	Complex vegetation	Evaluation	Relative value
Site A	-	33,074	-	33,396	-	-	Good	7
Site B	23,048	-	937	43,260	-	-	Ideal	9
Site C	-	-	464	16,186	2,897	959	Poor	4

6.3.4 Waste water

During the operation phase of geothermal power plants, impacts on the quality of surrounding surface or ground water in the shallow aquifer would not be expected during normal production and injection practices. The injected fluid would be released to the geothermal reservoir, which is not connected to the shallow ground water system. However, impacts could be experienced during the operation phase due to mixing of the geothermal fluid in the shallow groundwater aquifer through damaged well casings or accidental discharge of geothermal fluids to the surface. The local water quality could be affected if the well casing failed. Accidental discharge of geothermal fluids to surface drainage could occur due to blowouts during drilling, leaking pipes or wellheads, and overflow from well sumps. In some power plants the volume of injected fluids is not same as that of production fluid, thus the fluid is partially released into surface water bodies.

According to the flow diagram of proposed power plant in Námafjall 237 kg/s effluent water will produce in power plant. The waste water will be partially (60 kg/s) injected into injection wells in the southern part of Site A, and the part (177 kg/s) will be discharged into the Bjarnarflagslón (a small lake nearby) and finally flow through fractures and faults toward Lake Mývatn (Landsvirkjun, 2003). There is concern about the possible effect on the extraordinary nature and wildlife in and around Lake Mývatn only 2 km away from the Námafjall geothermal field. It is still considered important to evaluate the possible effect of increased geothermal development on the biology of the surrounding area. Careful monitoring of the biological effects of these effluents is highly recommended.

In the proposed project an area in the southern part of the proposed Site A has been selected for injection of effluent geothermal fluids and the lake Bjarnarflagslón is suggested to receive part of the effluent. In this part of the report the distance of each proposed site to the proposed injection site and discharge lake which is important economically and environmentally will be analysed. Figure 16 shows the location of the three proposed sites, the injection area and the Bjarnarflagslón pool. According to the proposal the injection site and effluent water surface discharge area are similar for the three proposed site from the environmental point of view, to evaluate the 3 proposed sites from an economical point of view, the distance to the injection area and Bjarnarflagslón pool are used as criteria for evaluating the sites, because with increased distance the cost and natural risks for a pipeline increase.

Table 20 shows the distances of the proposed sites to the injection and surface discharge areas, evaluation and relative given value for each site. The results are plotted in Figure 26 for distance to injection and Bjarnarflagslón for each site. According to these criteria site A is the best one and site C the worst.

TABLE 20: Distance of each proposed site to the injection and Bjarnarflagslón lake, evaluation and relative given value

Sites	Distance to the injection site (m)	Distance to the Bjarnarflagslón (m)	Evaluation	Relative value
Site A	600	1300	Ideal	9
Site B	2670	840	Good	7
Site C	3460	1600	Poor	6

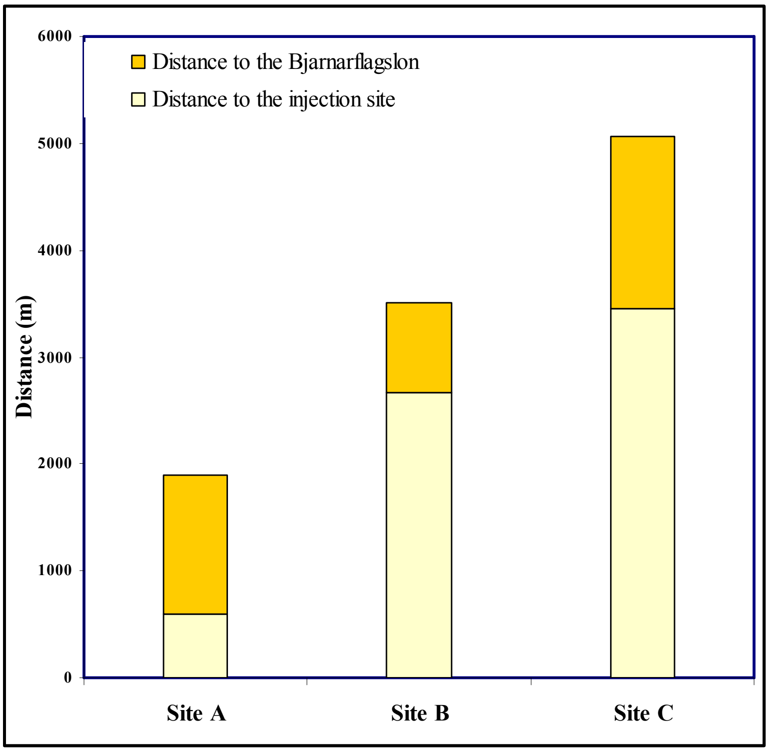

FIGURE 26: Histogram for distances to injection area and surface discharge area for each of the three sites

6.3.5 Noise impacts

Noise is a sound which is unwanted or not desired and which may disrupt or degrade human activities. During exploration for geothermal resources no environmentally significant noise is created.

Noise is of particular concern to nearby residents. Information of interest includes noise caused by plant construction and operations, distance of noise sources from sensitive locations such as tourist attractions and residential areas, and applicability of local noise regulations or other thresholds. Generally, more desirable sites maximize the distance between the noise source and the public, have landscape features that would absorb noise between the plant and the public, and have no receptors within any areas where noise guidelines or regulations are exceeded. It is preferred that no sudden, loud, or unpleasant noise be perceptible to most people in the area.

Noise is one of the most ubiquitous disturbances to the environment from geothermal development, particularly during the construction and operation phases. Many geothermal developments are in remote areas where the natural level of noise is low and any additional noise is very noticeable. Residents in such areas will probably regard any noise as an intrusion into their otherwise quiet environment. Animal behaviour is also affected by noise with reports of changes in size, weight, reproductive activity and behaviour (Brown, 1995).

The noise from the initial discharge of wells is intense and can create annoyance at a distance of several kilometres. It may affect birds and animals in the district as well as concern local residents. Unsilenced geothermal wells may produce noise levels of up to 120 decibels overall in their vicinity, and to prevent damage to hearing, workers must wear ear protectors. Using cylindrical type silencers the noise can be brought down to about 85 dB.

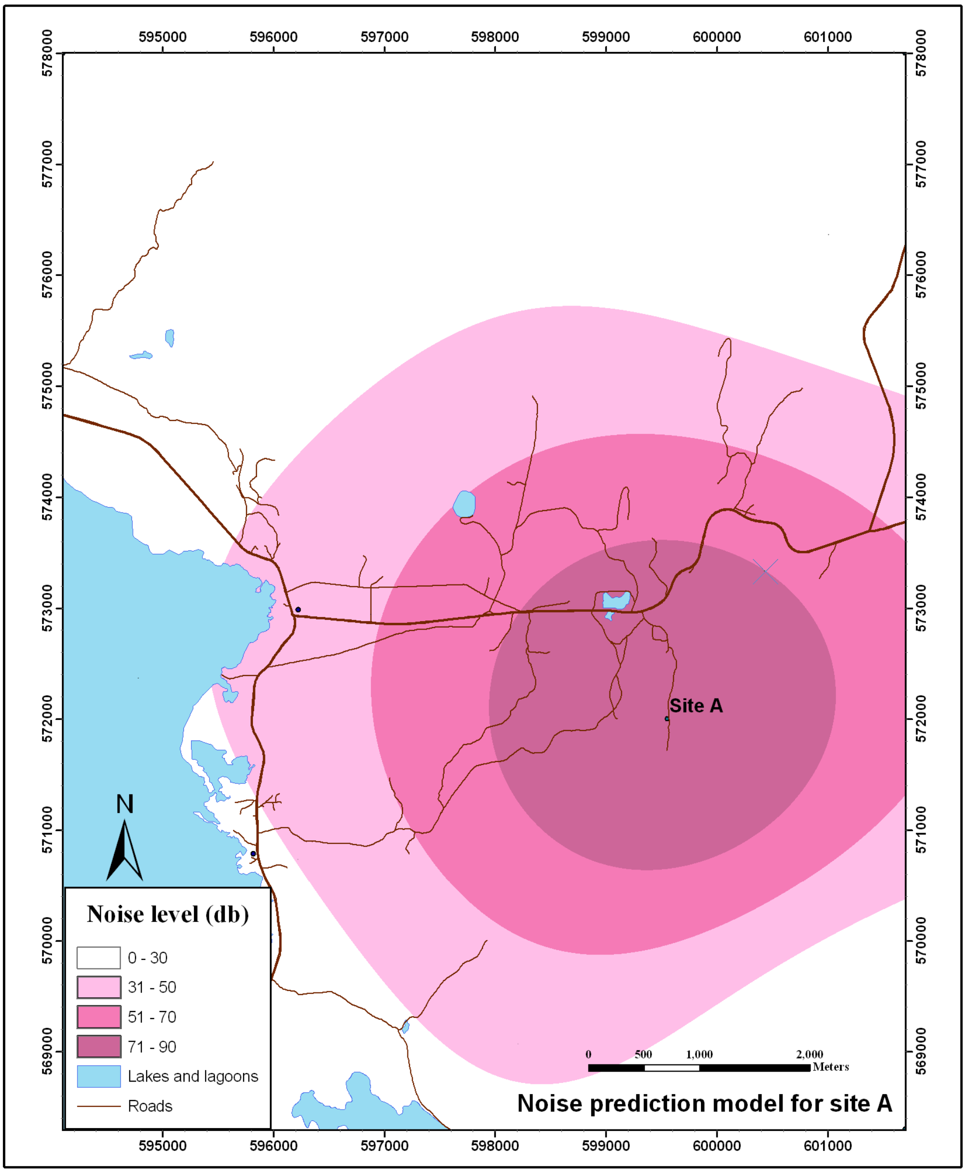

FIGURE 27: Predicted noise dispersion model from proposed power plant site A

Most of the noise from power plant operations results from the three power plant components: the cooling tower, the transformer, and the turbine-generator building. Once the plant has started operation, noise mufflers can be made effective enough to keep the environmental noise below even the 65 dB limit set by the U.S. Geological Survey (D'Alessio and Hartly, 1978).

Noise level prediction is a widely used tool for predicting the noise impact of changes in the noise environment, such as land development, changes to machinery or building use. This technique is also used to plan or design environments where noise management is necessary.

A noise dispersion model was developed using the ArcMap - Spatial analyst by using the Inverse Distance Weighted (IDW) method. The noise level decreases by the power 2 with distance ($1/r^2$). The noise levels were computed for each of the three sites. Figures 27-29 show the result from the dispersion model of the noise from sites A, B and C, respectively. Based on the model the sites are ranked. For ranking of the sites the predicted noise level in the area has a main role. Site A has minimum effects on residential and tourist attraction areas and got the best rank and relative value 9, site B is second with relative value 8 and site C is number three assigned the relative value 6.

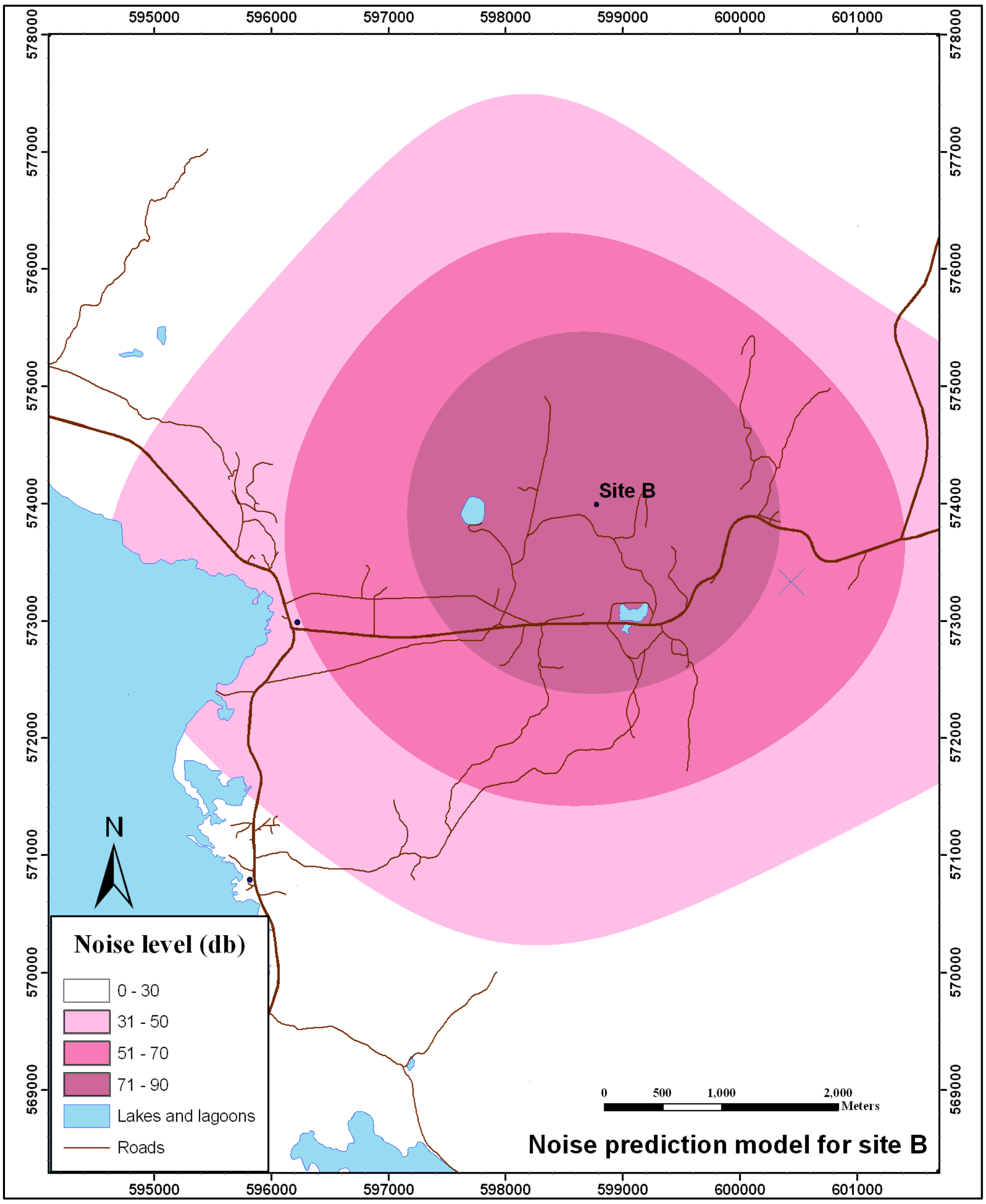

FIGURE 28: Predicted noise dispersion model from proposed power plant site B

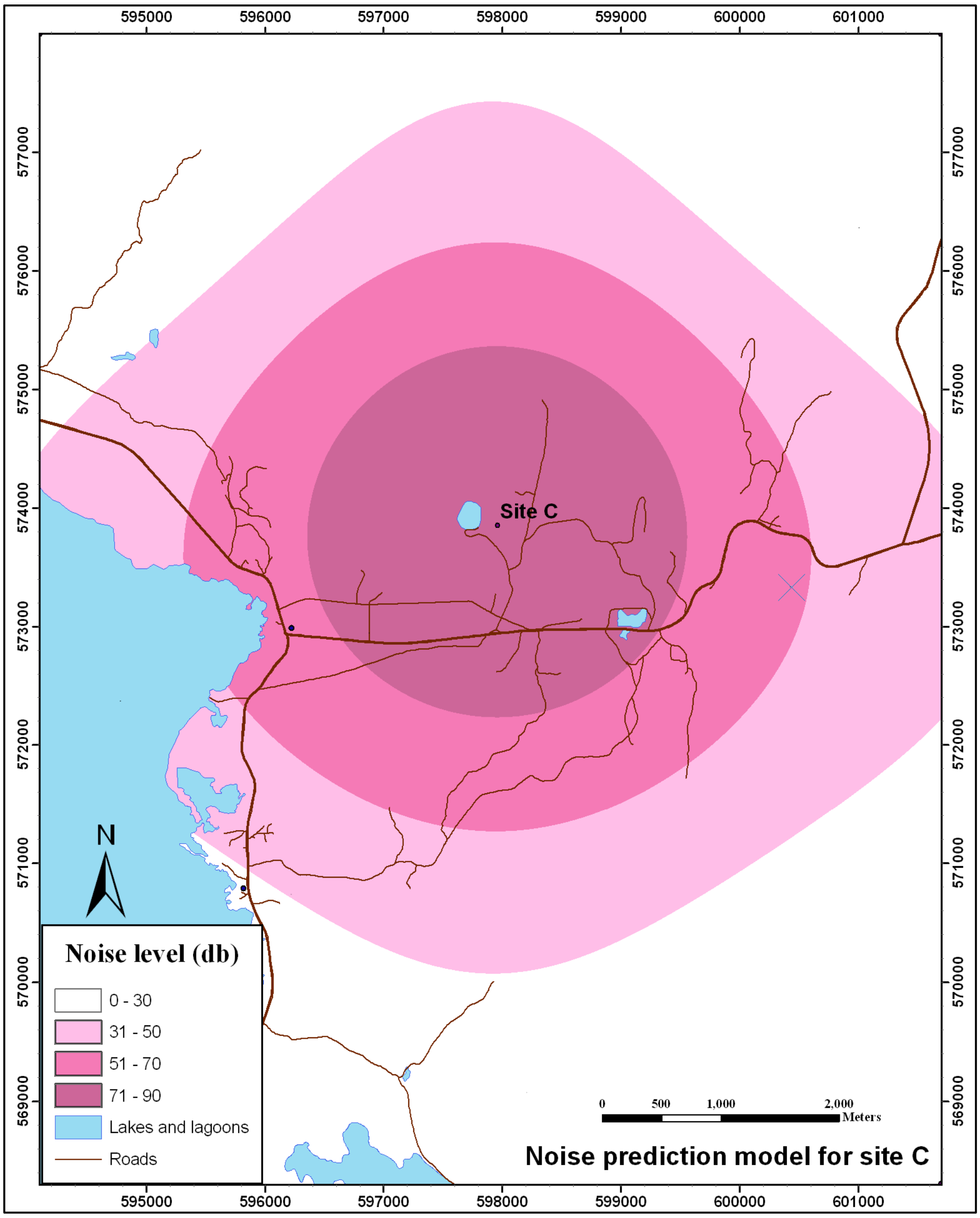

FIGURE 29: Predicted noise dispersion model from proposed power plant site C

6.3.6 Land stability and subsidence risk

As described in Section 3, subsidence is one of the important geothermal environmental impacts and attention to it increased when a 40 cm/year land subsidence was reported that in Wairakei geothermal field in New Zealand (Hunt and Brown, 1996). The subsidence intensity is highly related to the geological and reservoir condition, and production strategies. In Icelandic geothermal fields subsidence is very low, for example at Svartsengi, land has subsided over an area of 100 km^2, which is much more extensive than the borefield, where the subsidence is highest, i.e. 237 mm from 1976 to 1999. This corresponds to 10 mm/year. Subsidence rate was highest right after the exploitation started in Svartsengi in 1975 or 14 mm/year, but decreased to 7 mm/year during the time period from 1987 to 1992. From 1992 to 1999 the subsidence rate has increased again to 14 mm/year (Eysteinsson, 2000).

There is no proven method to predict the location of prospective land subsidence in a geothermal site, but it is reasonable to assume that the area of high risk where subsidence likely is a highly altered low- resistivity area from which the geothermal fluid is mainly extracted. To analyse the probability of subsidence in the three prospected power plant sites, a TEM-resistivity anomaly map and a map of intensity of alteration have been used. It is assumed that the subsidence risk is greater in these areas than others especially in areas where both are present. Figure 30 shows the location of the three proposed power plant sites, the altered area and the geophysical anomaly area. The three proposed sites are not located in highly altered areas but the location of site B is in a relatively highly altered area. As regards geophysical anomaly site A is mostly outside the anomaly area, site C is closer to the margin of the anomaly and site B is located inside the anomaly area, thus as regards subsidence risk site A is located in best area and the relative value 8 has been assigned to it, site C got the relative value 7 and for site B the relative value 4 was suggested.

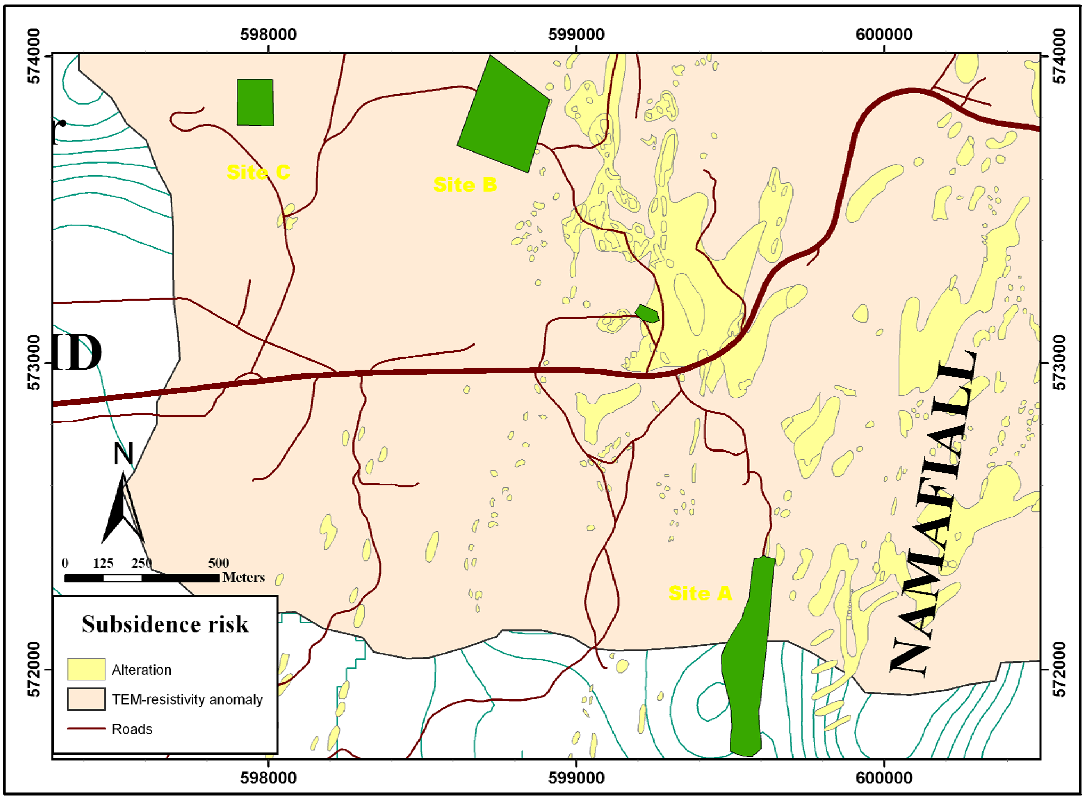

FIGURE 30: Location of the three proposed power plant sites with respect to the altered geophysical anomaly area

6.3.7 Slope and surface disturbance

Slope is one of the key factors in construction and development of projects. An area with a high slope causes more disturbance to the surface not only more negative effects on the environment such as vegetation losses, topographical changes, dust creation and soil disturbance and changes, but also increased cost for project developers. Thus a power plant site with a low slope is preferable to an area with a high slope.

The digital elevation map of the area was used for slope analysis of the sites in question. First using the ArcToolbox –extract raster by points. The DEM images related to each proposed power plant site are extracted and the slope for each site calculated by the method that was introduced in the previous chapter and finally the average slope for each site was calculated and used for evaluating each site. Figure 31 shows the result of the slope analysis for each site and Table 21 shows the area occupied by each class of slope, evaluation and assigned relative value.

TABLE 21: Area occupied by each class of slope, evaluation and assigned relative value

Sites	0-5 % (m^2)	5-10 % (m^2)	10-15 % (m^2)	15-50 % (m^2)	Evaluation	Relative value
Site A	24575	24108	5503	9995	Poor	6
Site B	48624	5332	7885	5542	Good	7
Site C	15471	5051	0	0	Ideal	8

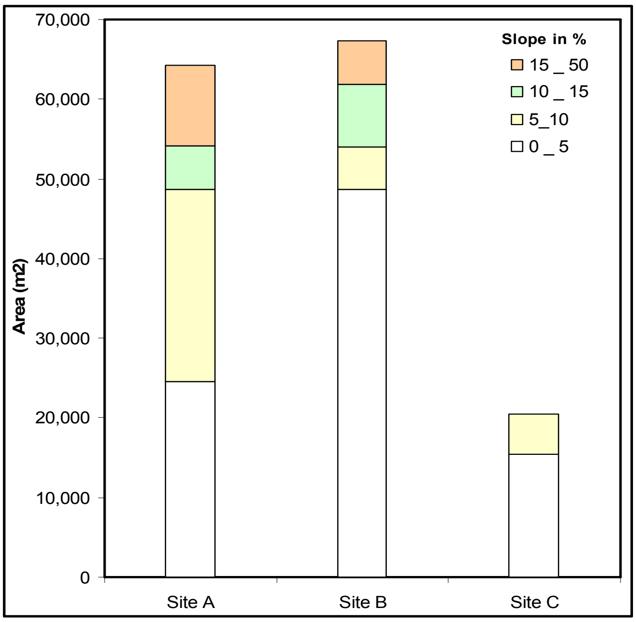

FIGURE 31: Slope class proportion in proposed power plant sites

6.4 Risk potential and economic considerations

6.4.1 Geology and site stability risk

The physical capabilities of various geological formations are different for particular land uses especially for heavy foundation. Many additional factors that influence land surface conditions vary considerably within individual terrain units and thus cannot be adequately assessed in a general manner. According to the geological map of the study area site A is located mostly in the "Lava with Phenocryst" geological unit, site B is located partially in the "Gravel terraces" unit and partially in new "Lava" also and site C is located totally in the "Gravel terraces" unit. It is clear that the mechanical strength of a lava formation for heavy construction is greater than that of the gravel terraces, Thus with respect to material strength from simple analysis the site A is best location with an assigned relative value of 9, site B is second with a relative value of 7 and site C is worst with an assigned relative value of 5.

Key factors involve ensuring whether there is or isn't a geological risk for a proposed power plant site to be perturbed by active faults, volcanic activity and hydrothermal eruption. The sites are evaluated on the basis of geological stability, an understanding of the long term plate-tectonics and the probability of occurrence of eruptions. The areas are assigned weighting values which could potentially be influenced by future activity around volcanic craters or by the active rift.

Igneous activity, including magmatic intrusions, volcanic eruptions and thermal and hydrothermal activity, may cause direct damage to the power plant and other facilities. Magmatic intrusions and volcanic eruptions caused by magma rising from deep underground chambers have to be avoided, as these phenomena may cause significant direct damage to a power plant. For this reason, areas that may be subject to volcanic activity (e.g. volcanic craters) are subject to higher risk than other areas because it is reasonable to expect the probability of a volcanic eruption in the next years to be limited to locations that have been active in past. With regard to craters the three sites are similar with craters close by, but with regard to fractures and faults site A is best situated because it is located in the marginal part of the active rift and the relative value 9 has been assigned to it, Site C is second because it is located in a less fractured area than site B, with a corresponding relative value 7 but site B is intersected by several faults and fractures (see Figure 32) and the relative value of 4 has been assigned to it. The total relative values given with respect to geological unit and natural risk have been averaged and are for sites A, B and C 9, 5.5 and 4.5 respectively.

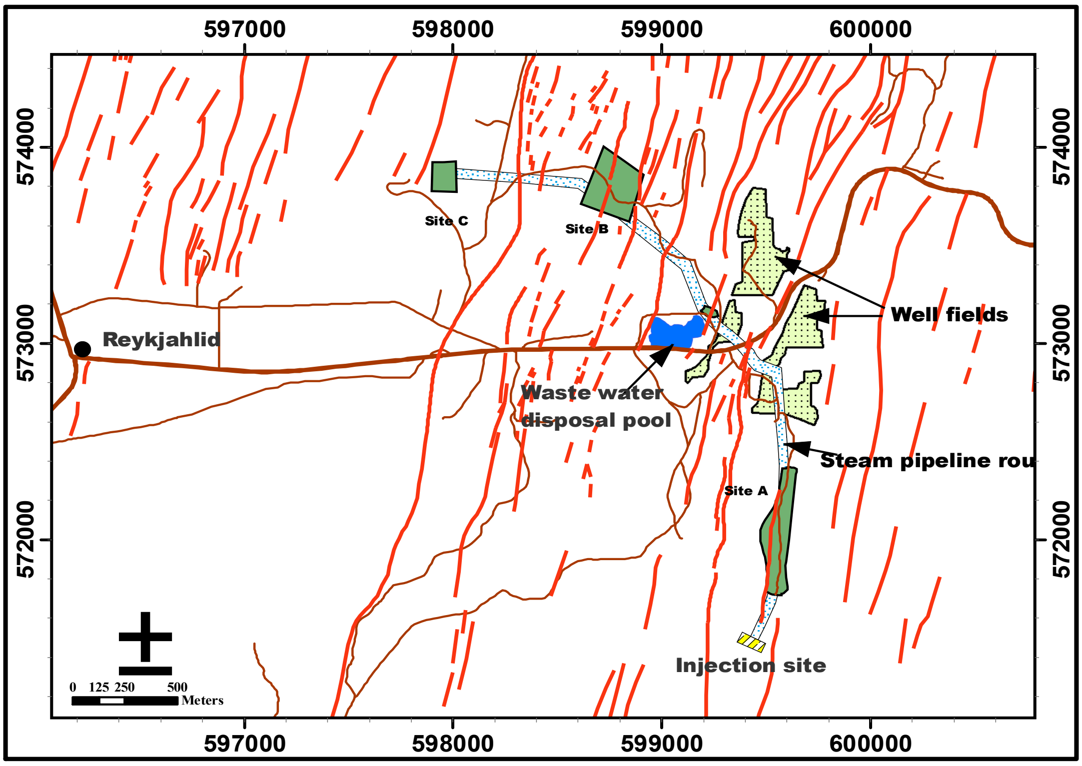

FIGURE 32: The location of faults and fractures and the three proposed power sites

6.4.2 Fractures and natural risk to pipelines

Analysis of the factures and faults in the study area to find out the risks for pipe lines from well fields to a power house, transmission lines and related accessories are an important factor for power plant site selection. During the project lifetime natural disasters are probable and an appropriate evaluation of those is needed.

The study area has been located in the rifting zone of Iceland and yearly rifting is detected and thus the evaluation of natural risk is highly necessary. As mentioned earlier, there are well fields and 3 proposed power plant site involved in this study and in this part of the report the potential of each power plant site with regard to fracture and probability of the faults and fractures activities is going to be evaluated. The location of the faults and fractures and the three proposed power sites are shown in Figure 32. As is clearly apparent in this figure the pipeline from the proposed well fields to the power plant sites through a defined pipeline route are crossing some of the fractures and faults.

The well fields and site A are located on the same side of the rifting zone and the pipeline is only going to cross one fracture and is parallel to some of them and thus the fault movement risk is low, from the well fields to site B there are about five intersecting faults and fractures and for site C the pipeline is also going to intersect perpendicularly seven fractures and faults, Thus the probability of risk for site A is low and for site C it is high. With regard to fractures and faults the natural risk for the proposed power plant sites are ranked and assigned relative values are 9, 5 and 3 for sites A, B and C respectively.

6.4.3 Land use or operation area

The operational area for each site is one of the factors considered for selecting appropriate power plant sites. In this investigation the minimum area needed is evaluated as the best choice for a power plant, because it will have minimum surface disturbance and less investment because of land ownership and preparation. Figure 33 shows the operational area of each proposed power plant site. Table 23 shows the proposed sites and the relative covered area, evaluation and relative assigned value for each site. Site C is the best site with regard to land use and site B is worst because of extensive land use.

FIGURE 33: Operational land use of each proposed power plant site

TABLE 23: Relative land use, evaluation and relative proposed value for ranking each site

Sites	Land use (m^2)	Evaluation	Relative value
Site A	64,277	Good	5
Site B	67,159	Poor	4
Site C	20,517	Ideal	9

6.4.4 Distance to production field

In power plant site selection distance to the production field is one of the important factors. Distance of the proposed site to the well fields is not only important as regards cost for pipeline and construction but it is also important as regards environmental degradation of the pipeline corridor. The area for the well fields which is proposed in Chapter 5 is used in this section to analyse the alternative power plant sites and rank them. The proposed well fields and power plant sites are shown in Figure 16. The distance has been calculated from central point of both well fields to the central point of the proposed power plant sites on a defined pipeline route. Table 23 shows the estimated distance from the well fields to each proposed power plant location, evaluation and relative given value for those. Site B is best and site C is worst.

TABLE 23: Distance to well fields, evaluation and relative proposed value for ranking of sites

Sites	Distance to well fields (m)	Evaluation	Relative value
Site A	1650	Good	8
Site B	1550	Ideal	9
Site C	2250	Poor	6

6.4.5 Access road required

Layout of plant roadways will be based on volume and type of traffic, speed, and traffic patterns. Type of traffic or vehicle functions for power plants can be categorized as follows:

- Passenger cars for plant personnel;
- Passenger cars for visitors;
- Trucks for maintenance material deliveries.

The length of required road for a proposed power plant from the main road to the area is not only important as an economical consideration but also as a environmental one, because road construction has a great effect on the environment and causes surface disturbances, vegetation removal, topographical changes, dust creation etc. The access road required has been defined as one of the criteria for selecting the appropriate power plant site from thee alternatives with regard to the environmental effects mentioned. All sites already have access to some kind of road but these roads are not appropriate for the traffic needed for power plant construction and operation and there is a need to develop the roads. The analysis for the development of the access road required for each site with evaluation and relative values is shown in Table 24.

TABLE 24: Required development of access road, evaluation and relative value for each site

Sites	Access road required (m)	Evaluation	Relative value
Site A	750	Ideal	9
Site B	1100	Poor	7
Site C	1000	Good	8

6.4.6 Power transmission line

A new power plant will require transmission and distribution changes and build up to connect the plant to the electrical transmission system. The potential for impacts from these changes is also of interest to local communities and adjacent landowners. Economic impacts of transmission and distribution changes, such as land use and right-of-way restrictions, should be identified. Generally, more desirable sites have fewer restrictions and impacts associated with required transmission and distribution changes. Thus, the construction of the transmission line required from a proposed power plant site to the distribution station is one of the factors necessary to take into account in power plant site selection. The proposed Námafjall power plant is planned to connect to the main transmission line from the Krafla power plant. The Krafla transmission line 1 (Kröflulína 1, 132 kV) is close to the Námafjall field to the west. The plan for the proposed Námafjall power plant is to construct a new transmission line from the future power plant to Krafla transmission line 1 and continue with the same route from the Krafla power plant distribution station. Figure 34 shows the location of Krafla transmission line 1 and the three proposed power plant sites. The distance to the existing 132 kV transmission line 1 is the basis of analysis in this section. As is clear in this figure the minimum distance to the existing 11 kV line which it is proposed to remove and install a new transmission line is from site C in its place and the distance from site B is shorter than from site A. Thus the given relative value for Sites A, B and C are 7, 8 and 9 respectively.

6.5 Final site selection

Selection of the site was the based on previously described and analyzed data and information. To evaluate the proposed power plant sites several components were taken into account and matrix analysis was employed for final the selection process. Thirteen different factors, i.e., air pollution, visual quality, vegetation, waste water, noise, land stability and subsidence risk, slope and surface

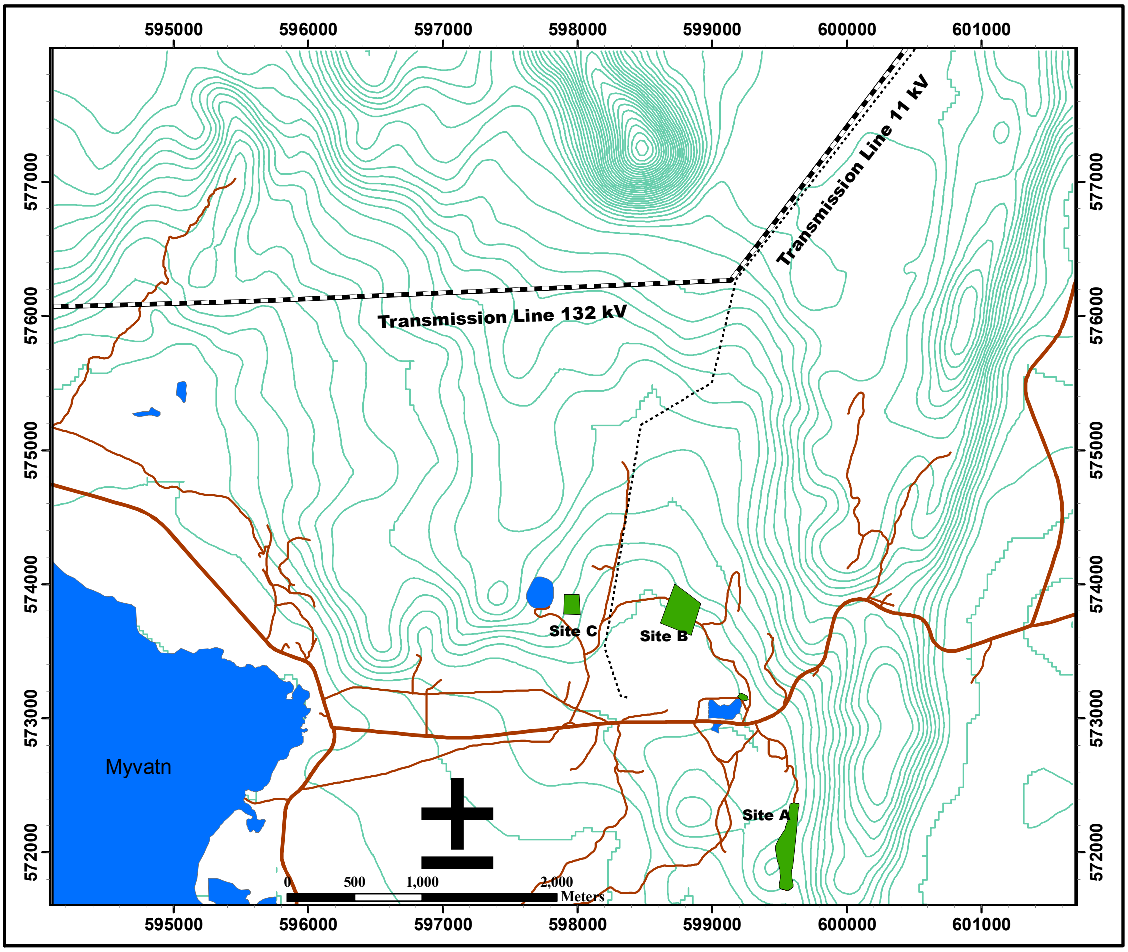

FIGURE 34: Existing power transmission in Námafjall area and
the location of the Krafla transmission line 1

disturbance, geology and natural risk site, faults and natural risk for pipelines, land use or operation area, distance to production field, access road and transmission line required which are important environmentally and economically are selected. The percentage importance of these 13 factors with respect to each other is also defined in the final matrix analysis. Every factor is analyzed at each site and modelled using data layers in GIS and some other software, and for the result, for each site a relative value from 0 to 9 is assigned and compared to those for the other sites, The relative value or weighting of each factor in each site is multiplied by the importance value of each factor and finally the aggregated weightings are used to rank the sites and make decision on site suitability. Table 25 shows the importance value defined for each factor with respect to the others and the assigned value for each factor to the relevant alternative sites.

If an ideal site is assumed, with a maximum relative value 9 for each factor, the total influence will be 900 [9 (maximum relative value) × 100 (% total influence)]. Compared to an ideal site with relative value 900, site A has scored 804. It means that this site scored 89 % of the ideal site score. Site B has scores 687 or 76 % and Site C 597 or 66 % of the ideal power plant site score. It is reasonable to conclude that site A is best and sites B and C are second and third best for installing a new geothermal power plant in the Námafjall geothermal field from the environmental and economical points of view. Figure 35 shows the comparison of suitability of alternative sites to the ideal site.

TABLE 25: Defined value of importance for each factor with respect to others and assigned value for each factor in relevant alternative sites based as result above

Environmental and economical factors	Relevant influence (%)	Site A		Site B		Site C	
		Relative value	Influence	Relative value	Influence	Relative value	Influence
Air pollution	9	9	81	8	72	6	54
Visual quality	9	9	81	6	54	3	27
Vegetations	9	7	63	9	81	4	36
Waste water	7	9	63	7	49	6	42
Noise	8	9	72	8	64	6	48
Land stability and subsidence risk	7	8	56	5	35	7	49
Slope and surface disturbance	7	6	42	7	49	8	56
Geology and natural risk site	9	9	81	5.5	49.5	4.5	40.5
Faults and natural risk of pipelines	8	9	72	6	48	4	32
Land Use or operation area	8	5	40	4	32	9	72
Distance to production field	8	8	64	9	72	6	48
Required access road	6	9	54	7	42	8	48
Transmission line	5	7	35	8	40	9	45
Accumulative weigh	**100**		**804**		**687.5**		**597.5**

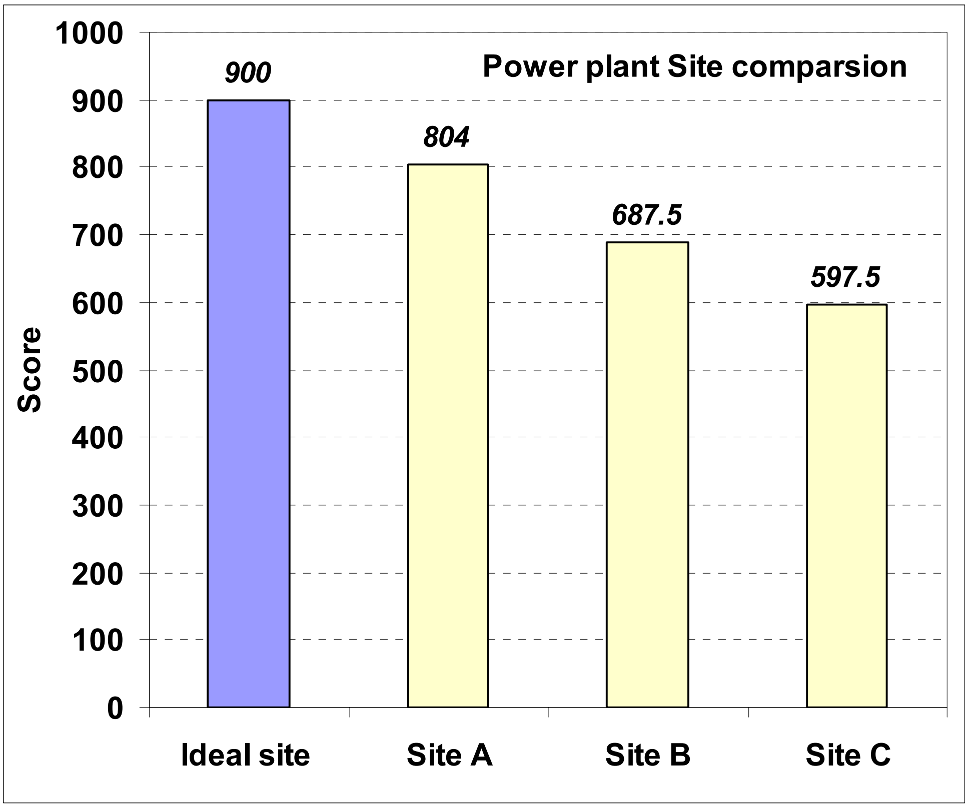

FIGURE 35: Suitability comparison of alternative sites and ideal site

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

7.1.1 Exploration and environmental management

The aim of this work is to find out the suitable area for geothermal well sites to carry out the geothermal exploration drilling. The GIS-based decision support system is used for combining data and suitability analysis. The geothermal exploration data and environmental information are used for finding the optimum location of the geothermal wells sites that cause minimum environmental impact. Combining these two themes (Exploration data and Environmental restrictions) is the research purpose to be developed using an approach of GIS-based suitability analysis to identify suitable well sites in the best area suggested by geothermal exploration data with low environmental effects during construction and operation. The conclusions can be addressed as follows:

- Remote sensing is a cost effective method for projects, because it makes it possible to map most features in high-resolution satellite images with minimum field work or only with ground point checking.
- Remote sensing is time effective and makes it possible to get satellite images for any given season in every time of the year and interpret it. In environmental studies it is especially necessary to do some investigation (vegetation study and mapping) in different seasons, remote sensing providing opportunity and tools to do it at any time.
- High resolution (spatial, temporal and spectral) satellite data in combination with GIS has proved to be an extremely useful technology for micro-level planning and implementation. Particularly artificial flight over the 3D map has made it possible to overlay satellite images over the TIN map in GIS, in ArcScene providing an opportunity for project developers and decision makers to fly artificially over the area to get a better view of the project area for better decision making.
- GIS-based decision making offers a way to engineers and scientists to decide on each factor individually instead of going through a very complex decision making process using the traditional analog method and also reduces the possibility of human errors in the decision making process.
- Comprehensive information needs to be available for each of the resource suitability factors applied in the exploration analysis. This information includes accurate geological mapping, a delineated geophysical anomaly area, and geochemically defined reservoir characteristics.
- Broad and accurate geographical, environmental and socio-economical data including vegetation, protected area, slope, aspect, land use and land cover, residential and industrial location, historical and cultural places etc. need to be available for an appropriate geothermal environmental management analysis.
- The environmental management system involves important analysis as a means of selecting the suitability factors and evaluating their relative importance.
- The GIS-based decision making process gives an opportunity to decision makers to account for particular criteria in overlaying the information layers according the special characteristics of the study area.
- In order to advance the act of geothermal resource suitability analysis, it is important that not only the result is repeatable within a study area, but also that the approach is transferable, or at least adaptable to other geothermal fields.
- Re-evaluation of initial concepts or updated information also can easily regenerate exploration and site selection strategies. The evaluation process is so explicit that alternative scenarios can be modelled without reconstructing the entire procedure. From the view at the technical level, this GIS-based suitability analysis approach is quite able to integrate exploration, environmental and geographical data with human knowledge in an objective and manageable manner. It allows

for all kinds of information from engineers, experts and decision makers to be used in the weighting process. From the point of view of the organizational level, the use of GIS technology brings people together, including engineers, scientists, planners and decision makers. The high level of cooperation and involvement generates a broad-based approach to multi-objective suitability analysis and decision making for geothermal resource exploration and environmental management.

- From this work it is possible to suggest that the approach applied in this study area can be adapted to other geothermal fields. In summary, the suitability results can provide helpful knowledge on the factors' interactions and their relation to the geothermal exploration and environmental management within the study area. It can be used to help decision makers to make better and more informed decisions.

7.1.2 Power plant site selection

Power plant site selection is the process of determining the optimum location for a power plant which is stable and should as possible suffer minimum environmental impacts during the construction and operation phases.

Power house size and arrangement depend on the plant equipment and the facilities selected including steam separators, generators, cooling towers, potential for future expansion, and aesthetic and environmental considerations. Since the selection of a plant site has a significant influence on the design, construction and operating costs of a power plant, each potential plant site should be evaluated to determine which is the most environmentally suitable and economically feasible for the type of power plant being considered. In power plant site selection the conclusions can be addressed as follows:

- High resolution remote sensing images, particularly DEM data can provide precise land development capability and environmental data.
- Ground source checking is highly recommended for checking the accuracy of the remote sensing data
- The number of factors employed depends on the site characteristics such as geological, geotechnical and environmental conditions of an area and may vary from one site to another.
- The relative percentage of importance for factors employed can be different with regard to the geological, geotechnical and environmental conditions of an area and they have to be defined by specialized experts, engineers, planners, decision makers and public opinion.

7.2 Recommendations

7.2.1 Exploration and environmental management

Nowadays many methods can be used to carry out suitability analysis, such as sieve mapping, greytone method (map overlay) and computer method (GIS). In this work, GIS is used to carry out the suitability analysis because it can handle a large number of data, powerfully visualize current and old information, produce new maps, avoid human error etc. When applying GIS to suitability analysis, what should be done first is to establish a set of suitability factors and a weighting system. This is the most important and difficult step in suitability analysis.

This work categorized selected factors into two main categories including exploration factors and environmental factors to use in the suitability analysis, exploration factors including information on geothermal manifestations, volcanic craters, faults and fractures, geochemical, and geophysical data and environmental factors including information on vegetation cover, vegetation cover density, protected area, slope, historic culture and socio-economic value. It is a relatively new method to use a GIS-based decision support system to analyze for suitability in geothermal well targeting in resource exploration. In some sense these factors may be not be sufficient for geothermal resource development. However, there are no other data available in the early phase of the project development. As to the well targeting system for complete development of the field, other reservoir factors such as temperature distribution, cooling factors, groundwater recharge, pressure distribution and decline, reservoir conceptual model, reservoir potential evaluation and some reservoir boundary effects should also be considered. Thus it is seen that the GIS-based decision making method can be used in covering all project development phases. So it is recommended to use GIS as an analytical, managerial, modelling and decision support system in the cooperation of engineers, scientists and planners in carrying out detailed studies of a relevant speciality and making up the foundation model applicable to most geothermal projects.

This work is a preliminary attempt to apply GIS-based suitability analysis to the Námafjall geothermal resource development. SPOT satellite images have been used as a partial data source for updating the old vegetation map, analyzing the built up area, and overlaying the digital elevation model to make a 3D map of the area. The digital elevation map has also been used for a topographical map and calculating a slope map. The ERDAS IMAGINE version 7.6 has been used for satellite image analysis. The GIS software (ArcInfo 9.0) used in the case study is of a vector-based (intersecting) raster-based (weighted overlay) design. The major advantages of vector-based analysis are the minimizing of the research area and for raster-based design its capability of individual pixel analysis and map algebra inherent in the raster systems, which make this suitability analysis much easier. However, depending on the scale of the individual cell values, the analysis may have been less precise than the vector-based design.

GIS and remote sensing are advancement in decision-making for suitability analysis, but there is still a clear need for further research in this field, including:

- To use thermal satellite images in the DSS process as new source of information for defining an area with high heat flow in large scale geothermal exploration.
- In different countries or different geological conditions it is recommended that it is reasonable to adjust the method in one known geothermal field for improving and defining more precisely the criteria employed for site selection such as the weighting of the different data layers in exploration and environmental phases and also the weighting of the exploration and environmental suitability with respect to each other. Thus it is possible to increase the usefulness of a GIS-based DSS, in geothermal resource exploration and environmental management systems.

7.2.2 Power plant site selection

Thirteen possible environmental impact and economical factors affecting the proposed project were investigated. The factors are defined according to the geological, environmental and geographical conditions of the study area. The proposed power plant specifications were also important in factor selection.

This work is a preliminary attempt to apply GIS-based characteristic analysis and matrix interpretation to the siting of geothermal wells and plants. For future analysis of similar projects the following recommendations are made:

- Careful environmental impact assessment of power plant construction and operation is necessary to find out the probable environmental impact for better criteria development.
- Prediction dispersion modelling of air pollution and noise is best carried out by the particular software used and they are the best way to predict further impacts and evaluate alternative sites.
- For air pollution prediction dispersion modelling the ISC3View software is recommended.
- The weighting of the factors with respect to each other is greatly related to the environmental, geological and geographical conditions of the study area and should be assigned with regard to them.

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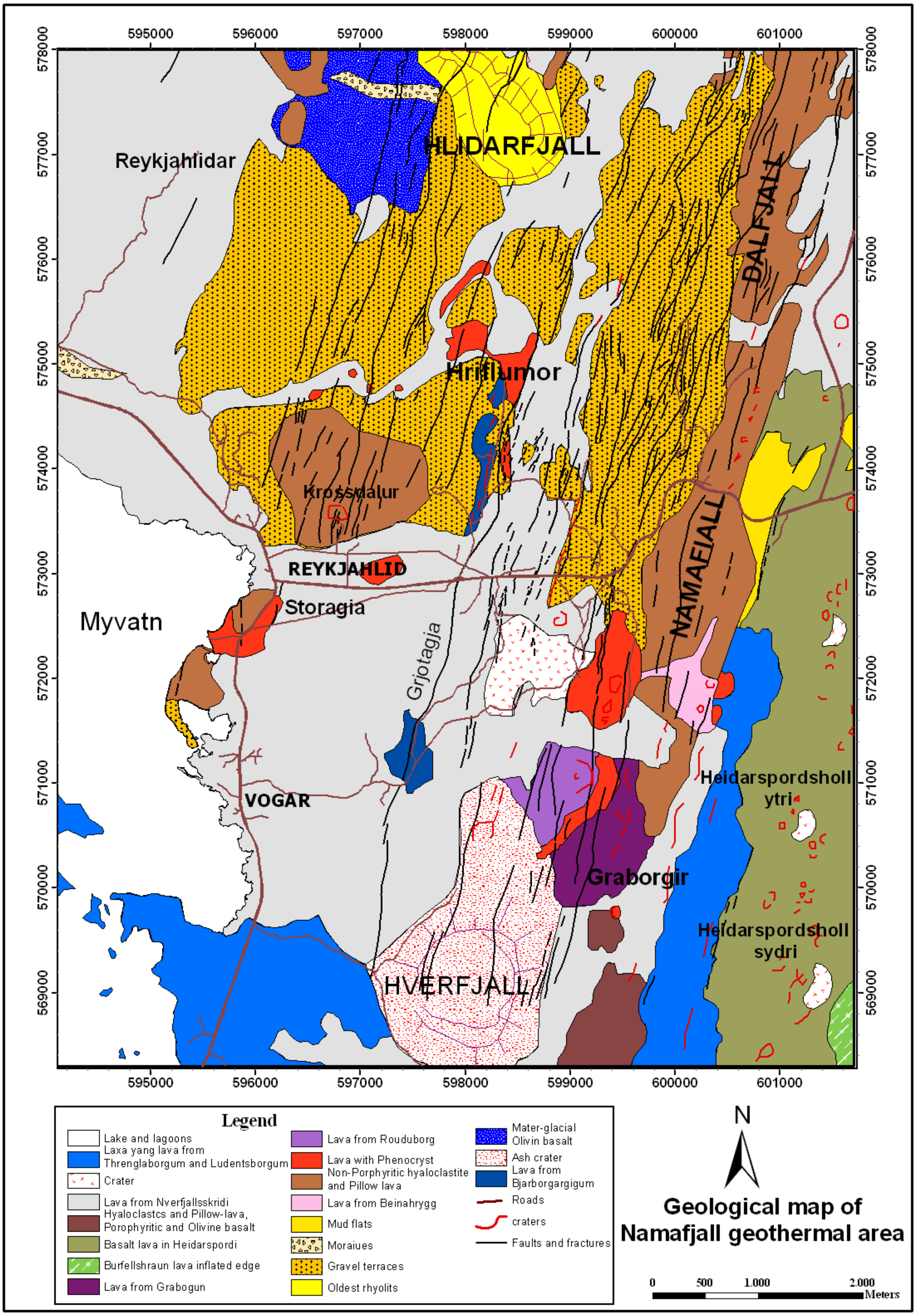
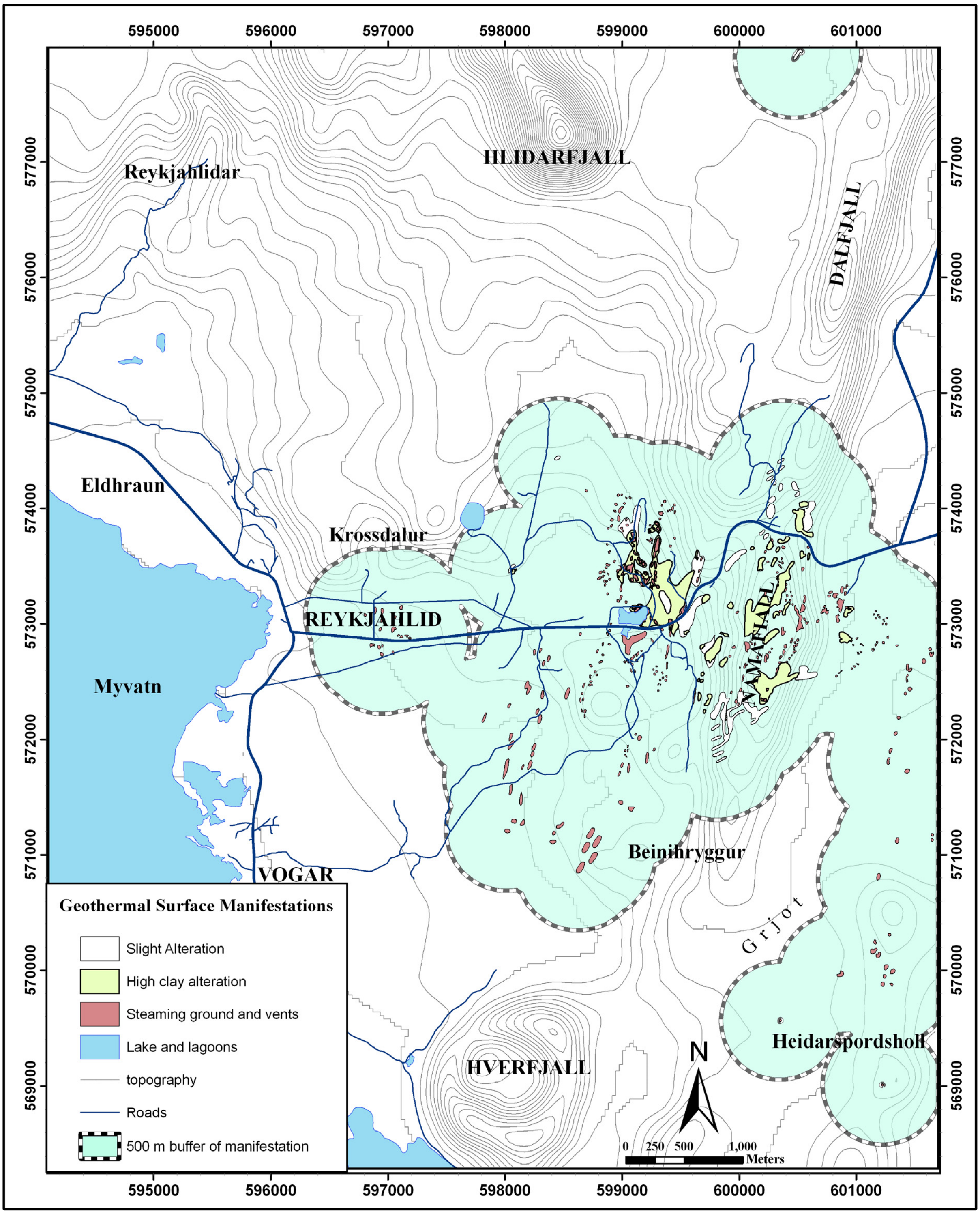
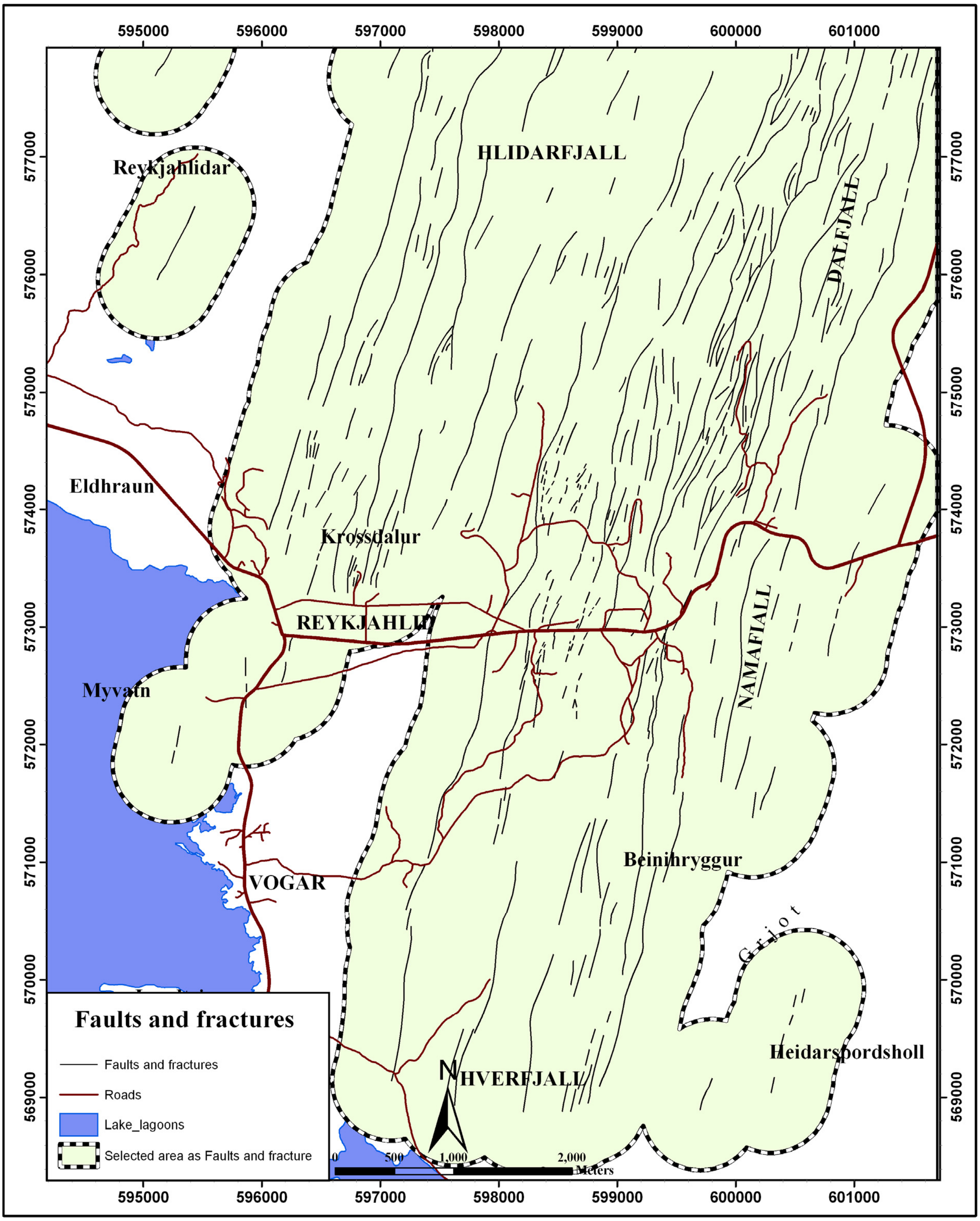
APPENDIX I: MAPS



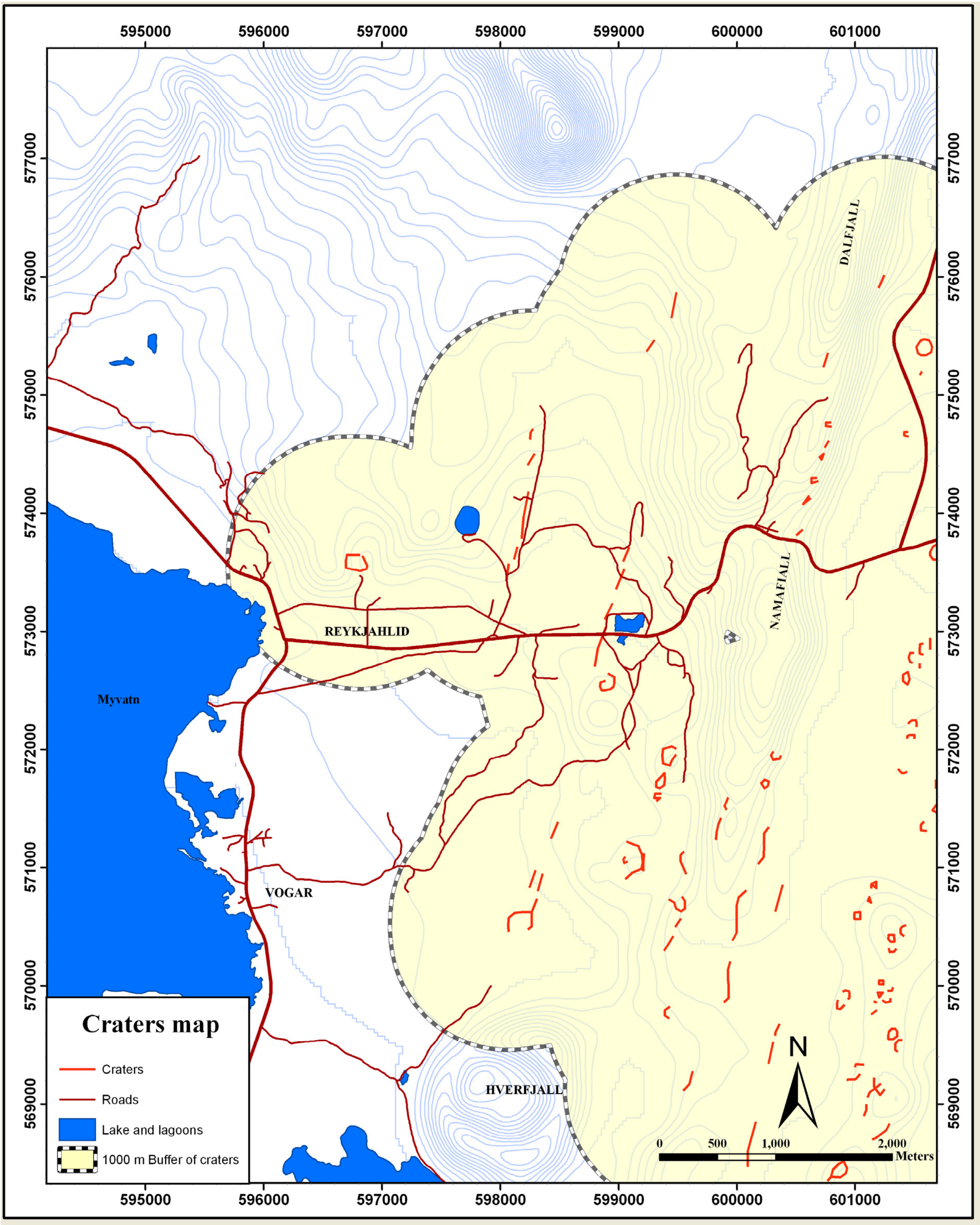
Map 1: Geological map of the Námafjall area (Saemundsson, 1991)



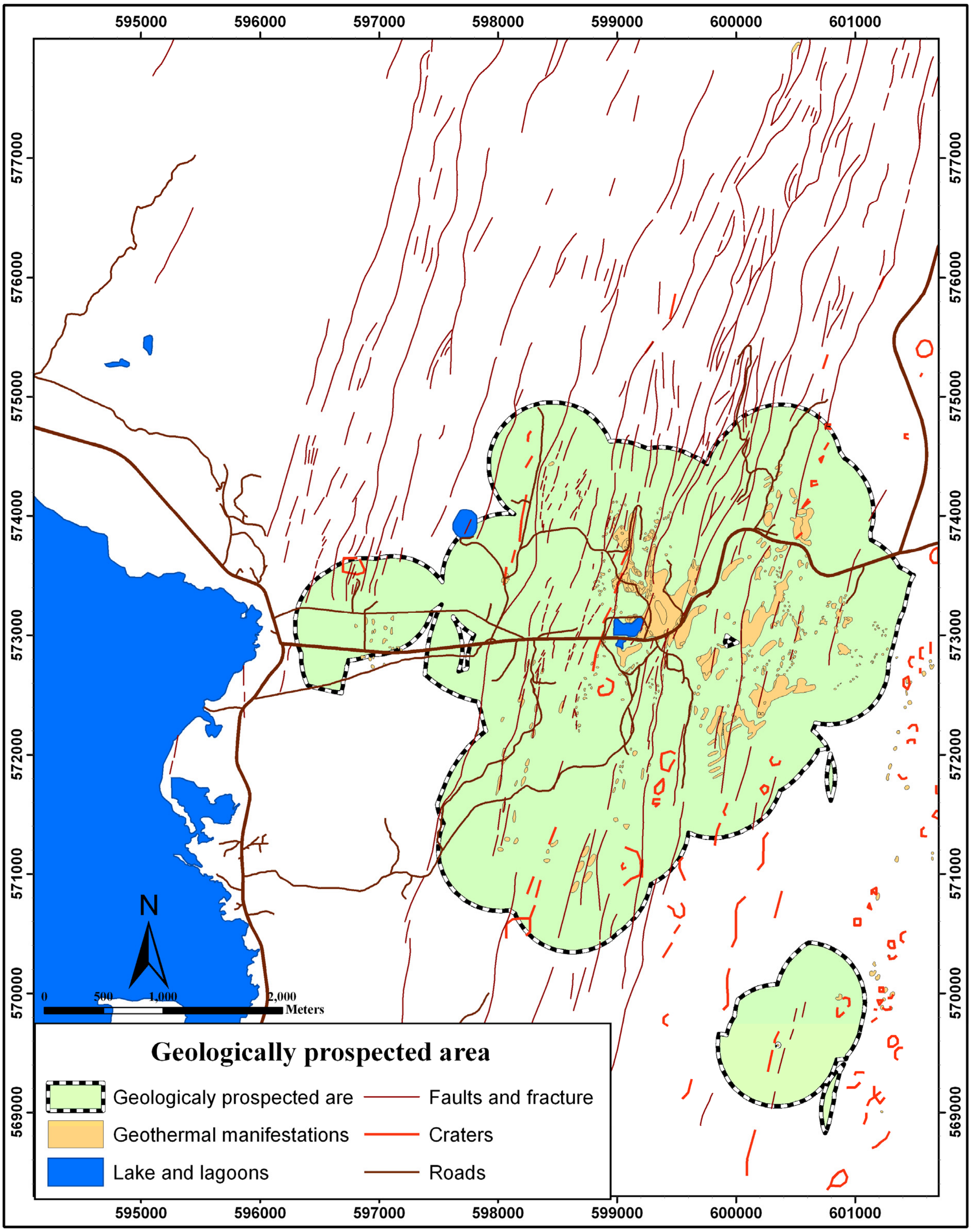
Map 2: Geothermal manifestation map and relative prospected area



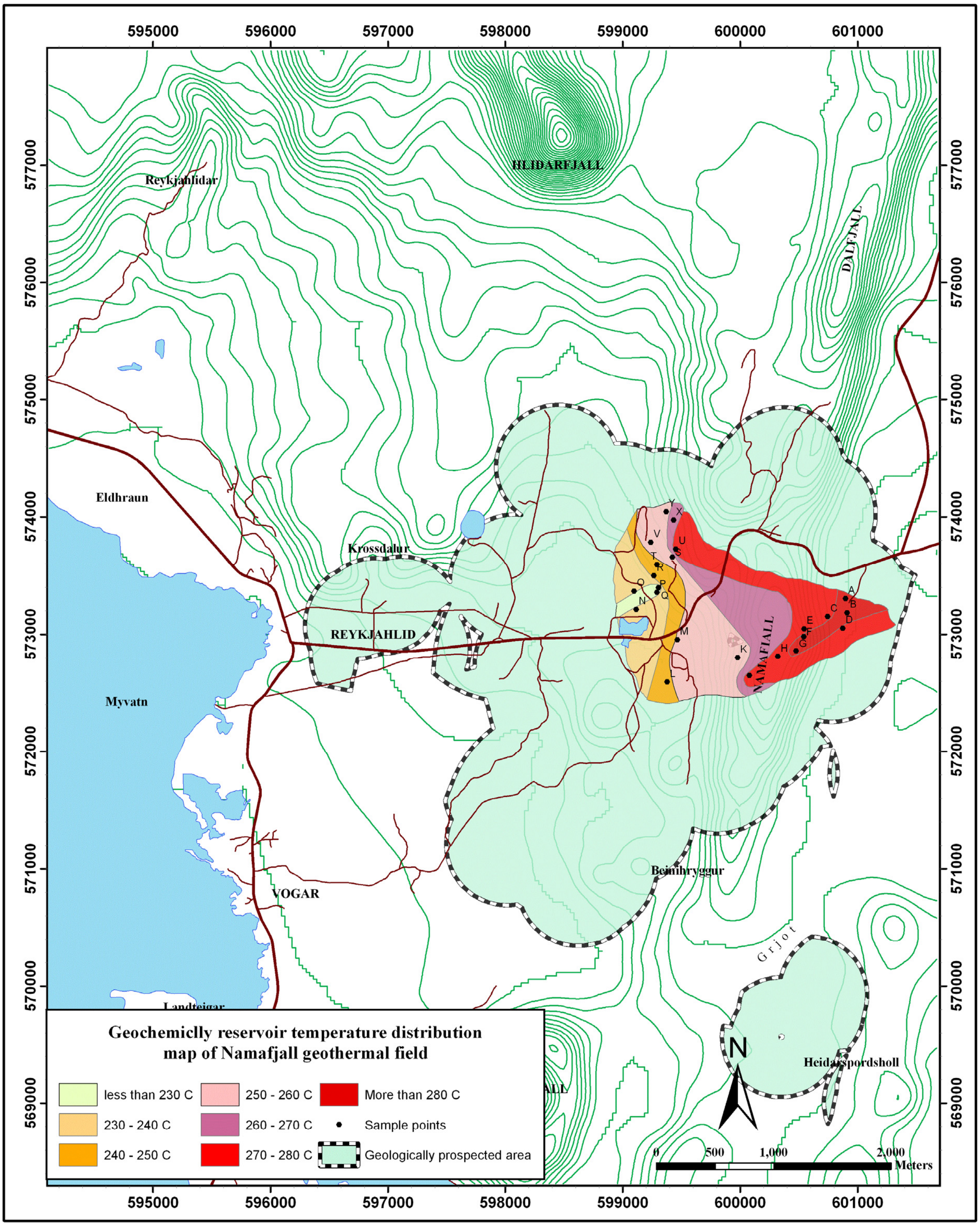
Map 3: Prospected geothermal resource area according to the faults and fractures



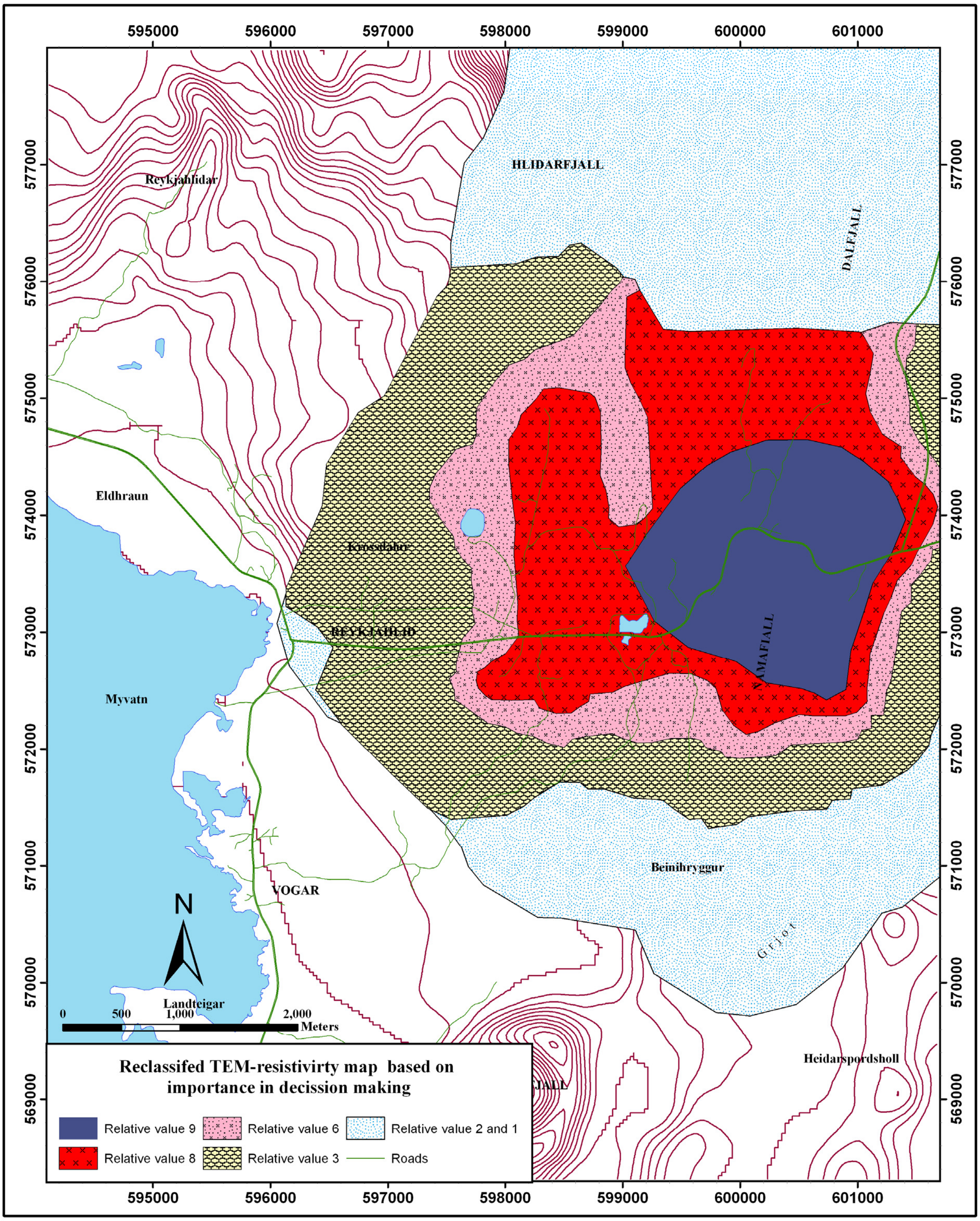
Map 4: Craters and selected prospecting area



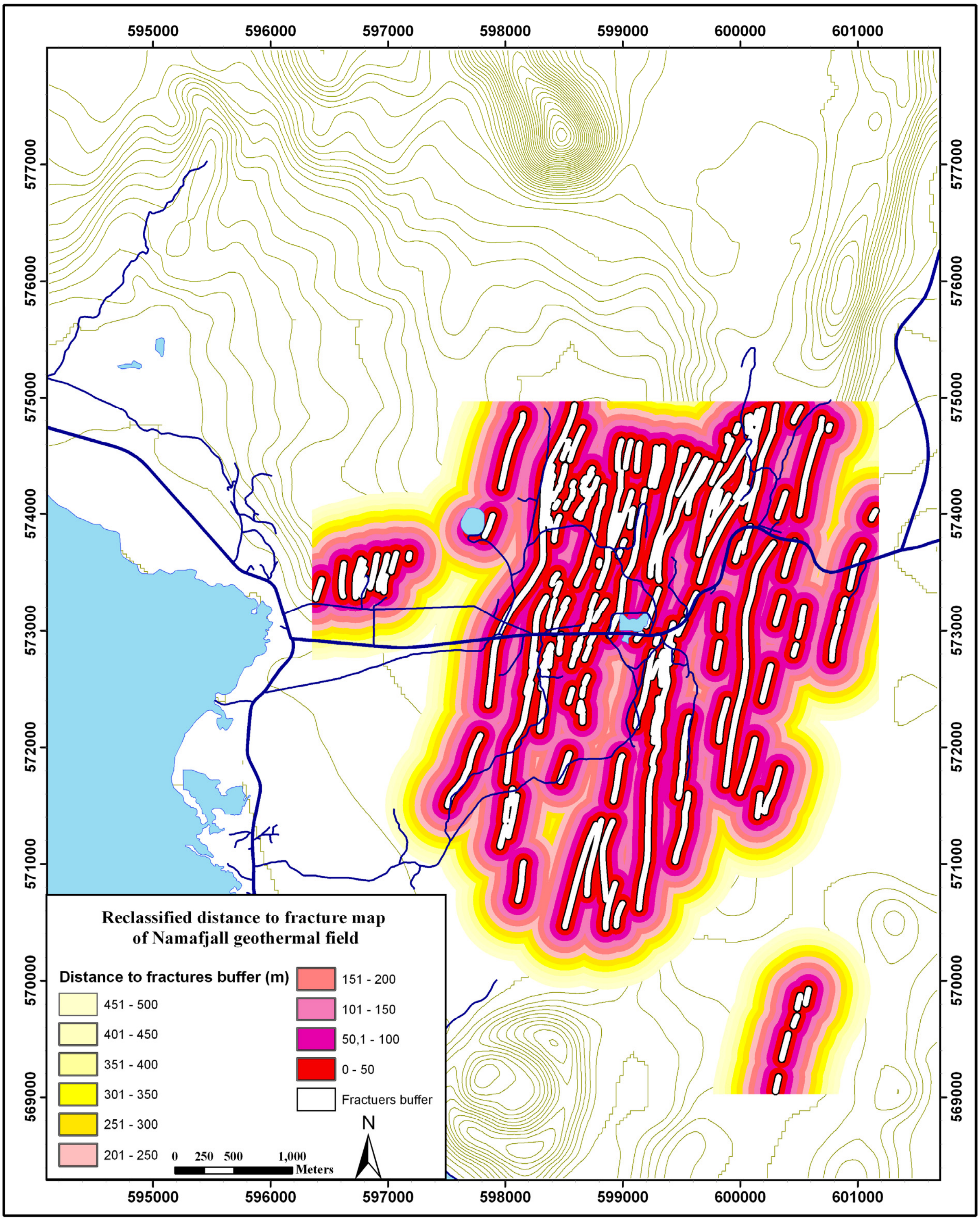
Map 5: Geothermal resource prospect area based on geological considerations



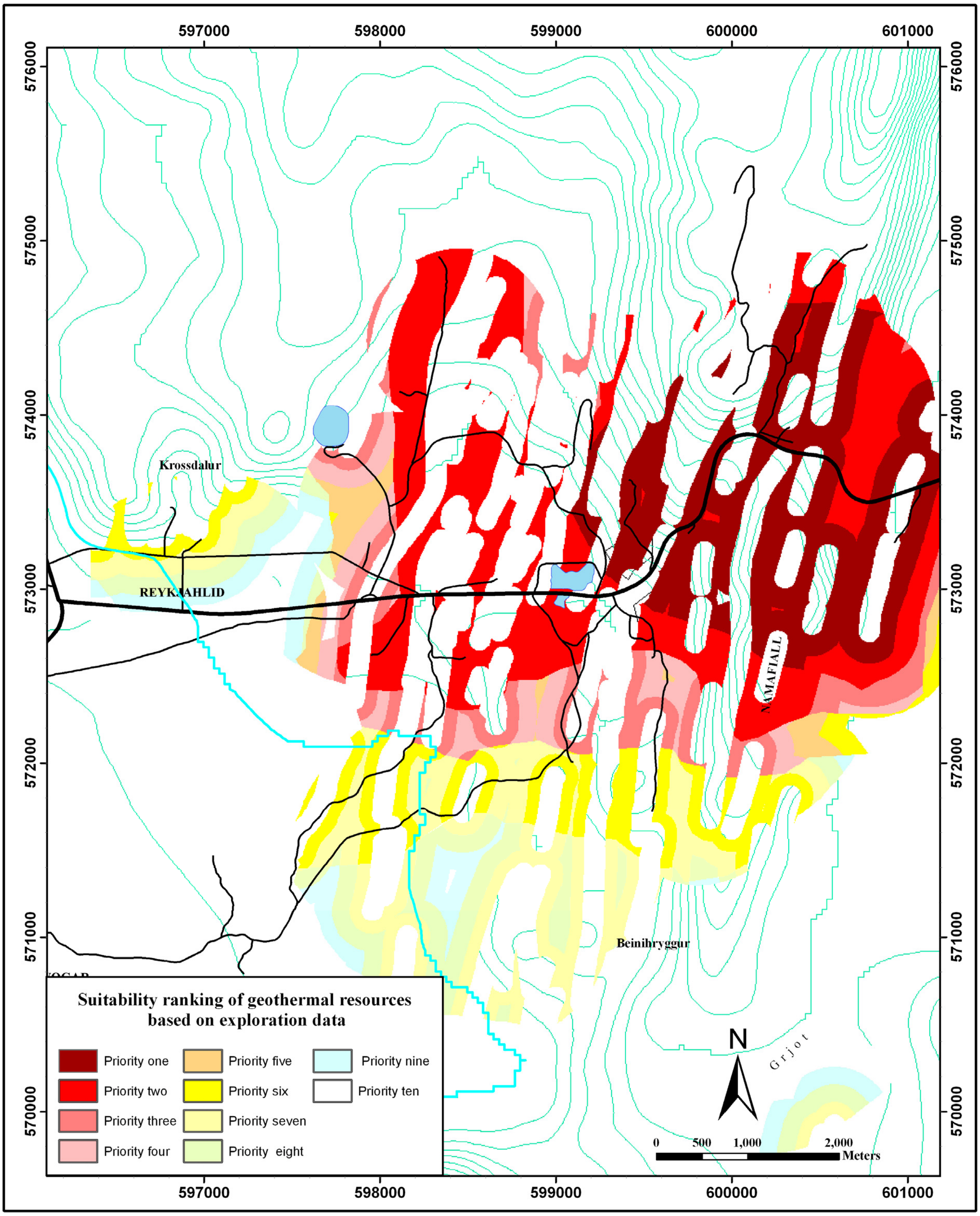
Map 6: Modelling of estimated reservoir temperature by geochemical investigations



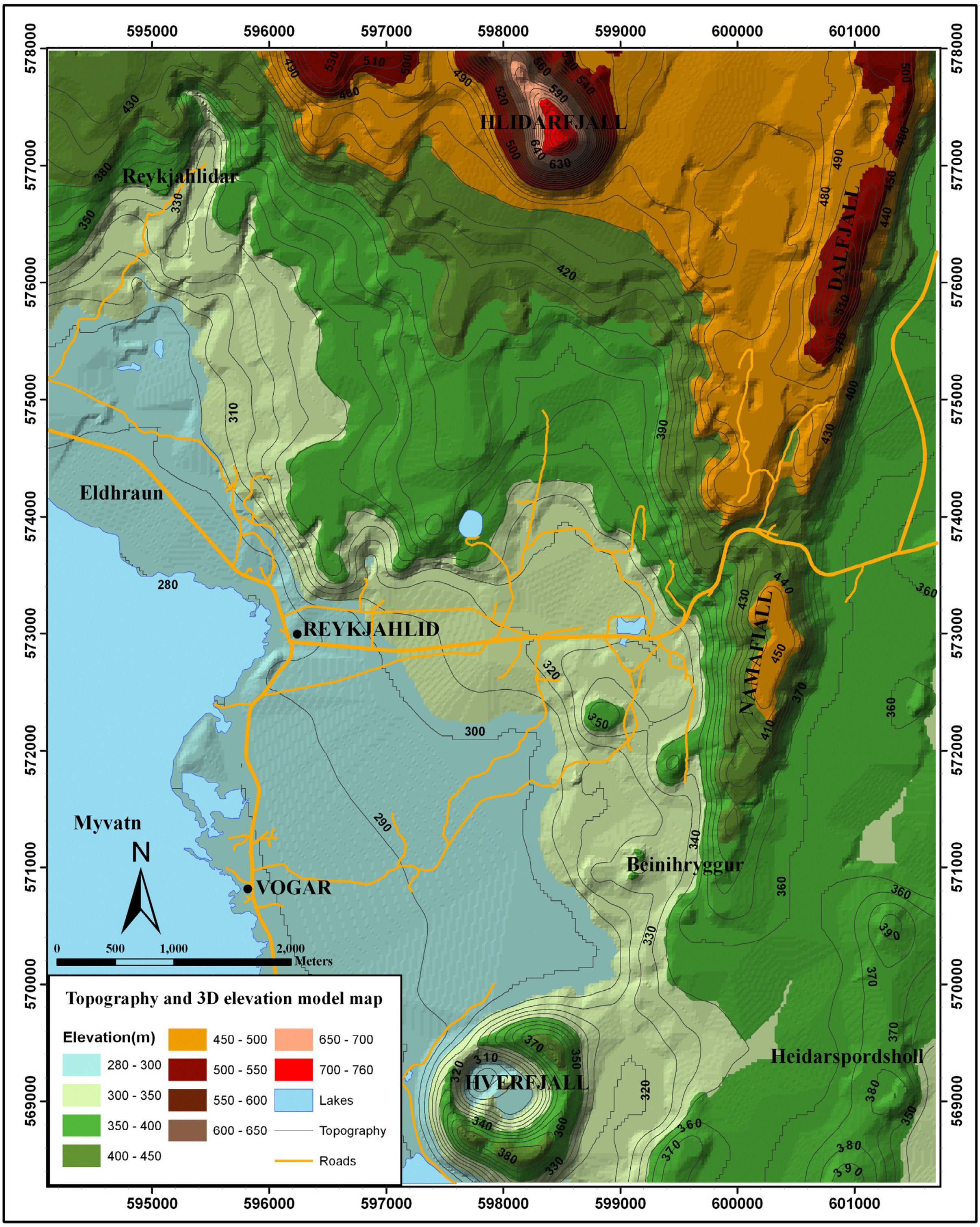
Map 7: Reclassified TEM-resistivity map based on importance in decision making



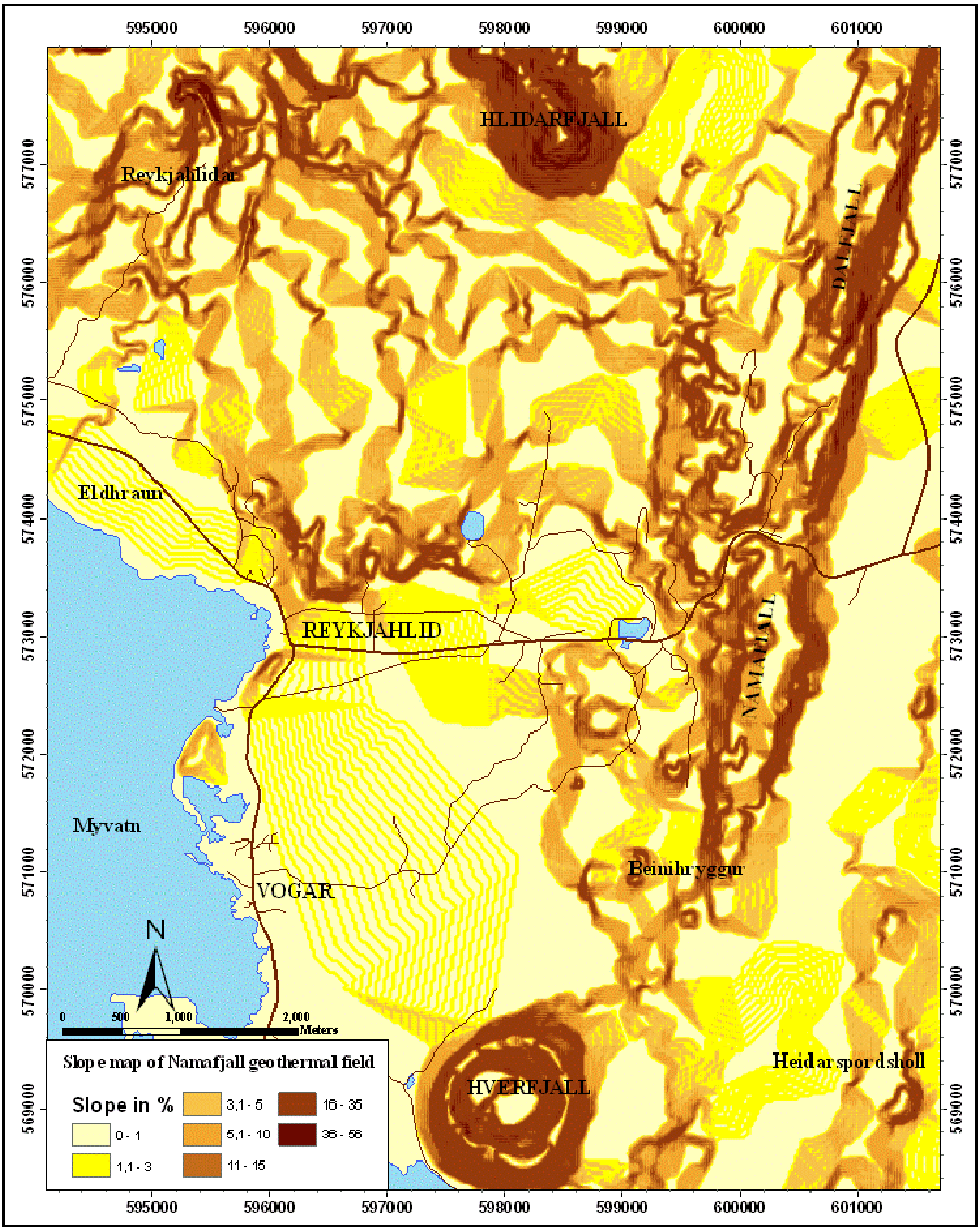
Map 8: Reclassified distance to fracture map



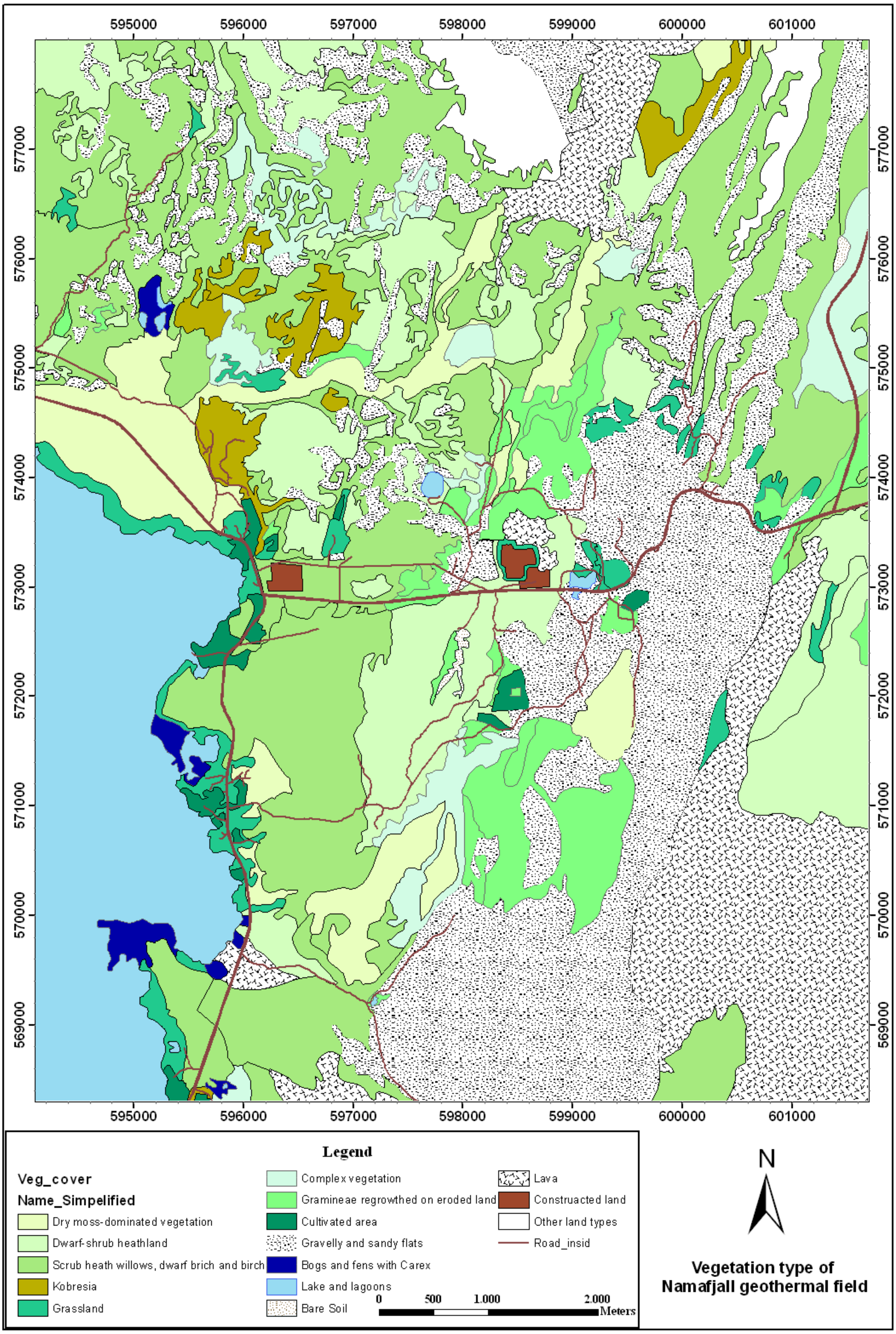
Map 9: Ranking of study area according to suitability of geothermal resources, based on exploration data.



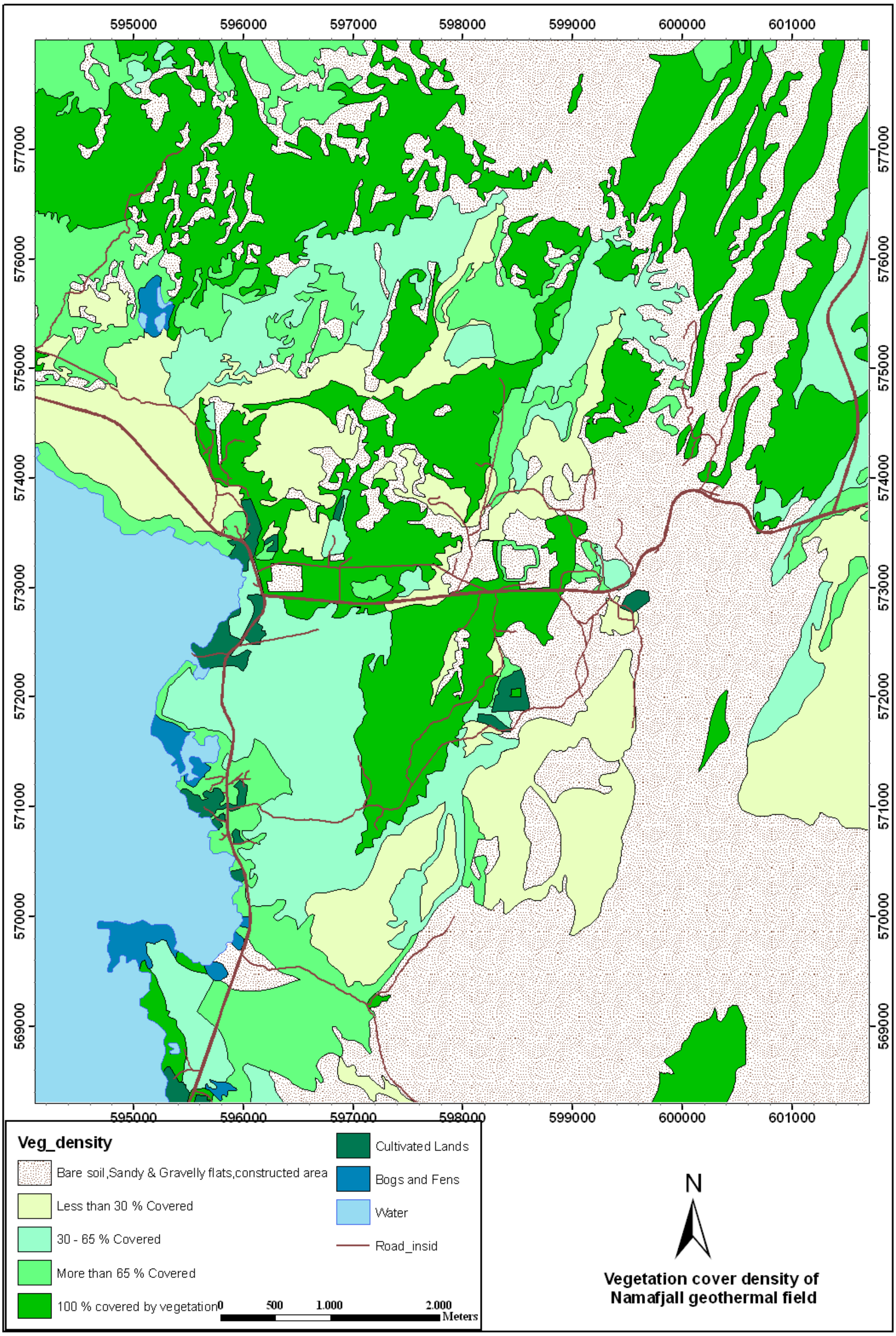
Map 10: Topography and TIN model of the Námafjall area



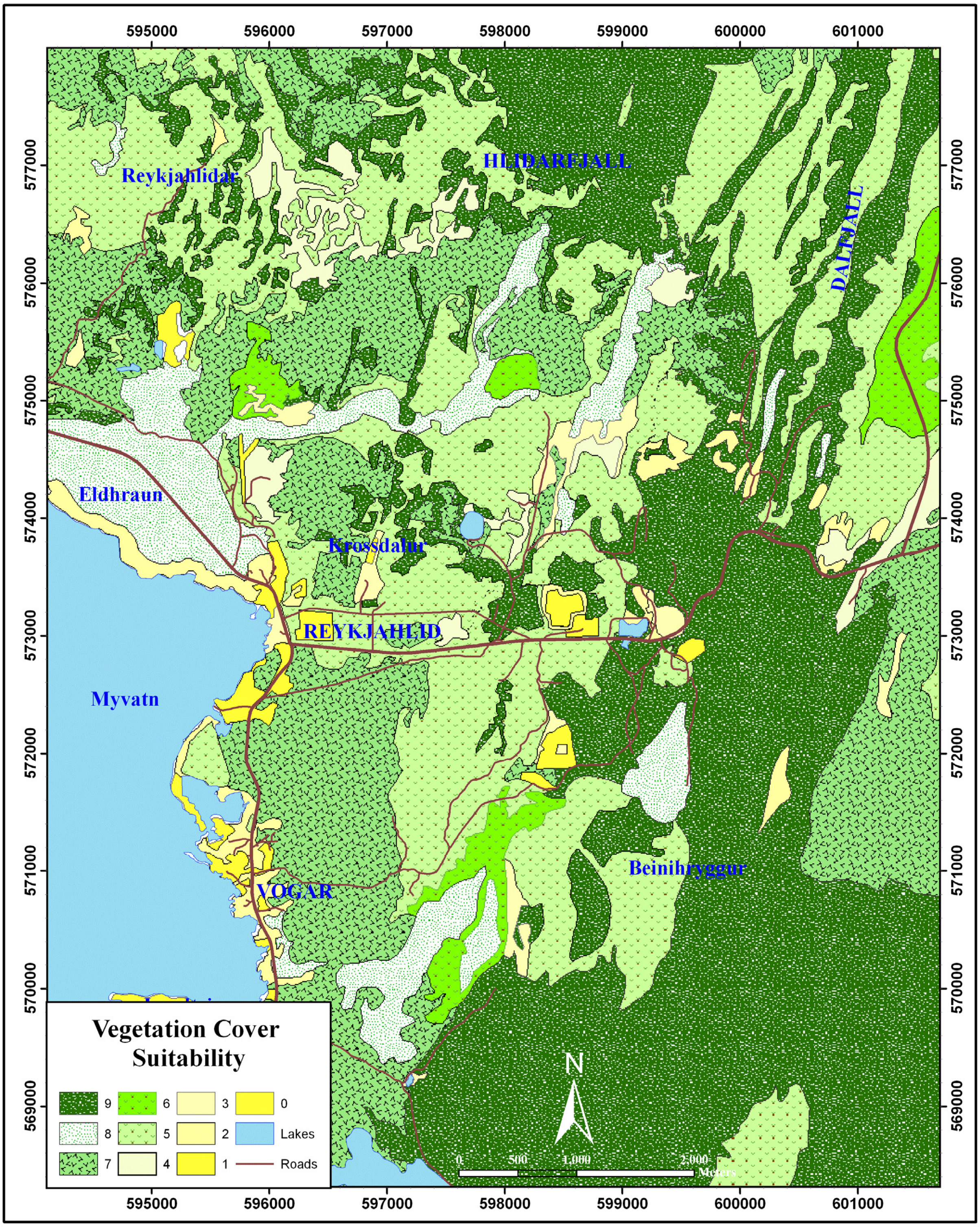
Map 11: Slope map of the Námafjall area



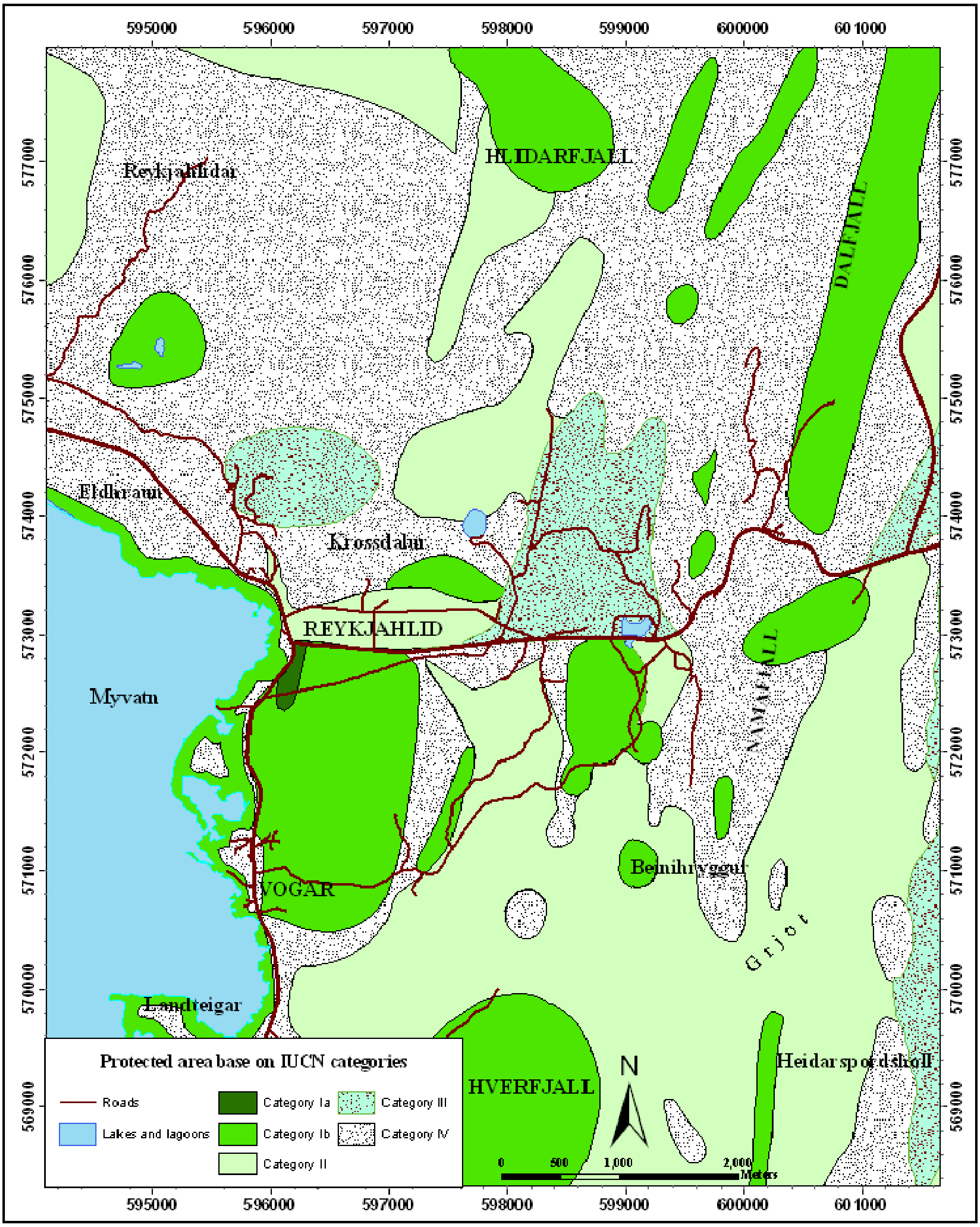
Map 12: Vegetation cover map of Námafjall geothermal field



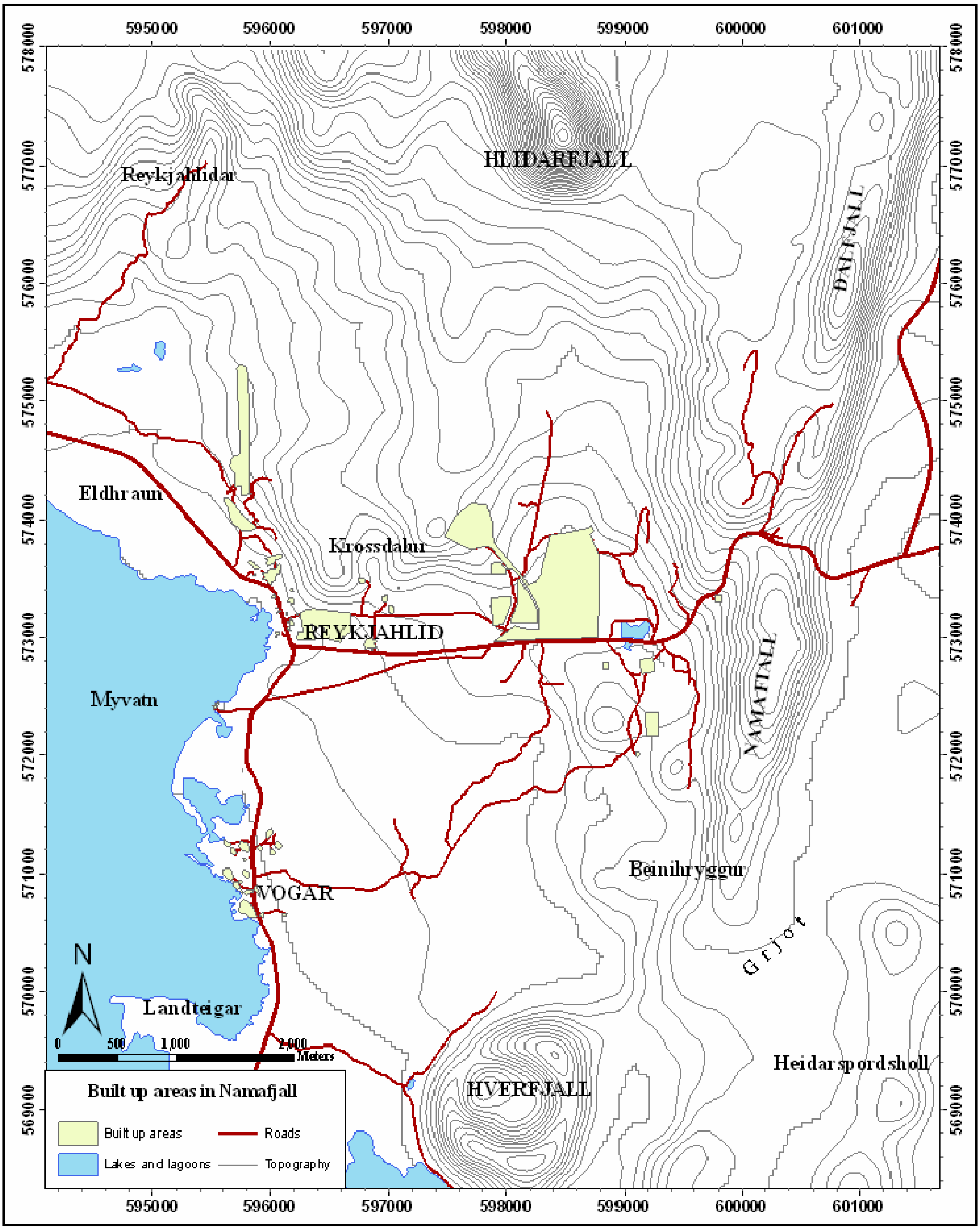
Map 13: Vegetation cover density map of the Námafjall area



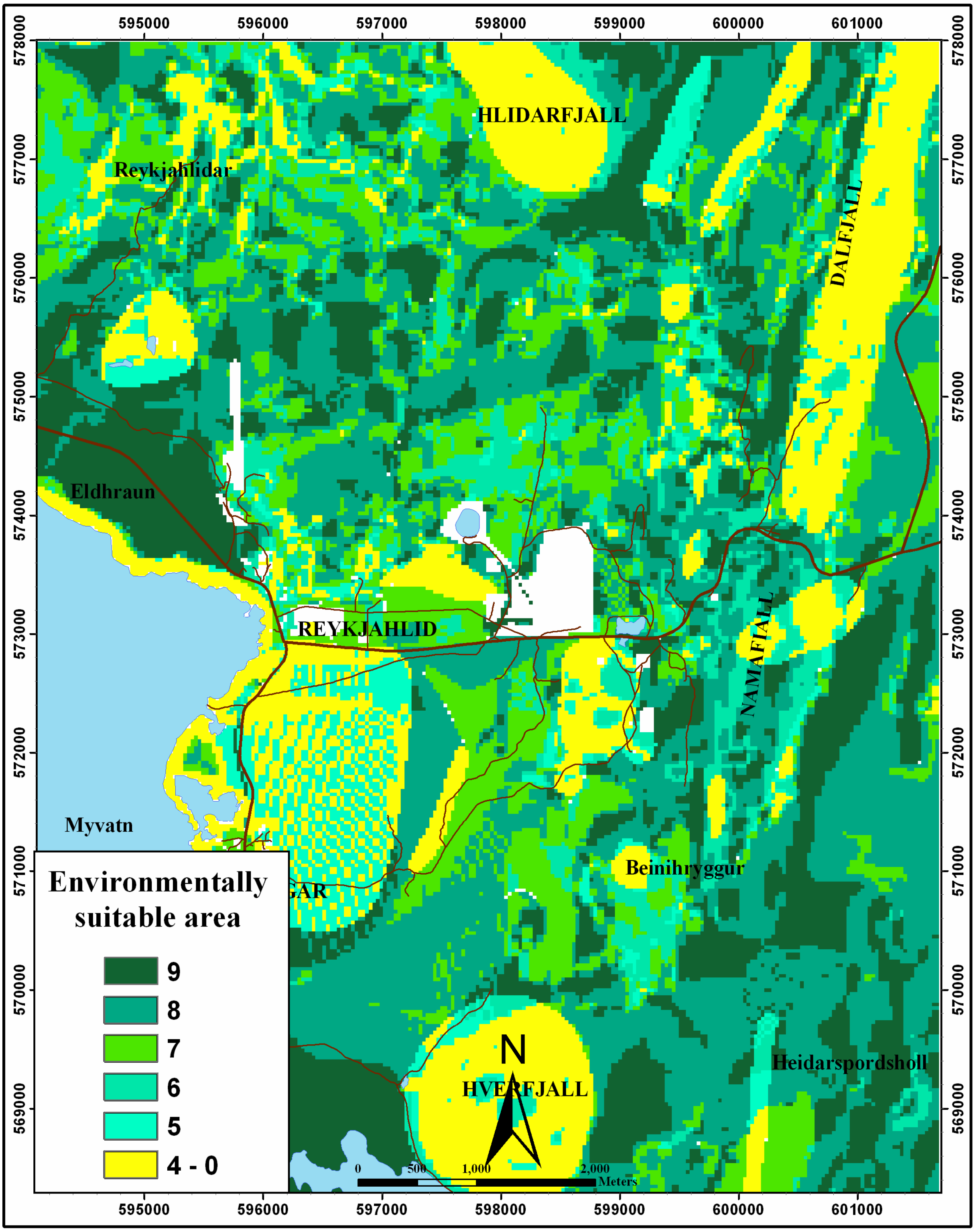
Map 14: Vegetation cover and density - suitable areas



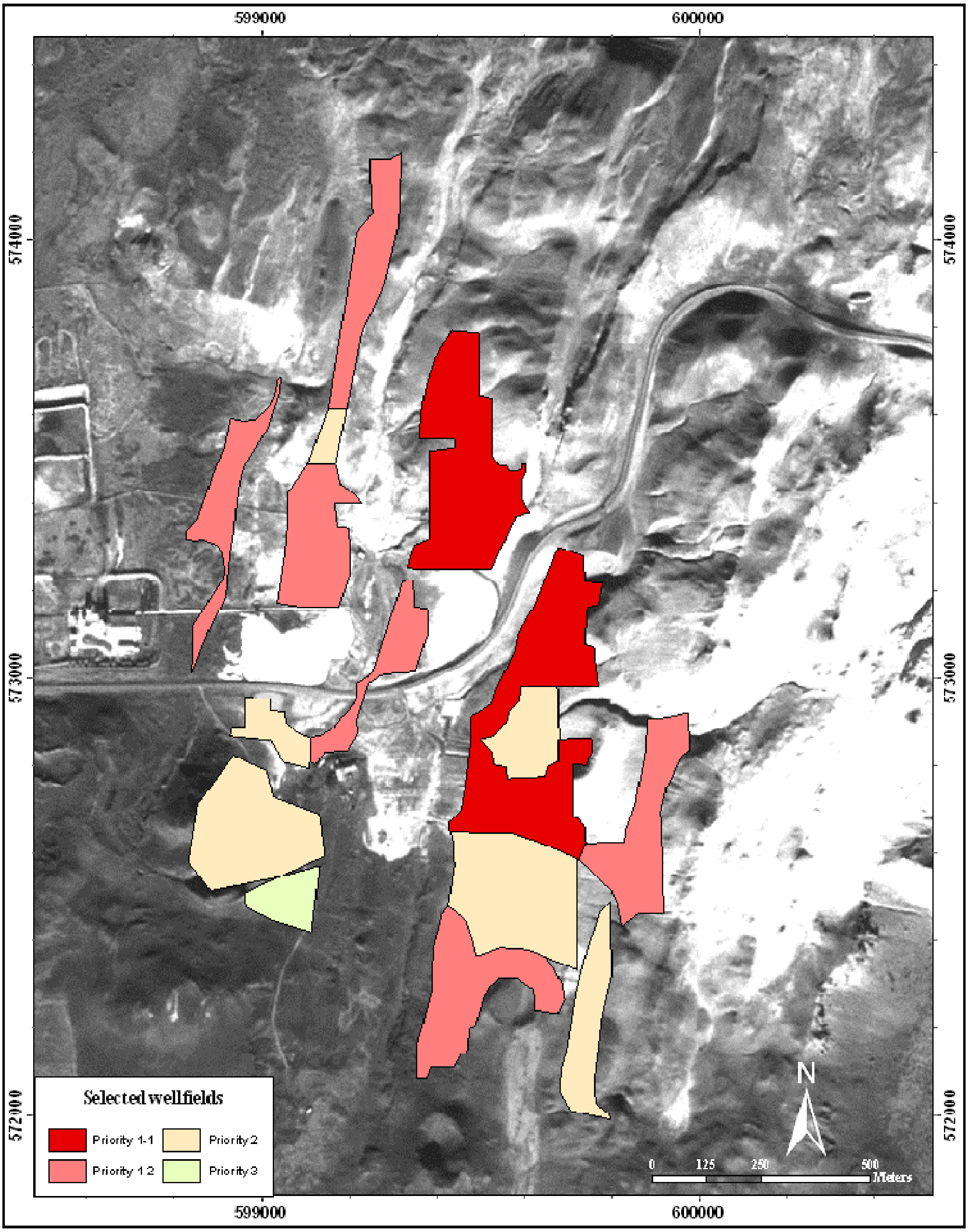
Map 15: Map of protected areas in the Námafjall area



Map 16: Built up areas in the Námafjall area



Map 17: Classified environmental suitability map of the study area



Map 18: Final selection of well sites