Assessing the Geothermal Potential of Central America: A Web Based Favorability Map Project

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ABSTRACT

Central American countries are well known for their great geothermal potential. Although mainly high enthalpy projects have been developed so far, the potential for development is still considered strong, especially in countries where high enthalpy is not yet fully developed. However, additional interest was announced for direct use applications with lower grade, yet economical temperatures. Here, limited costs for shallower wells in areas of high geothermal gradients are expected to initiate new exploration activities in the vicinity of districts with growing economies and energy demands.

This study demonstrates an open source data processing workflow for the setup of a geothermal database and a favorability map, using Costa Rica as an example. However, it is intended to be suitable for all Central American countries when data are available. The favorability map is designed to be available as a web-based geographic information system (GIS) to support local decision makers and international investors to start or proceed with further exploration activities.

The assessment of the geothermal potential was made based on the work of Aravena and Lahsen (2013), where fault locations, occurrence of volcanic or sedimentary rocks, seismicity, and the proximity to the volcanic arc and to geothermal surface manifestations are considered indicators for favorable geological conditions. The surface potential for viable projects was derived from infrastructural data available from OpenStreetMap and the Energy Database from the Interamerican Development Bank (IDB). Sectors included industrial, residential, and general. Ancillary data, such as roads, powerlines, protected areas or migration pathways, are made available to provide the user with relevant surface information.

A GIS analysis process with weighting factors produced five potential maps for projects including power generation or direct use in the vicinity to the volcanic arc and sedimentary basins. Combined, these maps provide an overall favorability map for geothermal projects. The result was calibrated and evaluated with a known exploration target as a proof of the concept. Finally, a conceptual geological scheme was developed to discuss the geothermal exploration and applicability of the favorability maps.

1 INTRODUCTION

Central America is well known for its great geothermal potential. However, each country has developed and implemented their geothermal projects with differing velocities in the past. Costa Rica is a role model for renewable energy production, producing near to 100% of power from renewable resources. While hydropower is the predominant source of electricity, geothermal contributes around 15%. Closely behind Costa-Rica, El Salvador follows with 205 MW_e of installed geothermal capacity. While Guatemala, Nicaragua and Honduras are actively developing geothermal projects, Panamá is in an initial stage of development with no or very limited exploration knowledge.

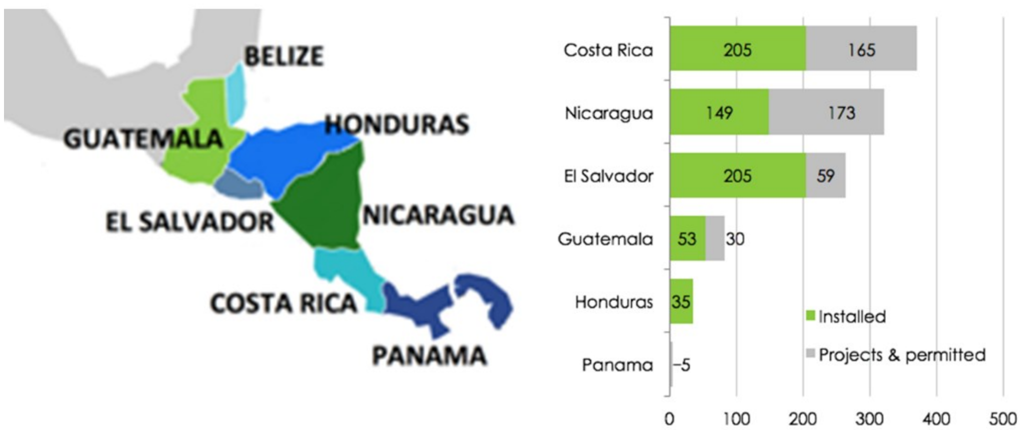


Figure 1: Installed geothermal capacity in MWe, and the geothermal project situation in Central America (after TGE, IGA & GEA (2017)).

The differing progress (Figure 1) is most likely related to the specific national political or socio-economic factors, defining the legal and financial conditions for investment. The recently established Geothermal Development Fund (GDF) has made inroads towards setting up a reliable investment framework for international applicants. However, the local resource and infrastructure knowledge is mostly owned by the National Energy Regulator and is not accessible on a regional scale for interested third parties, such as investors.

At the end of 2018, the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH together with ERDWERK GmbH started a project to create a geothermal database from freely available (open source) or accessible data, to carry out a territorial resource and infrastructure assessment and to create "Favorability Maps" for each of the Central American countries. The study focused on data collection, creating a regional geothermal database, developing a territorial demand estimate and compiling favorability maps. With the developed classification scheme, not only conventional geothermal potential can be assessed, but also hot sedimentary aquifers and direct use of heat, where data is available to do so. The mapping project also defines a geothermal favorability index based on existing geological data or proximity to known geothermal anomalies.

Relevant geothermal entities in Central America, such as universities, utility companies, chambers of industry, and relevant ministries were contacted in order to obtain freely available data. This report summarizes the preliminary results for Costa Rica, since the data available for this country turned out favourable in resolution and quality. It presents the processed data and the development steps of a GIS processing and analysis scheme used to test the data on its applicability and performance for the favourability map. The resulting workflow can be applied for the other countries. The final web-based favourability map, as it is available online, will be presented.

2 DATA

2.1 Data Situation

For most of the region, the geothermal data situation relevant for a desired favourability map is heterogeneous and has to be unified significantly in order to be comparable and processable on a regional scale. Significant differences in data quality surfaced throughout the countries during the initial data assessment; the available data varied in resolution and especially in availability, particularly for digital formats. In Costa Rica, e.g., there is plenty of data available on geology, infrastructure, census, and energy (e.g. powerlines) in digital and GIS format, whereas for Panama or Nicaragua, data and its accessibility is limited. Geological maps and data are only partly available in a unified resolution over the Central American countries. Data on infrastructure or demand in a reconnaissance map resolution is also only available when digitized from publications.

Given the difficult data situation, the favorability maps regarding energy demand were derived from open source data. Relevant ancillary data was added as self-sufficient datasets (layers) depending on data availability and quality for the country.

2.2 Data Acquisition

The overall data acquisition was determined by distinguishing reservoir (subsurface) and energy demand (surface) information. Subsurface geological data is usually scientific data and hence available through publications. Papers and online publications were reviewed, and if necessary homogenized, digitised and georeferenced to a GIS compatible data format. Table 1 gives an overview of the geo-data acquired and references.

Table 1: Overview of data sources acquired for the determination of the reservoir indicators (subsurface indicators).

Content	Author	Name/Description
Seismicity	NOAA (2019)	NCEI/WDS Global Significant Earthquake Database, 2150 BC to Present
Volcanoes	Smithsonian Institution (2019)	Global Volcanism Program
Geology	Ortiz-Malavasi, Edgar (2014)	Atlas de Costa Rica
Hot springs	Bundschuh (2008)	Evaluación de los recursos geotérmicos de baja entalpía
Faults	Ortiz-Malavasi, Edgar (2014)	Atlas de Costa Rica

Surface information is usually also freely available up to a certain resolution; however, if needed in higher resolution (especially the energy demand data) open access and availability is restricted. Direct communication with relevant entities was initiated during the project, but most of the data provided was not available in a GIS compatible format and could not be integrated in the favourability map as such. As a workaround, information from web data was identified and found relevant to calculate energy demand estimations in a suitable resolution. Information from the IDB Energy Database (Espinasa & Hester, 2016) in combination with spatial data from OpenStreetMaps (© OpenStreetMap contributors, 2019) was used.

The IDB Energy Database contains information on national electricity demand (MW) categorized by sectors: industrial, residential and general. The first category includes all the major consumers such as e.g. manufacturers, major airports and harbors, while the second includes housing establishments and residential areas and the latter the remaining consumers, with exception of the transportation sector. The OpenStreetMap (2019) database renders the corresponding spatial data.

To access the data from OpenStreetMap, the QuickOSM plugin for the QGIS program was used, which is designed to receive and process the data. An overview of the acquired data and source is given in Table 2.

Table 2: References for the energy demand.

Content	Author	Name/Description
Energy demand	Espinasa & Hester (2016)	Dataset: Energy Database, Interamerican Development Bank IDB
Industrial Sector	© OpenStreetMap contributors (2019)	Large industries including manufactures, major airports and harbours
Residential Sector	© OpenStreetMap contributors (2019)	Housing establishments and residential sectors
General Sector	© OpenStreetMap contributors (2019)	Electricity consumers that are not industrial or residential such as schools, hospitals, governmental establishments, universities, etc.

Additional data for each country (where available) such as main roads, power lines, power stations and power plants was then added to the resulting demand map as reference. The data obtained for Costa Rica is listed in Table 3.

Table 3: Ancillary information for Costa Rica.

Content	Author	Name/Description
Electricity demand	Ulate (2017)	Índice de Competitividad Cantonal Costa Rica 2006-2016
Energy consumers	PROCOMER (2018)	Lista_Empresas_Zona_Franca_Publica_web_27-03-2019
Energy consumers	Sis. Costarricense de Inform. Jurídica	IFA_06_Uso_Actual_del_Suelo_GAM
Sectors of the economy	Morales Aguilar et al. (2011)	Programa Estado de la Nación e INEC. 2013. Indicadores cantonales.
Demography	INEC (2017)	Estadísticas Vitales 2006 and 2016
Power Lines & Stations	Ortiz-Malavasi, Edgar (2014)	Transmission Lines and Substations
Main Roads	Ortiz-Malavasi, Edgar (2014)	Main Roads
Land Use	Ortiz-Malavasi, Edgar (2014)	Land Use

3 PROCESSING

3.1 Reservoir Classification (Subsurface Indicators)

The geothermal energy supply is coming from the subsurface and its potential is derived from geological features visible and accessible from the surface (see 5.1). Aravena & Lahsen (2013) developed a geothermal favorability map for Chile which is used in this study as a conceptual baseline. This includes a two-step approach according to data maturity and availability. For this study, data are considered to be available for the first of the two steps.

The data mentioned in the previous chapter was used to derive geothermal probability indicators. Data specifications and GIS analysis is described in the following section and the maps are shown in Figure 2. For the purpose of further GIS analysis, a general classification scheme was applied, ranging from 0-10, with 0 for low and 10 for high potential.

3.1.1 Fault Density

The proximity to and density of geological faults is used as an indicator for higher thermal gradients. Figure 2a shows the known geological faults (Ortiz-Malavasi, 2014) transformed into a line-density raster image. A classification scheme is applied based on density per square kilometre.

3.1.2 Proximity to Volcanoes

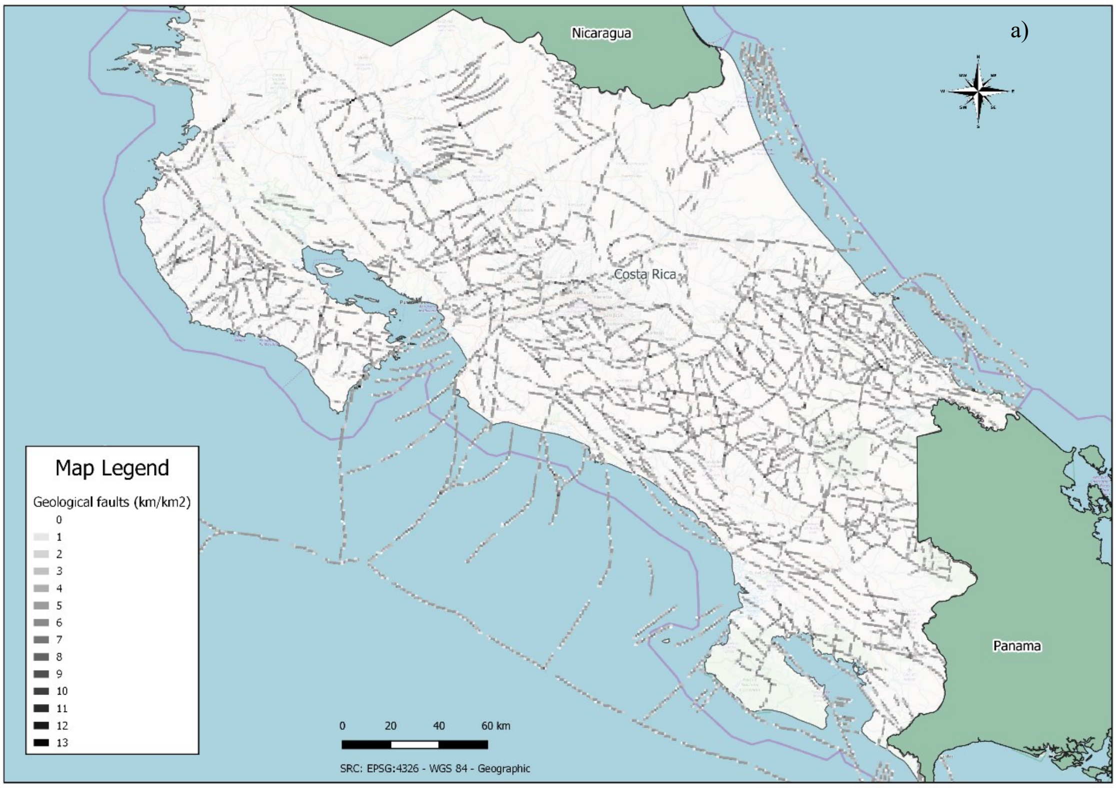
Volcanoes indicate the presence of an active heat source in the subsurface and thus a higher thermal gradient. Figure 2b shows the location of major volcanoes (Smithsonian, 2019) with a classification based on the proximity to the crater. The area covering a radius of 5 km around the crater is classified as 10, the classification then decreases to 0 over 20 km.

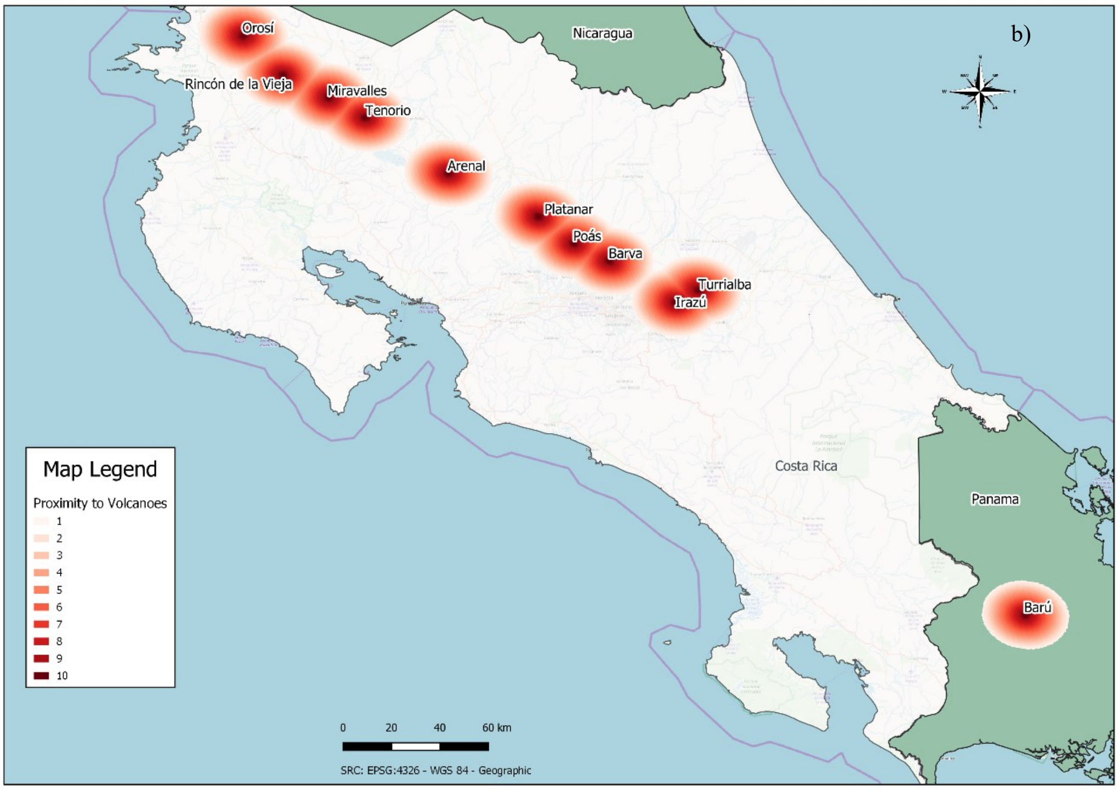
3.1.3 Volcanic and Sedimentary Rocks

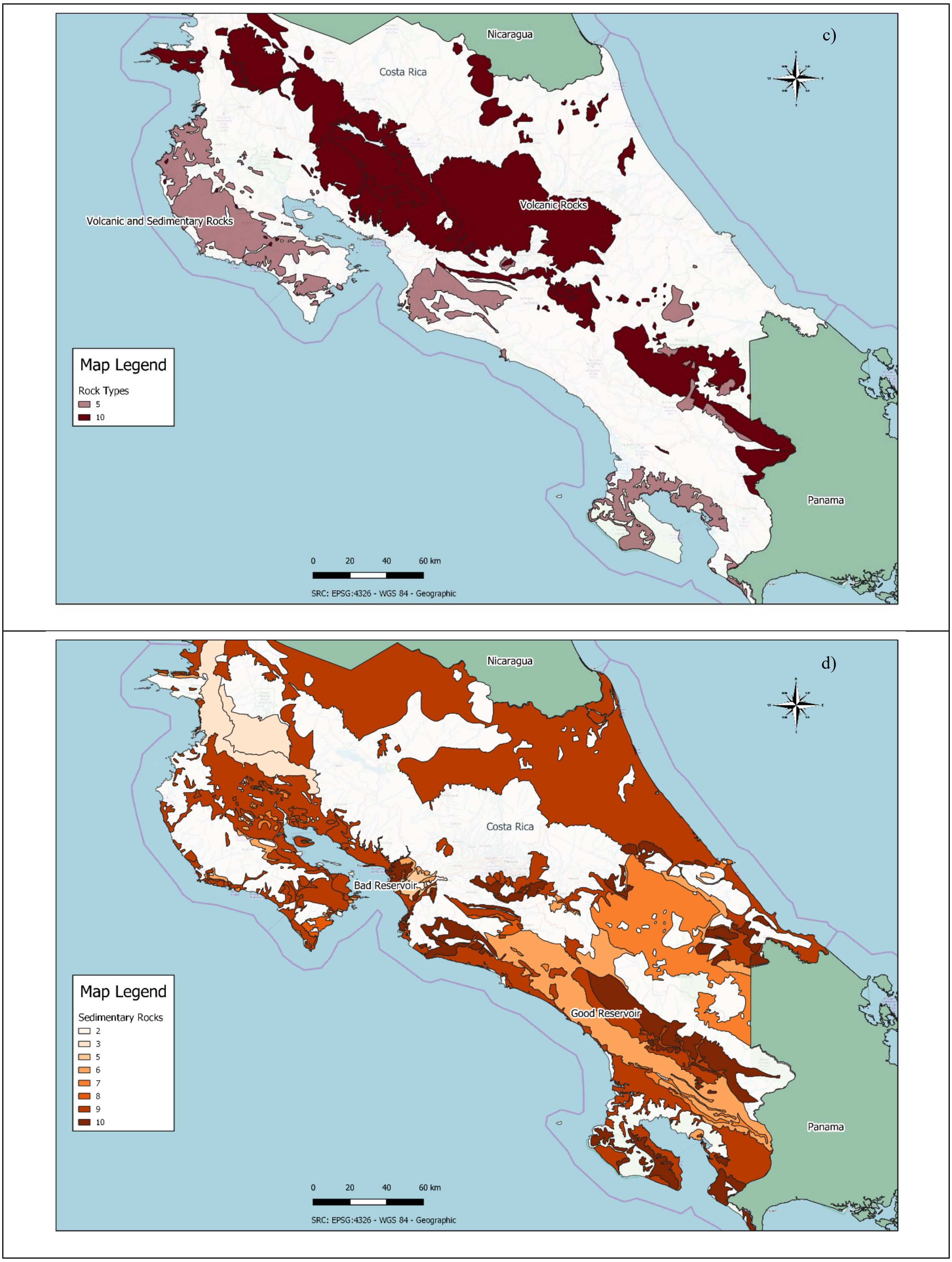
The geology map after Ortiz-Malavasi (2014) was used as input for two layers of different rock types.

Figure 2c displays the classification focusing on volcanic rocks and mixed volcanic/sedimentary rocks. The classification scheme assigns a higher potential (10) for volcanic rock, since its brittle behaviour and tendency to form fractures under stress causes for better aquifer conditions. Mixed volcanic/sedimentary rock on the other hand may show reduced permeability due to intercalated clastics and are therefore assigned the value 5.

The classification shown in Figure 2d takes solely sedimentary units into account, but is nevertheless similarly based on expected petrophysical properties. These include the aquifer potential (0 – poor, 10 – high), with higher potential assigned to high probabilities of the occurrence of either clean sandstone and/or fracture porosity, and lower potential to more impermeable, fine grained clastic sediments deposited in low energy environments.


a)
Nicaragua
Costa Rica
Panama
Map Legend
Geological faults (km/km2)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
0 20 40 60 km
SRC: EPSG:4326 - WGS 84 - Geographic


b)
Nicaragua
Orosí
Rincón de la Vieja
Miravalles
Tenorio
Arenal
Platanar
Poás
Barva
Turrialba
Irazú
Costa Rica
Panama
Barú
Map Legend
Proximity to Volcanoes
1
2
3
4
5
6
7
8
9
10
0 20 40 60 km
SRC: EPSG:4326 - WGS 84 - Geographic


c)
Nicaragua
Costa Rica
Volcanic Rocks
Volcanic and Sedimentary Rocks
Panama
Map Legend
Rock Types
5
10
0 20 40 60 km
SRC: EPSG:4326 - WGS 84 - Geographic
d)
Nicaragua
Costa Rica
Bad Reservoir
Good Reservoir
Panama
Map Legend
Sedimentary Rocks
2
3
5
6
7
8
9
10
0 20 40 60 km
SRC: EPSG:4326 - WGS 84 - Geographic

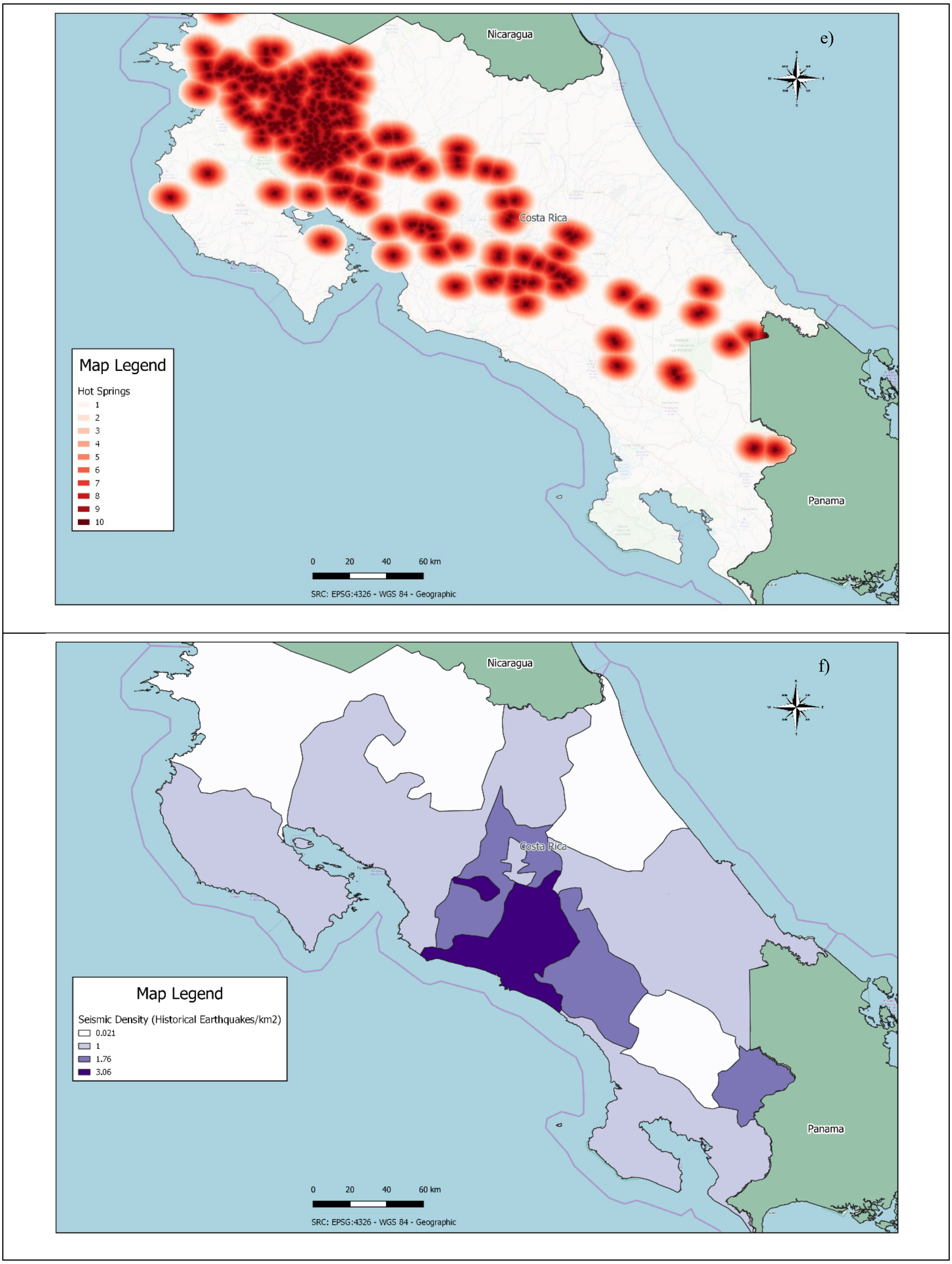


Figure 2: Indicators for subsurface potential in Costa Rica, following the workflow. Classification based on a) density of known geological faults per square kilometre, b) proximity to major volcanoes, c) share of volcanic rock, d) grainsize of sedimentary rock, e) proximity to hot springs, and f) density of seismic events.

3.1.4 Hot Springs

Hot springs are commonly used as an indicator for geothermal potential. However, this information is often biased since measurements are repeatedly not standardized and the process for the temperature development is often not clear. Nevertheless, Costa Rica's hot spring locations in Figure 2e are used as a layer for the favourability map creation and is based on recorded thermal manifestations throughout the country (Bundschuh, 2008). The classification is related to the spatial proximity to the spring, the increment is 0.5 km from 0-10 for a total radius of 5 km around each hot spring.

3.1.5 Seismic Density

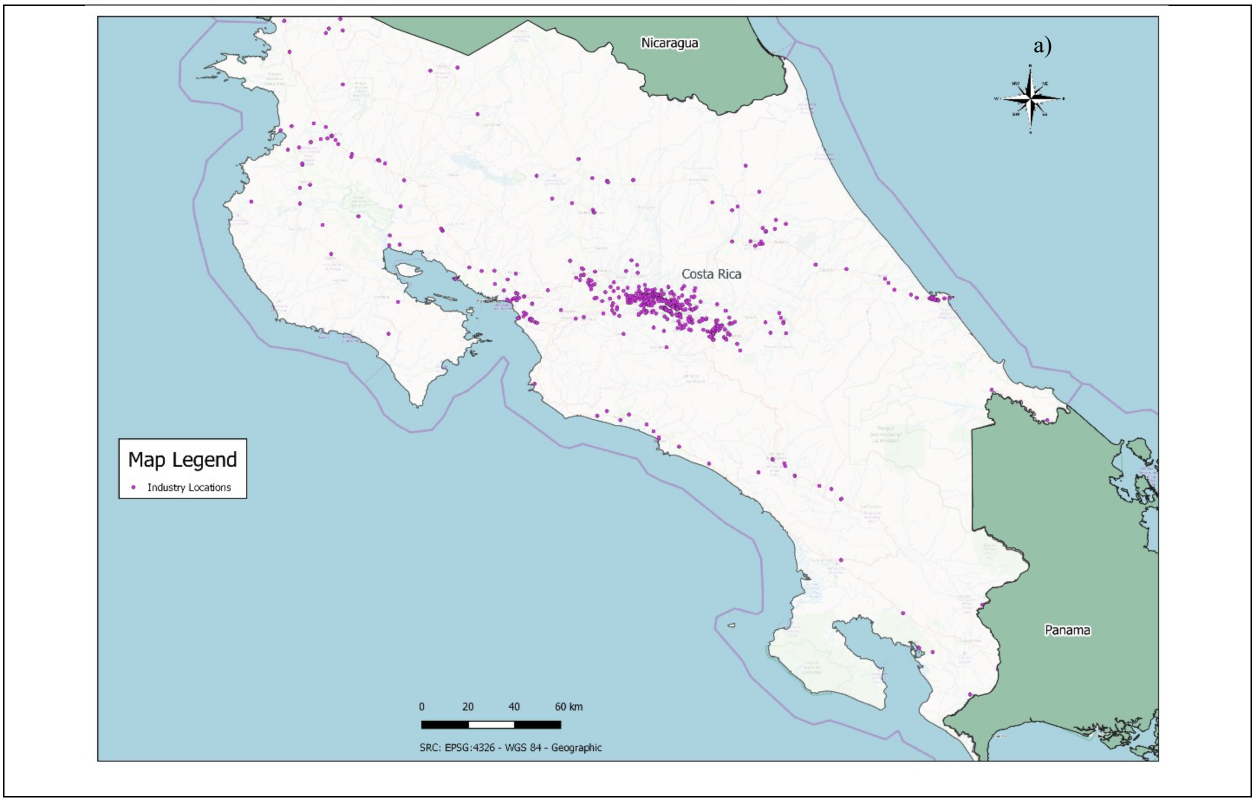
Seismicity is an indicator for subsurface activity and as such for a potential thermal anomaly. Figure 2f displays the seismic density derived from the amount of historic seismic events per square kilometre after NOAA (2019). The classification distinguishes among areas (marked polygons after NOAA (2019)) and is based on the average density of seismic events within each area.

3.2 Energy Demand (Surface Indicators)

The surface potential for geothermal projects is often driven by its spatial vicinity to the energy demand and/or infrastructural setting. Just like energy demand and the location of electricity consumers, population density, migration routes and existing infrastructure such as main roads, power lines and substations can be seen as an incentive for determining the location of a planned geothermal project. The following chapter describes the data used and prepared to determine surface potential of a geothermal project.

3.2.1 Electricity Consumers by Sectors

The different energy sectors derived from OSM are available as polygons, lines and points. In a first step, polygons and lines were transformed into points by their center coordinate. Secondly, quality control and a harmonization process were necessary to assure that the points spatially fit to their origin and were not redundant. This was done manually by a visual onscreen interpretation together with high resolution imagery. Figure 3 shows the resulting point layers distinguished by the sectors Industrial (a), Residential (b) and General (c).



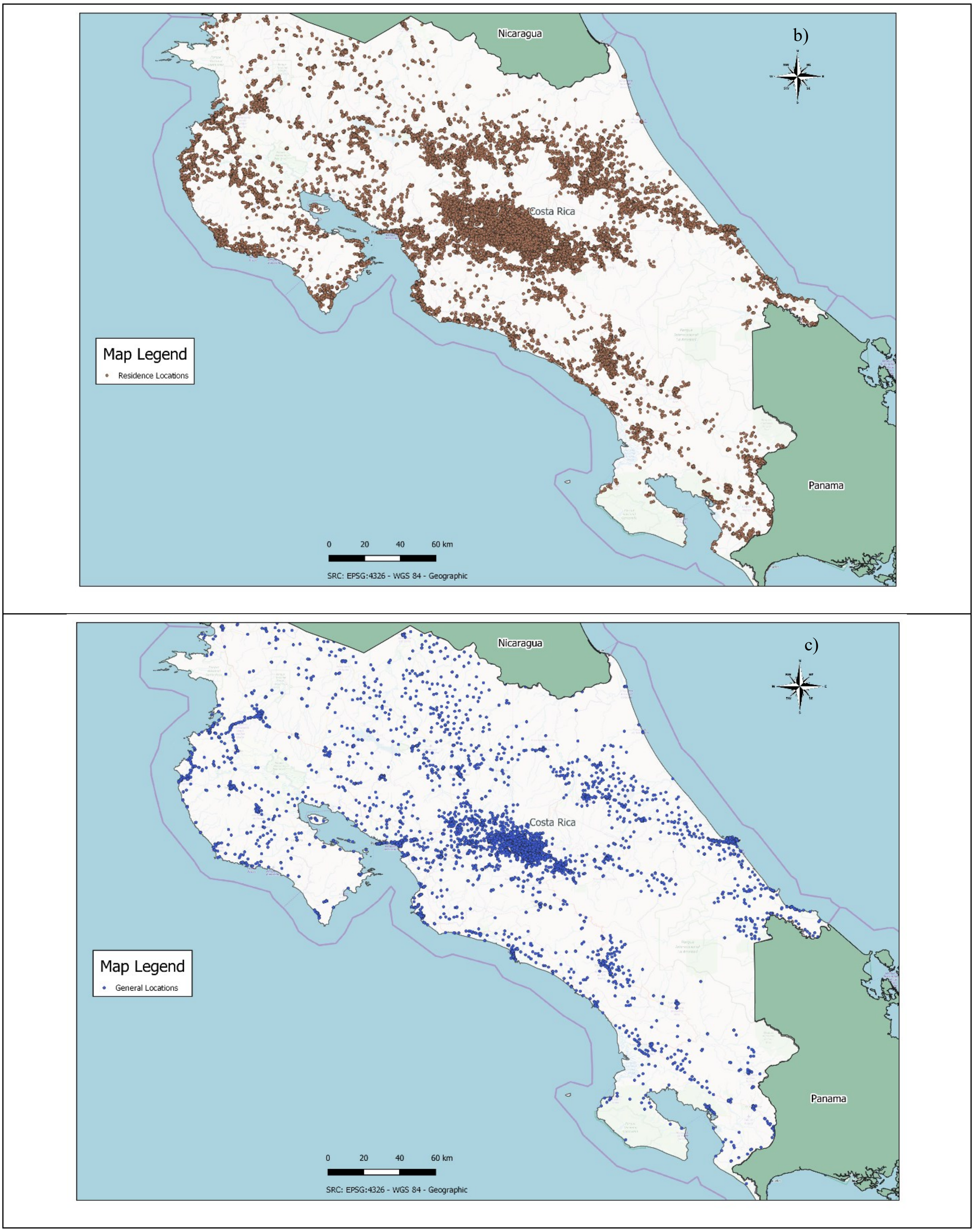
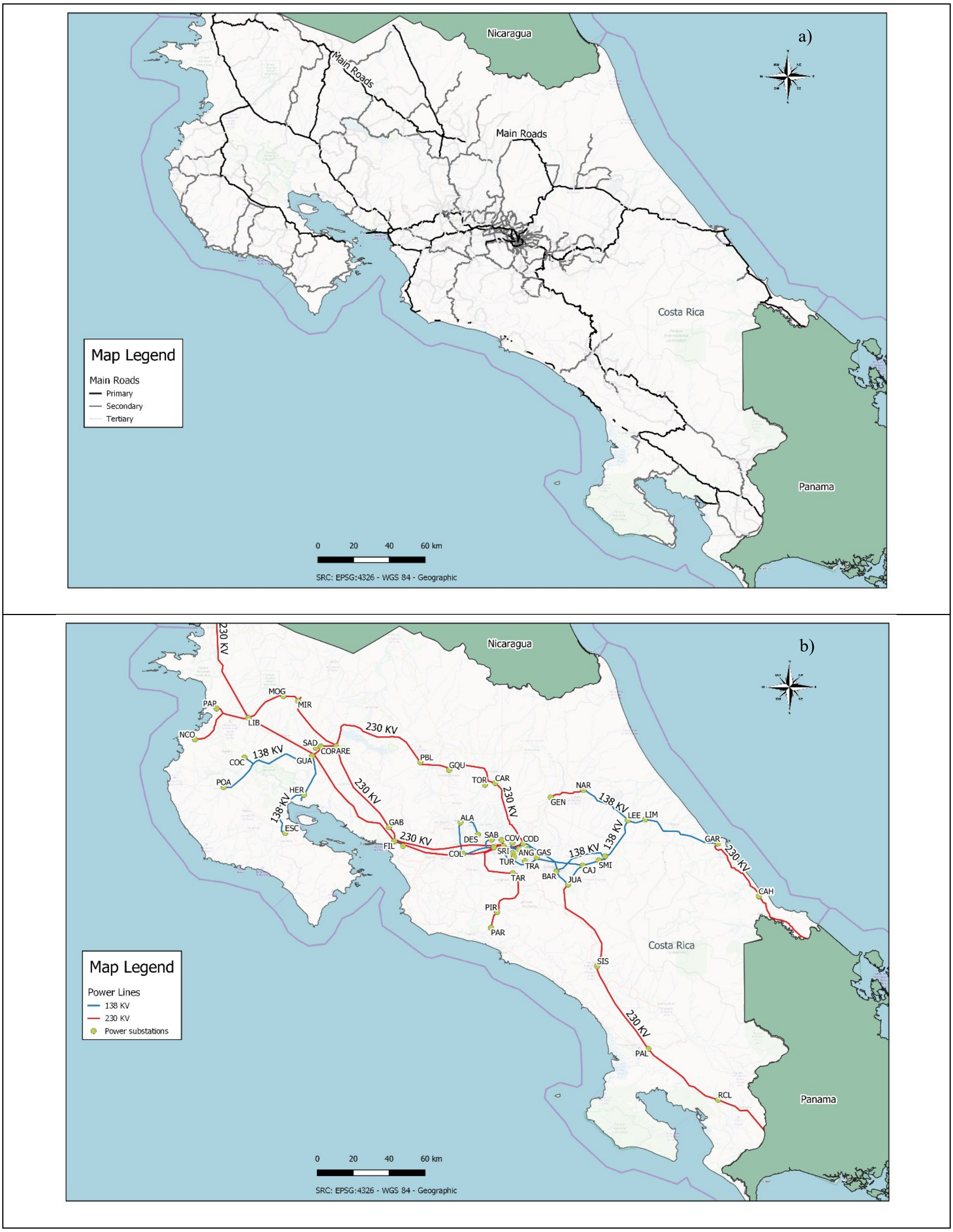


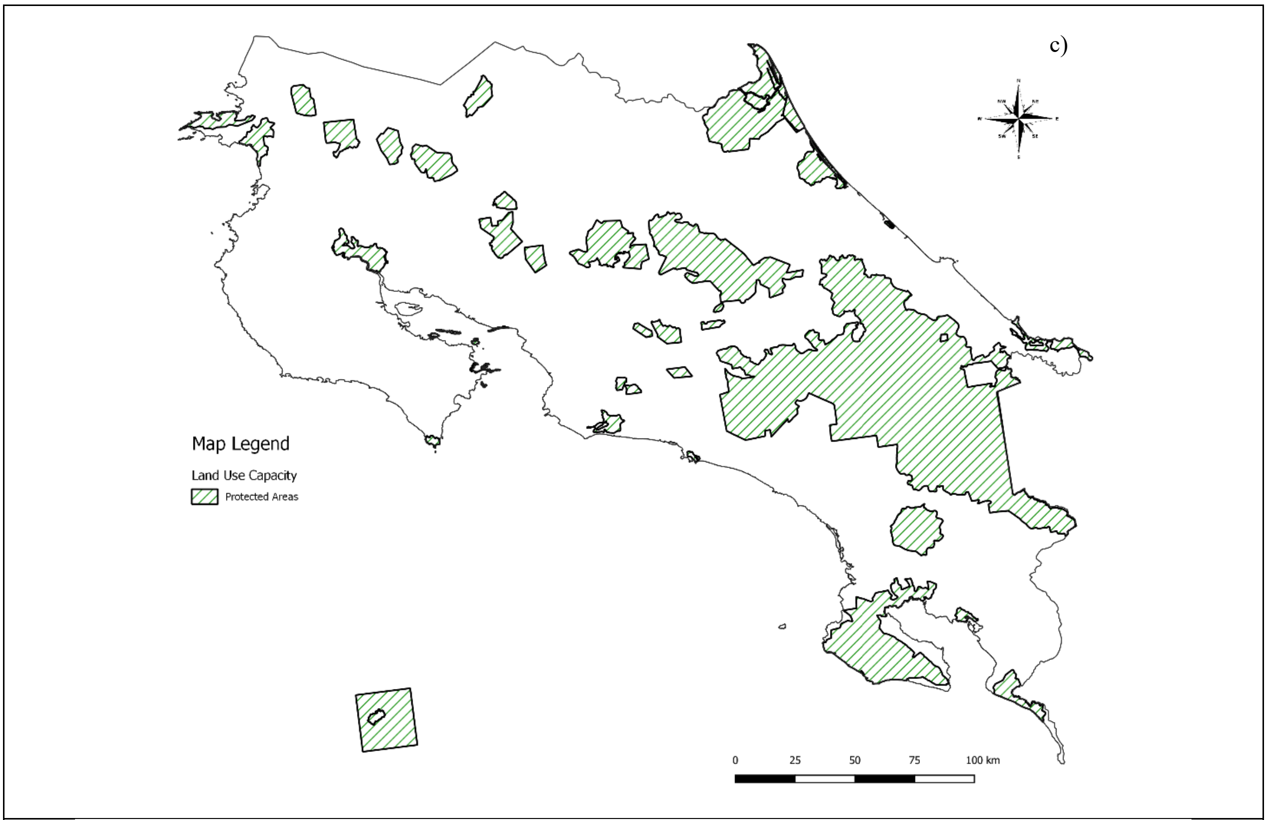
Figure 3: Point data according to sectors Industrial (a), Residential (b) and General (c) after manual quality control and harmonization.

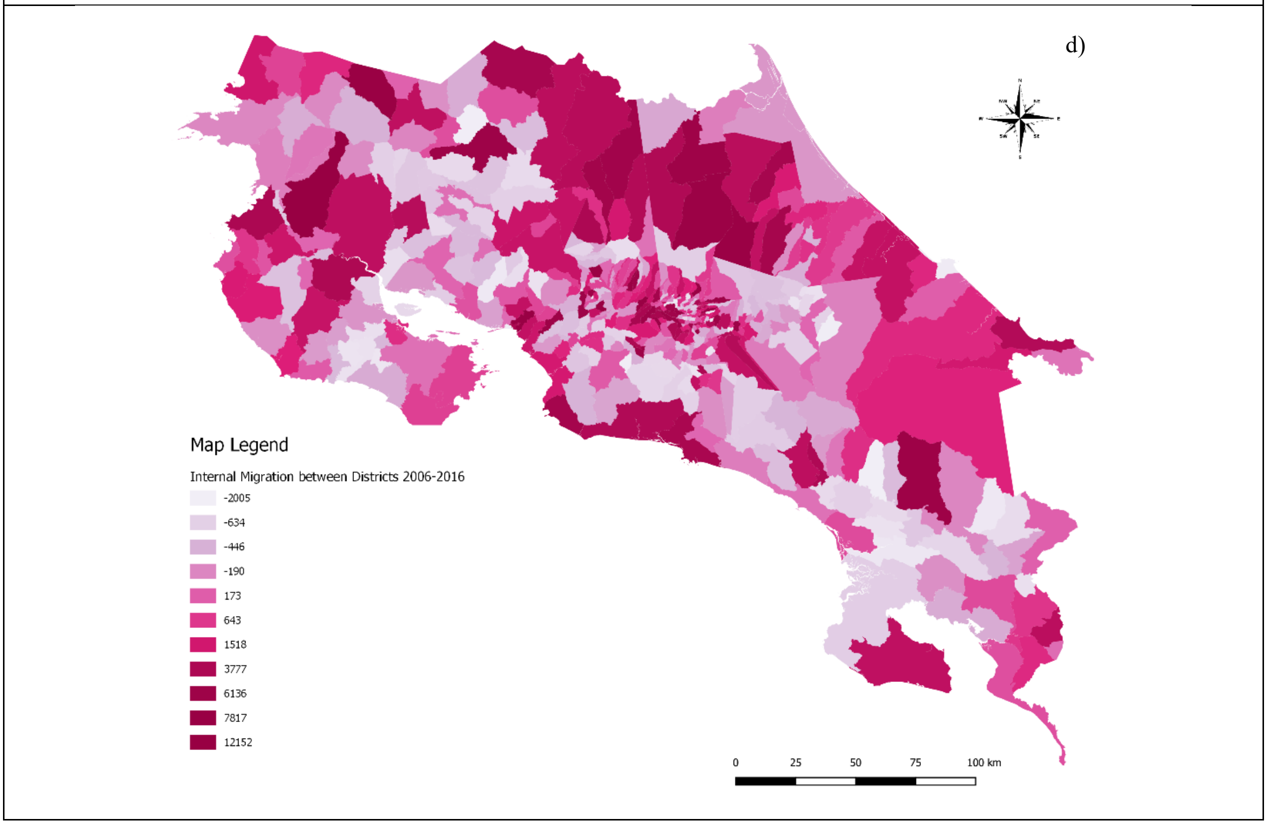
3.2.2 Ancillary Data (Background Information)

Ancillary data is added to the favorability maps as self-sufficient data in form of vector layers. These layers are indicative for setting a geothermal project and can give further insight for future developers.

Main Routes: The presence of a main route is considered as an indicator for economic activity in the area, which is favorable to start the first exploration activities for geothermal projects. Data is divided into primary, secondary and tertiary roads (see Figure 4a) and taken from the Atlas of Costa Rica (Ortiz-Malavasi, 2014).


a)
Nicaragua
Main Roads
Main Roads
Costa Rica
Panama
Map Legend
Main Roads
Primary
Secondary
Tertiary
0 20 40 60 km
SRC: EPSG:4326 - WGS 84 - Geographic
b)
Nicaragua
230 KV
PAP
MOG
MIR
LIB
NCO
230 KV
SAD
CORARE
COC
138 KV
GUA
POA
PBL
GQU
TOR
CAR
230 KV
HER
138 KV
ESC
230 KV
GAB
230 KV
FIL
ALA
DES
SAB
COV
COD
COL
SRI
ANG
GAS
TUR
TRA
TAR
BAR
JUA
CAJ
SMI
138 KV
138 KV
GEN
NAR
138 KV
LEE
LIM
GAR
230 KV
CAH
PIR
PAR
SIS
Costa Rica
230 KV
PAL
RCL
Panama
Map Legend
Power Lines
138 KV
230 KV
Power substations
0 20 40 60 km
SRC: EPSG:4326 - WGS 84 - Geographic


c)
Map Legend
Land Use Capacity
Protected Areas
0
25
50
75
100 km


d)
Map Legend
Internal Migration between Districts 2006-2016
-2005
-634
-446
-190
173
643
1518
3777
6136
7817
12152
0
25
50
75
100 km

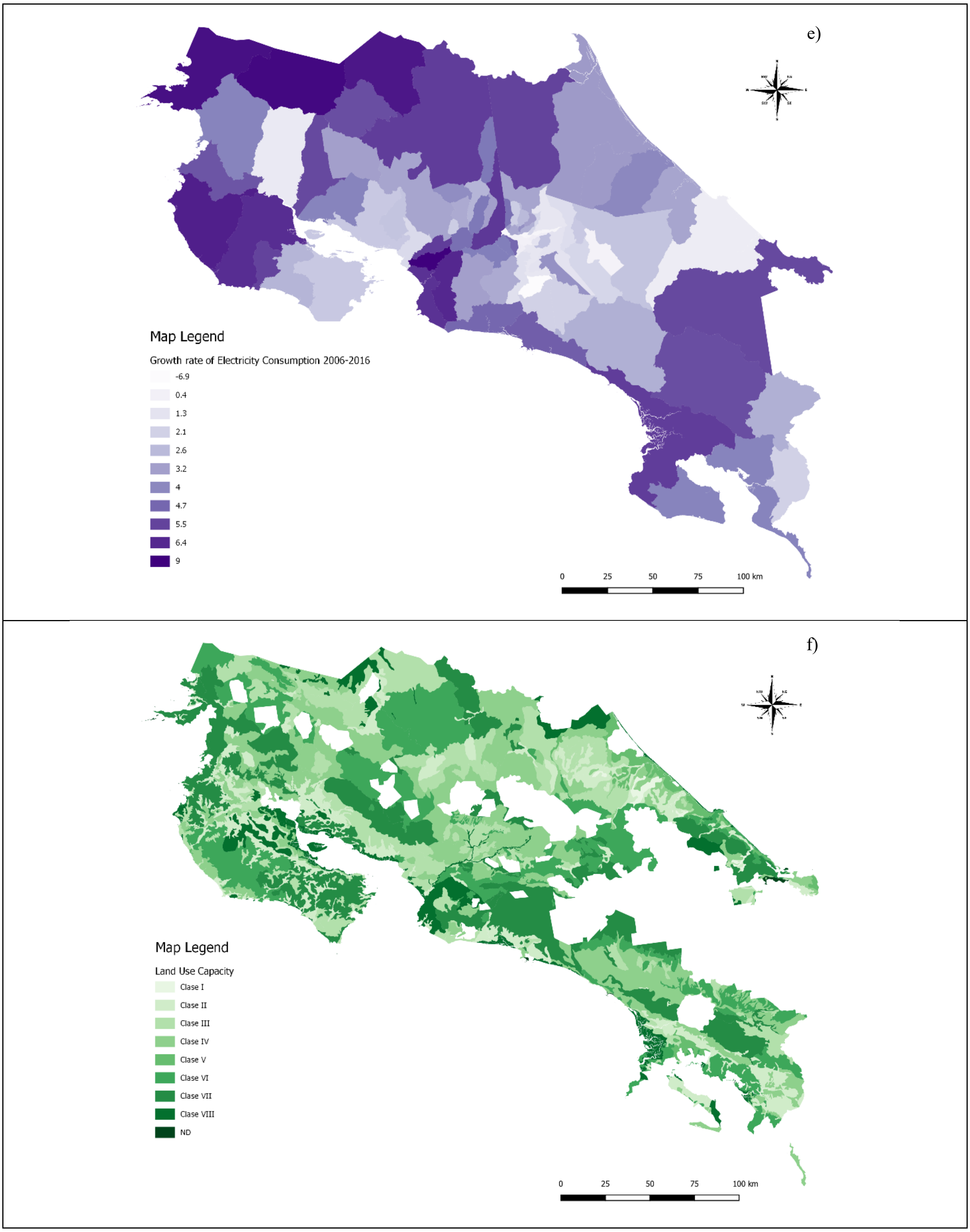


Figure 4: Indicators for surface potential in Costa Rica following the workflow: a) main routes, b) transmission electricity network, c) protected areas, d) migration within the country, and e) land use.

Transmission Electricity Network: Transmission power lines and substations are an important part of the infrastructure. The existence of this feature indicates opportunities to connect power plants to the electrical grid. It is also an indicator for economic activity in proximity to the substations. Data used is shown in Figure 4b, which distinguishes 138 kV and 230 kV power lines (Ortiz-Malavasi, 2014).

Protected Areas: The map displayed in Figure 4c shows the location of restricted areas indicating where project development is not permitted due to regulations for the protection of the environment (Ortiz-Malavasi, 2014).

Migration within the Country by Districts: This parameter shows the change in population and can be assumed as an indicator for the increase in energy consumption. The migration phenomenon was derived from "Estadísticas Vitales 2016" (INEC, 2017) (Figure 4d).

Increments of Energy Consumption – average (Period 2006 – 2016): On the base of the increments in energy consumption (Ulate, 2017) for 10 years, Figure 4e displays the growth rate for each district. This parameter can be considered for a prognosis of future energy consumption.

Land-Use Classification: The land-use layer highlights regions according to their sustainability (Figure 4f). Regions classified with values from I to IV are intensively used for agricultural purposes. These specific uses of the soil indicate energy requirements (direct use) with regard to the industrialization of agricultural products. (Ortiz-Malavasi, 2014)

3.3 Favorability Analysis

3.3.1 Weighting of Indicators

Aravena & Lahsen (2013) developed a geothermal favorability map for Chile using GIS analysis processing with raster calculations. Based on the available data, this calculation was adapted to the conditions in Central America, respectively for Costa Rica. The GIS processing yielded layers comprised of pixels containing a classification value. Aravena & Lahsen (2013) distinguish between "individual" and "global" coefficients in their weighting process (see Table 4). With regard to the global coefficients, all geological indicators are assigned with higher factors to emphasize their significance against geochemical and geophysical indicators. Subsequently, a further differentiation into individual coefficients is made to illustrate the greater importance of rock units and volcanic activity compared to fault density. Furthermore, the probability along the volcanic arc and in the sedimentary basins is regarded differently.

Table 4: Coefficients for each layer and group according to Aravena & Lahsen (2013).

Description	Individual coef.	Global coef.
Geological Map	0.4	0.6
Fault density per square km	0.2	
Volcanoes proximity (25 km)	0.4	
Hot springs proximity (5 km)	0.4	0.3
Historical Earthquake density per square km	0.1	0.1

3.3.2 Geothermal Favorability in the Volcanic Arc

The geothermal favorability in the Volcanic Arc zone is determined using of **Error! Reference source not found.** (adapted from Aravena & Lahsen (2013))

$$GFv = 0.6 * (0.4 * A + 0.2 * B + 0.4 * C) + 0.3 * (0.4 * D) + 0.1 * (0.1 * E) \qquad [1]$$

where GFv is the geothermal favorability index of the volcanic arc, A is the classification value of the geological map layer, B is the classification value of the fault density layer, C is the classification value for proximity to volcanoes, D is the classification value for proximity to hot springs, and E is the classification value for seismic density.

3.3.3 Geothermal Favorability in the Sedimentary Basin

Accordingly, **Error! Reference source not found.** is used to calculate the geothermal favorability in the Sedimentary Rock zone (adapted from Aravena & Lahsen (2013)). In contrast to Equation 1, the volcanic arc A is replaced by the sedimentary rock layer F.

$$GFs = 0.6 * (0.4 * F + 0.2 * B + 0.4 * C) + 0.3 * (0.4 * D) + 0.1 * (0.1 * E) \qquad [2]$$

GFs is the geothermal favorability index in sedimentary rocks, F is the classification value of the sedimentary geologic map layer, and other terms are as described in Equation 1.

3.3.4 Energy Demand Classification

Due to the lack of a consistent dataset on the energy consumption in the region, a statistical approach was chosen. This approach averaged the overall electricity demand per sector and use, and created a density map based on a grid of 1x1 km^2 resolution. **Error! Reference source not found.** provides the energy demand

$$ED = \left((NPD * SS) \div TPS\right) * GEP \qquad [3]$$

where ED is the average energy demand per grid element (MW), NPD is the national power demand (MW), SS is the sector share of total power demand (%), TPS is the total points per sector, and GEP is the number of points within each grid element (point density).

4 RESULTS

4.1 Reservoir Favorability (Subsurface Indicators)

4.1.1 Geothermal Favorability in the Volcanic Arc

Figure 5a shows the geothermal favorability in the volcanic arc from the source or reservoir aspect. The best favorability occurs where expected reservoir properties i.e. volcanic and clastic rock units are in a close distance to existing and active volcanoes. With growing distance to the volcanoes, the favorability decreases and is only locally enhanced in areas where faults are mapped, seismic activity is high, or springs with a temperature anomaly are located.

4.1.2 Geothermal Favorability in the Sedimentary Basins

Figure 5b indicates the favorable areas where only sedimentary rocks are expected. Aquifer potential according to the rock types are discussed in section 3.1.3. The favorability decreases with growing distance to active or known volcanoes.

4.2 Electricity Demand - Surface Potential

The results of the energy demand assessment for the industrial sector (Figure 6a), the residential sector (Figure 6b) and the general sector (Figure 6c) include a classification according to the calculated statistical demand in MW. Each pixel represents an area of one square kilometre, and is assigned a value by the calculation based on the average statistical demand value per point.

5 DISCUSSION AND CONCLUSIONS

5.1 Resource Assessment

Figure 7 displays the concept of the geothermal systems as a basis for this favorability study.

It differentiates between the following regions:

- Volcanic sediments in the vicinity of a volcano with a magma chamber as the heat source: The aquifer properties in the upper horizons are assumed to be fair to good and the heat flux is high. A cap rock covers the deep reservoir, earthquakes may occur. Since the major heat source is located here, the potential of encountering hot groundwater is high, indicated by a high potential in the favorability map. Hot springs are present downhill when shallow groundwater heats up and discharges along layer boundaries or faults. Elevated areas of the volcano mountains are probably the major recharge areas.
- Areas with combined volcanic and sedimentary units: Here, the situation is quite similar, however, the potential has to be estimated successively lower due to fair to poor aquifer properties of potentially more intercalated or fine-grained deposits and less heat flux with distance to the magma chamber. With increasing distance to the heat source, the surface groundwater may be mixed again with colder meteoric water, lowering the water temperature.
- Areas with sedimentary units: Meteoric and colder water dominates the near surface groundwater, the influence of the magmatic heat source is decreasing. Fault anomalies may locally interrupt this effect and warm/hot water may be present adjacently. The deep aquifers are potentially very suitable for low to medium enthalpy geothermal projects, however, in most cases the actual depth/geothermal gradient and the hydraulic aquifer properties must be validated by pilot drillings.

5.2 Application Example

The objective of this study was to bring together surface and subsurface potential by combining high-resolution energy demand data with low resolution geological information. As an extract of the above presented results, Figure 8 shows the combined analysis results for the area surrounding the city of San Jose, demonstrating the application of the developed workflow.

The example shows, how decision makers can use the information provided to identify their potential project. The developed map can be used to locate possible areas of interest or to provide an initial assessment of the viability of a conceptual project in Central American countries. Nonetheless, following restrictions need to be kept in mind when using the favorability map:

- It was not possible to distinguish between power and heat demand due to the lack of further data. Still, a certain spatial relation and, in some cases, also a dependency of both can be assumed.
- The visual interpretation and manual harmonization process includes an uncertainty regarding location and quantity assessment of power consumers, however, this being the character of a favorability map, the trained user should be aware of this restriction.
- The approach of statistical averaging of the power demand is inappropriate for a more detailed assessment, however it should not be the intention of a favorability map to replace a dedicated feasibility study.

Finally, in an appropriate feasibility study a closer look must be taken at the geology and hydrogeology, hydrochemistry and geophysics as well as the identification of heat (direct use) and electricity users or access. The GDF assigns for surface studies additional exploration drillings (Dickson & Fanelli, 2005). In practice, however, this is usually only done for high enthalpy reservoirs, whereas for low enthalpy reservoirs the first drilling is generally already planned as a production well since overall project size and budgets are smaller scale.

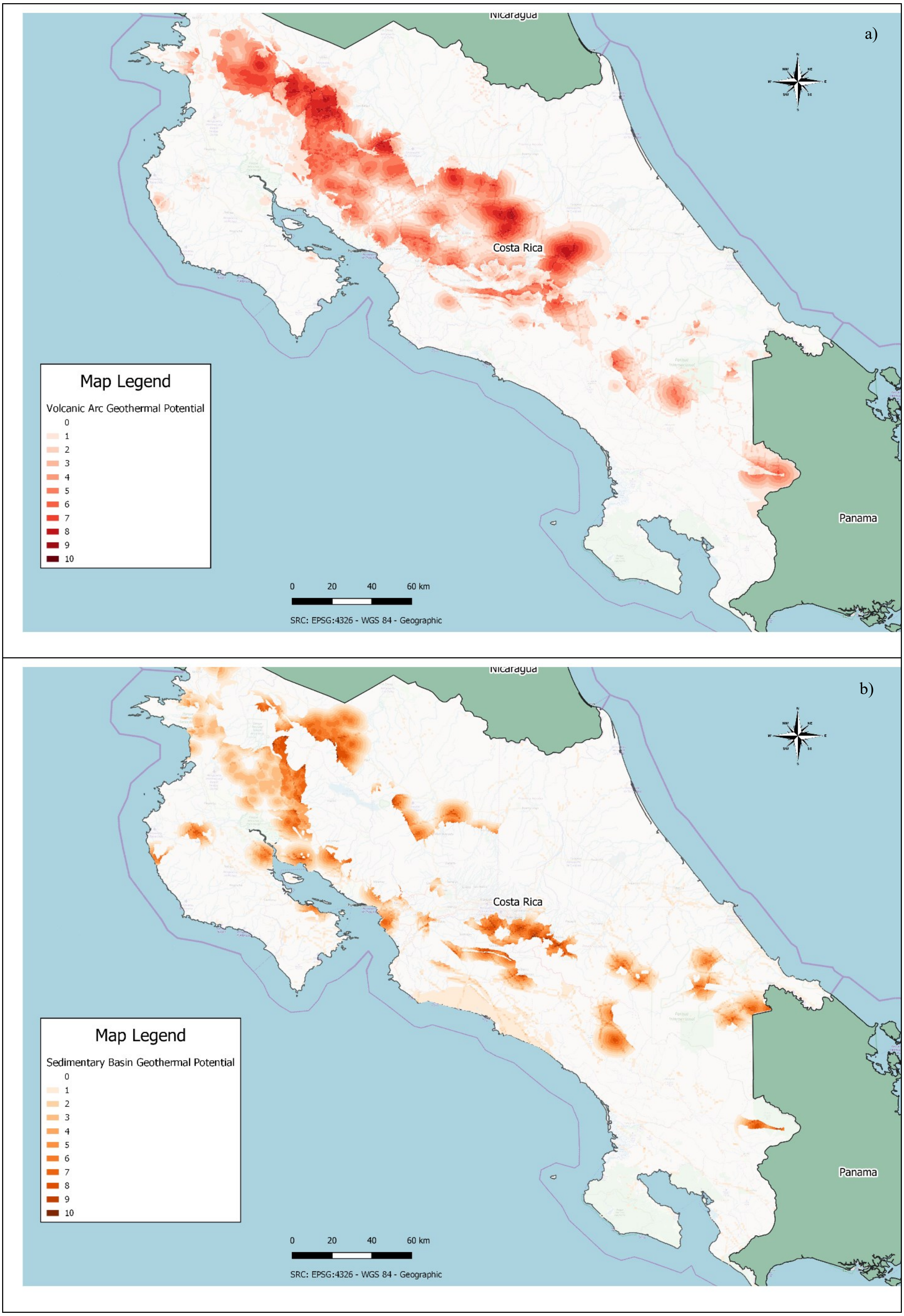
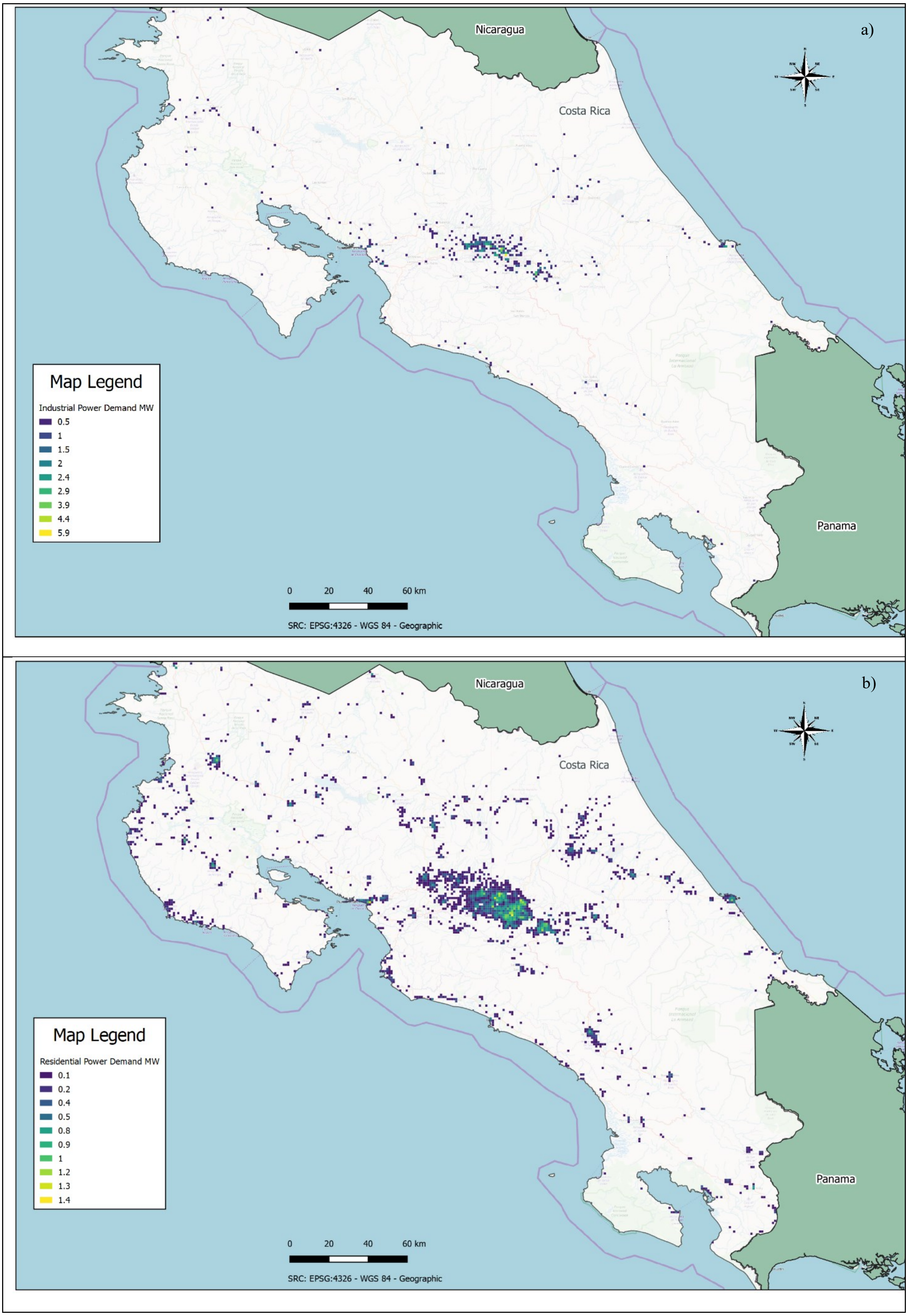


Figure 5: Geological favorability maps for a) the volcanic arc and b) the sedimentary basin.


a)
Nicaragua
Costa Rica
Panama
Map Legend
Industrial Power Demand MW
0.5
1
1.5
2
2.4
2.9
3.9
4.4
5.9
0 20 40 60 km
SRC: EPSG:4326 - WGS 84 - Geographic
b)
Nicaragua
Costa Rica
Panama
Map Legend
Residential Power Demand MW
0.1
0.2
0.4
0.5
0.8
0.9
1
1.2
1.3
1.4
0 20 40 60 km
SRC: EPSG:4326 - WGS 84 - Geographic

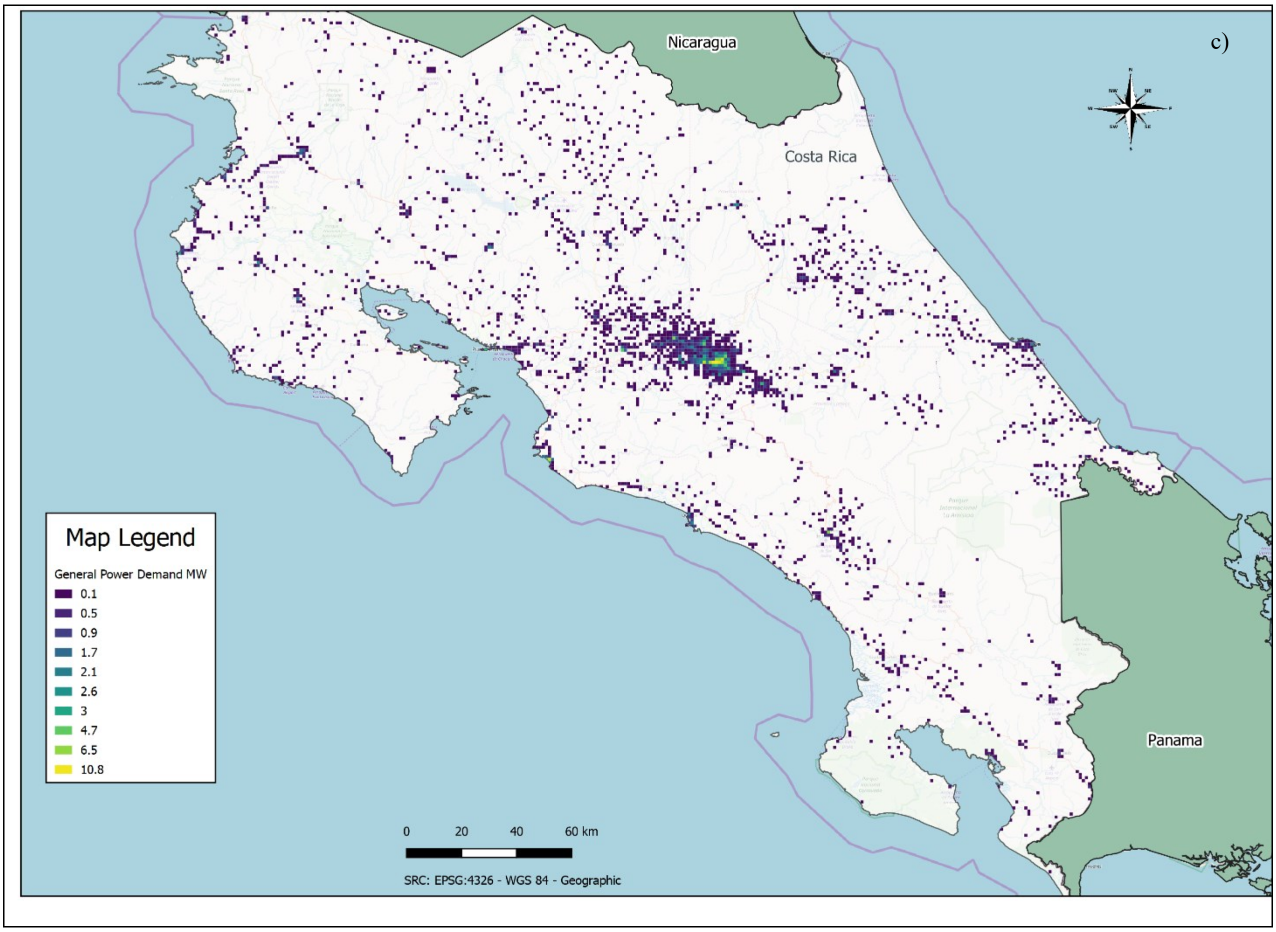


Figure 6: Sector based power demand in MW a) Industrial sector b) Residential sector c) General sector.

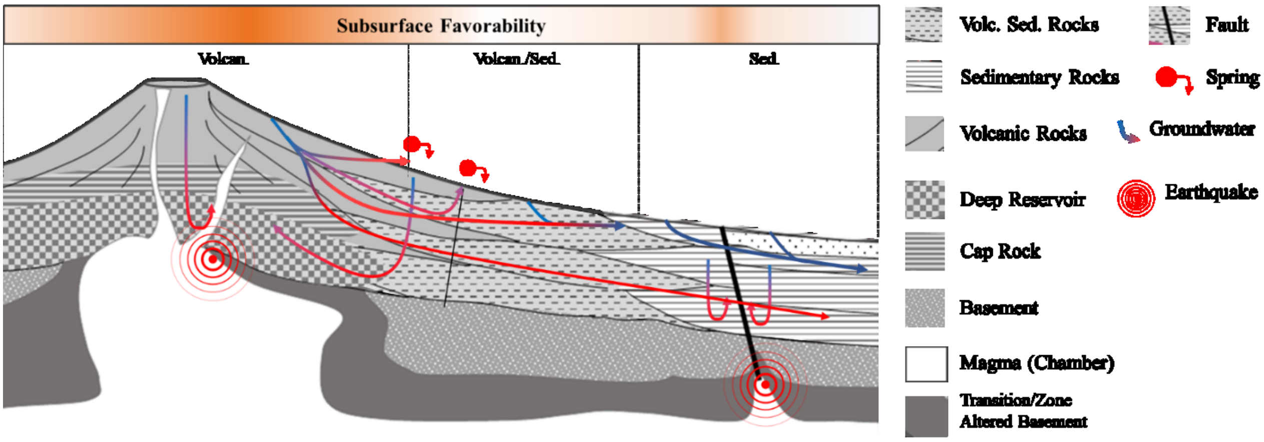


Figure 7: Sketch of geothermal energy sources according to their location with respect to the volcanic arc.

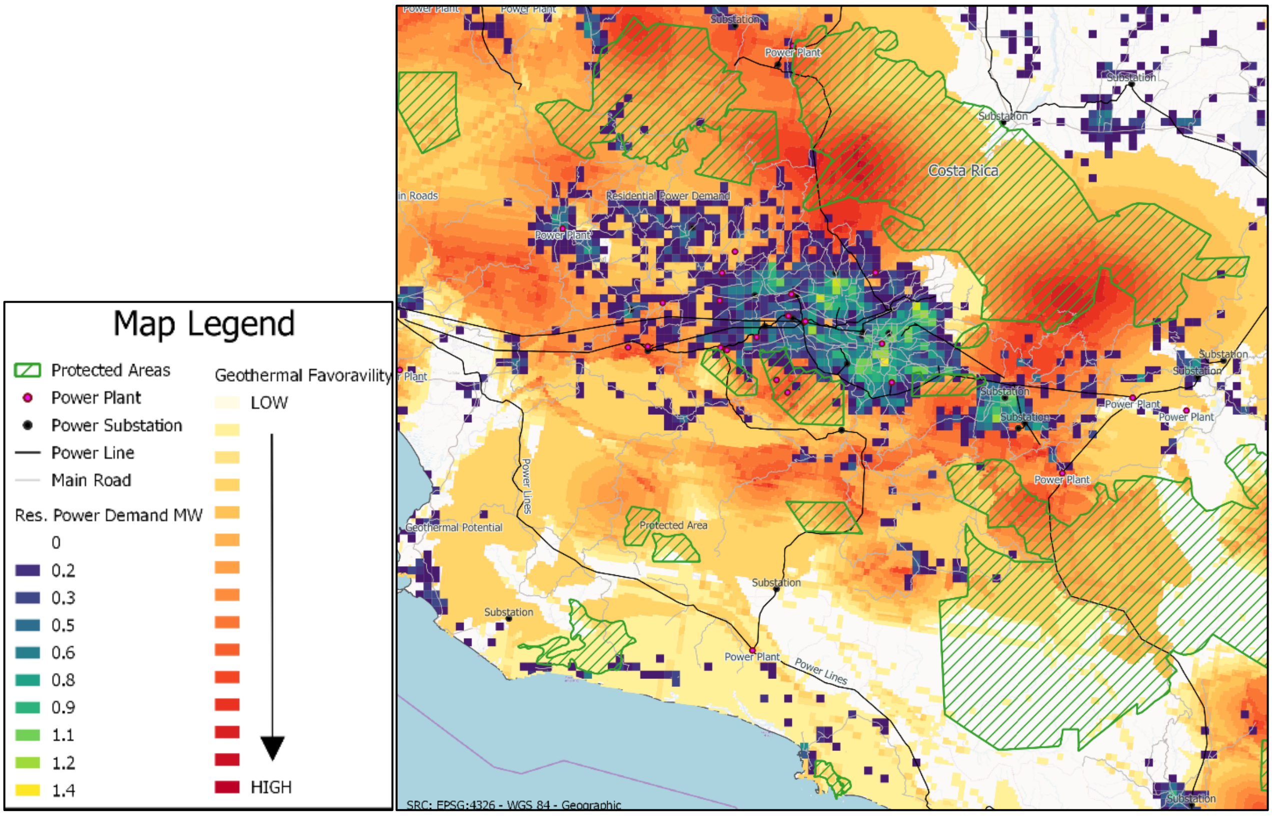


Figure 8: Geothermal favorability and residential power demand (MW) for the areas surrounding San Jose, Costa Rica.

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REFERENCES

© OpenStreetMap contributors. (2019, July). Openstreetmap.

Aravena, D., & Lahsen, A. (2013). A geothermal Favorability Map of Chiles, Preliminary Results. (Universidad de Chile, & CEGA, Eds.) *GRC Transactions*.

Bundschuh, J. (2008). *Evaluacion de los recursos geotermicos de baja entalpia.* San Jose, Costa Rica: Instituto Costaricense de Electricidad.

Dickson, M., & Fanelli, M. (2005, 6 8). *Geothermal Energy: Utilization and Technology.* Paris: Routledge. Retrieved from http://www.thinkgeoenergy.com/

Espinasa, R., & Hester, A. (2016, October). Dataset: Energy Database. Washington, DC, USA.

INEC. (2017). *Estadisticas Vitales 2016.* San Jose, Costa Rica: INEC.

Morales Aguilar, N., Segura Carmona, R., Rodriguez Calvo, S., Solano Salazar, E., Mora Prado, O., & Mora Steiner, S. (2011). *Indicadores cantonales. Censos Nacionales de Poblacion y Vivienda 2000 y 2011.* Costa Rica: Programa Estado de la Nacion.

NOAA. (2019, April 5). *National Geophysical Data Center/World Data Service: NCEI/WDS Global Significant Earthquake Database.* Retrieved from National Centers for Environmental Information: https://data.noaa.gov/metaview/page?xml=NOAA/NESDIS/NGDC/MGG/Hazards/iso/xml/G012153.xml&view=getDataView&header=none

Ortiz-Malavasi, E. (2014). *Atlas de Costa Rica 2014.* Tecnologico de Costa Rica.

Procomer. (2018). *Empresas del Regimen de Zona Franca.* Retrieved from Procomer: https://www.procomer.com/es/

Smithsonian. (2019, May 1). *Global Volcanism Program*. Retrieved from Smithsonian Institution: https://volcano.si.edu/

TGE, IGA, & GEA. (2017). *Central America Installed Capacity & Projects.* Think GeoEnergy.

Ulate, A. (2017). *Indice de Competitividad Cantonal 2006-2016.* San Jose, Costa Rica: Universidad de Costa Rica.