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A GIS-based Multi-Criteria Analysis for Suitability Assessment of Micro Hydropower Stations

A Case Study from Suriname

by

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Zürich, August 8th 2017

SCIENCE PLEDGE

By my signature below, I certify that my thesis is entirely the result of my own work. I have cited all sources I have used in my thesis and I have always indicated their origin.

Zürich, August 8^{th} 2017 ___________________________

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PREFACE

On a global scale, electricity and heat generation account for more than 40 % of CO2 emissions (International Energy Agency, 2016a). Electricity production is thus one of the main drivers of climate change. Due to an expected rising demand across all economies, global electricity consumption is forecasted to rise significantly in the coming decades (International Energy Agency, 2016b). If the commitment made in the Paris Agreement towards limiting global warming to 2 degrees is to be adhered to, then decarbonising of the economy has to proceed at a much faster pace than so far (ibid.). In addition, affordable and clean energy is one of the United Nation's Sustainable Development Goals (United Nations, 2015). Being "one of the most environmentally clean forms of energy with the least emissions of greenhouse gases among all the types of new and renewable energy" (Yi et al., 2010), small hydropower will be crucial. In the context of these broader global developments, vortex energy plants (VEPs) offer a co-benefit strategy for both contributing to de-carbonising the economy as well as providing development opportunities for local communities. In this study, a GIS-based generic suitability assessment procedure is developed that will provide a planning tool in order to enable a rapid and scalable implementation of a potentially large number of micro hydropower stations and thus contribute both to the mitigation of climate change and sustainable development.

ACKNOWLEDGMENTS

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Furthermore, my thanks go to Prof. Dr. Josef Strobl and Dr. Gudrun Wallentin for their competent support and advice, which contributed significantly to the successful conclusion of the thesis. I would like to extend my gratitude to the whole UNIGIS team at the Department of Geoinformatics of the University of Salzburg for their excellent content-related as well as administrative support throughout the course of my studies.
Last but not least, I would like to express my great personal gratitude to my family and friends for having given me encouragement and for being sympathetic when I have only dedicated limited time to them recently.

ABSTRACT

Vortex Energy Plants are a specific type of ultra low-head run-of-river micro hydro power plants. They offer a large potential in the context of rural electrification, since the technology and maintenance are unpretentious and the site requirements can be fulfilled accordingly.

A methodology based on GIS-Multi Criteria Decision Analysis has been developed in order to localize suitable sites for VEPs within a large area of interest. The decision model is based on the requirements *head*, *electricity demand* and *water availability*. These requirements are operationalized by the criteria of *slope*, distance to a village and distance to a water body and transformed into a suitability raster by a Weighted Linear Combination procedure. The criteria's value ranges are defined such as to identify all feasible alternatives. A ranking methodology has been designed in order to compare and rank the feasible alternatives.

While the developed methodology does not deliver exact single locations for VEP development, it provides perimeters with high probabilities of being suitable, which can be taken as a starting point for large scale analyses. The methodology is designed for application in a development context where data scarcity and limited information are usual. It has been applied and tested in an embedded case study located in Suriname relying completely on open data. Shuttle Radar Topography Mission (SRTM) elevation data and Open Street Map (OSM) hydrologic and village location data served as a basis for identifying 110 feasible alternatives. They are to be taken as a coarse resolution starting position providing an overall impression over the whole perimeter of analysis. Based on the identified locations, further in-depth and high-resolution analysis of sites can be considered.

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LIST OF ABBREVIATIONS

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CRS	Coordinate Reference System
EBS	N.V. Energie Bedrijven Suriname (National Electricity Utility Company)
DEM	Digital elevation model
ESRI	Environmental Systems Research Institute
FOB	Stichting Fonds Ontwikkeling Binnenland (Foundation for the Development of the Hinterland [of Suriname])
GIS	Geographic information system
GIS-MCDA	GIS-based multi criteria decision analysis
GS Pro	DJI Ground Station Pro
NPO	Non-profit organization
OSM	Open Street Map
kW	Kilowatt
kWh	Kilowatt-hour
MADA	Multi-attribute decision analysis
MODA	Multi-objective decision analysis
MCDA	Multi-criteria decision analysis
MW	Megawatt
VEP	Vortex energy plant
WLC	Weighted linear combination
SRTM	Shuttle Radar Topography Mission
swisstopo	Federal Office of Topography, Switzerland

1. INTRODUCTION

1.1 Starting Position

In 2011, a Swiss Non-Profit Organization (NPO) won a national innovation prize for the development of a pilot installation of a new type of micro hydropower generation (Swiss Federal Office of Energy SFOE, 2017). The technical functionality behind the idea was persuasively simple, and thus ambitions were high that in the wake of the Fukushima incident, this technology would contribute to a completely renewable, decentralized and low-risk future energy supply system. After initial euphoria, the promoters suffered a harsh landing on the ground of hard facts. Soon it was clear that in the context of a country with very strict environmental regulation already utilizing a substantial proportion of its hydro potential, such as Switzerland, it would be extremely difficult to establish a new type of micro hydro technology, let alone in an economically successful manner.

Within the context of developing countries however, the technology has the potential to contribute significantly to the electrification of remote settlements and to the transformation of the energy supply system towards a sustainable basis thanks to the low technical complexity, the simple maintenance and the comparably low capital investments necessary and thereby generating co-benefit effects in terms of sustainable economic development. In Suriname, which is the subject of the case study embedded in this thesis, diesel is partially flown in to remote villages situated in the sparsely populated, densely forested and hardly accessible hinterland in order to power worn-out and ineffective generators, which often are the only source of electricity, resulting in electricity production costs of partially more than 1 USD/kWh. The remoteness and inaccessibility of the area poses huge challenges to changings of the status quo by planning and developing alternative energy supply systems, especially considering the high importance of topographic and hydrological conditions in the context of hydropower (Yi et al., 2010). This is where the benefits of state-of-the art GIS-technology and remotely sensed data with regard to accurate location analysis come in, which shall be leveraged in this study.

1.2 Research Aim

The aim of this research is to develop a methodology for a generic GIS-based procedure for assessing the suitability of a project perimeter with regard to a specific type of micro hydropower plants called vortex energy plants (VEP)[1]. The procedure shall be capable of generically and repeatedly locating all potentially suitable sites within a possibly large area (i.e. the area of a country) in order to lay the basis for further analysis in the course of project planning. The suitable sites shall be rated according to their level of achievement in terms of site requirements. The methodology shall rely on open data.

1.3 Approach

Considering the research aim, which consist of a suitability analysis with regard to specific site requirements, suggests a GIS-MCDA approach capable of distinguishing unfeasible from feasible alternatives and of rating the feasible alternatives. Weighted Linear Combination (WLC) has been identified as the most suitable approach to be used. Based on a case study in Suriname, field trips to two known suitable pilot sites for VEPs have been udertaken in order to gather data and information to define the set of criteria to be considered for the MCDA and to have a basis for the definition of criteria weights and value ranges. Based on this data, a WLC model is designed.

1.4 Expected Results

a) Development of a general methodology that can be used further
b) Delivery of suitable sites for the case study in the form of a map
c) Rating of the suitable sites according to their level of achievement of the requirements

[1] See definition in Section 1.7.5 Vortex Energy Plant (VEP)

1.5 Thematic Delimitation

Since the results of the site selection methodology developed in this study do not represent final decisions, a range of relevant factors for project execution will not be considered within the analysis model. Socio-economic considerations, such as the profitability or the social acceptance of a VEP, are not taken into account. The environmental impact is excluded as well. The analysis is not based on the calculation of the theoretical hydro potential, since it is not intended to maximize power output. Hydrologic suitability is only considered insofar as a criterion considering the availability of water is established. Fluctuations of runoff throughout the year are not considered. Furthermore, operational aspects, such as transportation of building material, construction and maintenance are excluded from the analysis as well.

1.6 Target Audience

The study is designed as applied research with a strong focus on practical implementation of its results. As a subordinate goal, the interested members of the GIS community shall be encouraged to take the results as a basis for further development of more comprehensive GIS-based MCDA by extending the methodology to criteria not taken into account in this study, such as those mentioned in Section 1.5.

1.7 Definitions

1.7.1 Geographic Information System (GIS)

"[A] GIS is a system for collecting, storing, manipulating, analyzing, and presenting geographic data to obtain information for decision making." (Malczewski and Rinner, 2015)

1.7.2 GIS-based Multi Criteria Decision Analysis (GIS-MCDA)

"GIS-MCDA can be thought of as a process that transforms and combines geographical data and value judgments (the decision-maker's preferences) to obtain information for decision making." (Malczewski, 2006)

1.7.3 Open Data

"**Availability and Access**: the data must be available as a whole and at no more than a reasonable reproduction cost, preferably by downloading over the internet. The data must also be available in a convenient and modifiable form.

Re-use and Redistribution: the data must be provided under terms that permit re-use and redistribution including the intermixing with other datasets.

Universal Participation: everyone must be able to use, re-use and redistribute – there should be no discrimination against fields of endeavour or against persons or groups. For example, 'non-commercial' restrictions that would prevent 'commercial' use, or restrictions of use for certain purposes (e.g. only in education), are not allowed."

(Open Data Handbook, 2017)

1.7.4 Taxonomy of Hydroelectric Power Stations

Hydroelectric power stations are classified according to their electric power output. While the term small hydropower is often used in general to summarily include all power output ranges up to 10 MW[2], **Error! Reference source not found.** gives an overview of the commonly used detailed taxonomy (Bódis et al. (2014), Williamson et al. (2014)), which is also used in this study.

[2] Some authors include hydropower stations up to a higher power output in the class of small hydropower, such as Khandekar et al. (2015), who draw the line at 25 MW.

Table 1-1: Taxonomy of Hydropower

Category	Electric Power Output
Pico Hydro	< 5 kW
Micro Hydro	5 kW – 99.9 kW
Mini Hydro	100 kW – 999 kW
Small Hydro	1 MW – 10 MW

1.7.5 Vortex Energy Plant (VEP)

A vortex energy plant is a specific type of micro Hydropower station based on the vortex technology[3]. It is a run-of-river hydropower station allowing for electricity generation at ultra-low heads starting at 1.5 m with runoff volumes starting at 1 m^3/s. Figure 1-3 shows a vortex energy plant with a head of approximately 2 m and an average runoff volume of approximately 1 m^3/s. A technical illustration is given in Figure 1-1. The electric power output of VEPs is, as with any conventional hydropower station, a function of the head (altitude difference between inlet and outlet, also termed drop) and water runoff volume. The VEP depicted in Figure 1-3 is designed for a peak performance of 15 kW. An overview of performance curves for different specifications of vortex stations is given in Figure 1-2.

[3] Although vortex energy plants are theoretically feasible within the pico range (see **Error! Reference source not found.**), economic considerations pose restraints to the operational feasibility of plants with outputs of less than 7 kW.

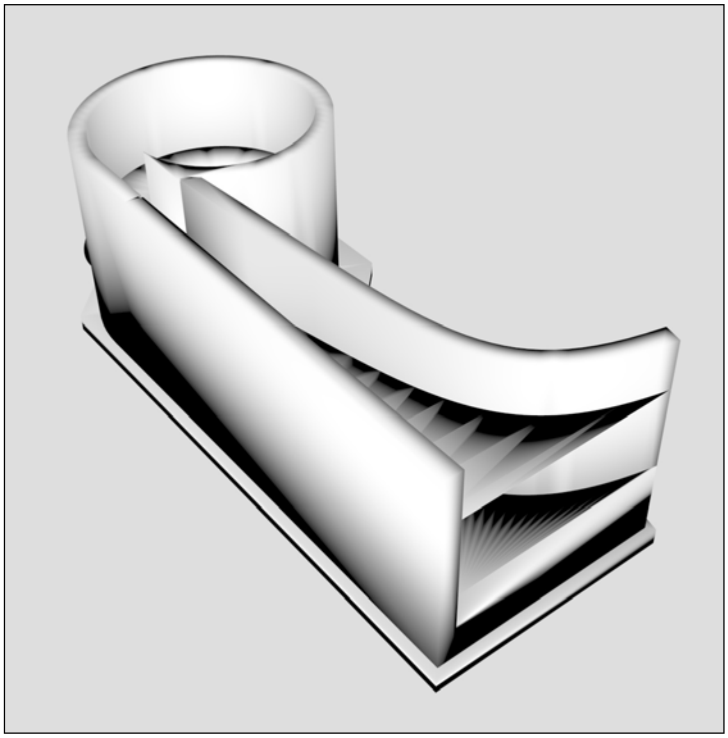

Figure 1-1: Technical illustration of a VEP with inlet and vortex basin (Illustration: K. Petrasch and C. Bolli/Verde Renewables).

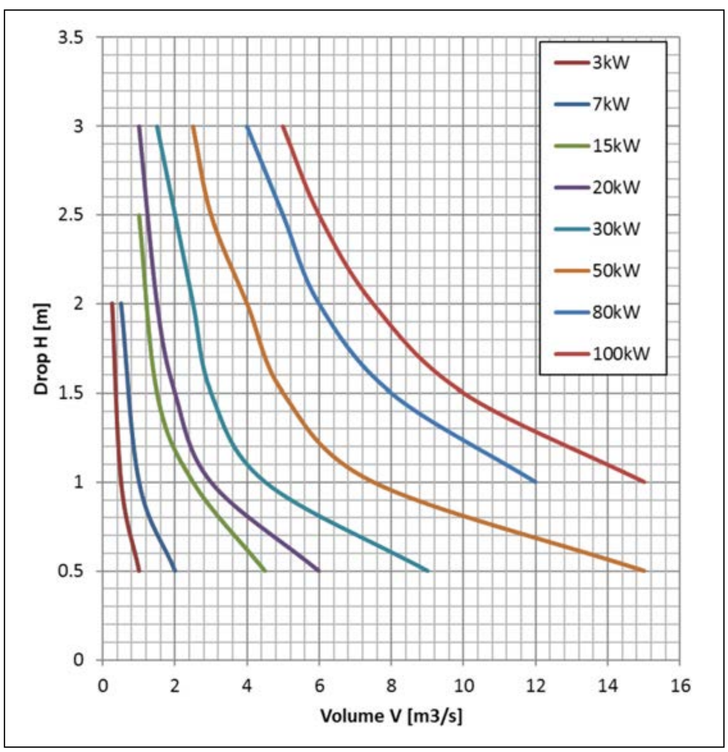

Figure 1-2: Theoretic performance curves for VEPs with different specifications (Source: Verde Renewables).

Figure 1-3: Vortex energy plant "Dr. Bertrand Piccard", Schöftland AG, Switzerland (Source: Verde Renewables).

2. STATE OF RESEARCH

2.1 Introduction

In the broader context of this study's subject, three strands of research can be identified. First and foremost, multi-criteria decision analysis (MCDA) and GIS-based MCDA (GIS-MCDA) provide the methodologic and theoretic background for the development of an analysis model. Secondly, there is a considerable amount of studies dealing with GIS-MCDA-based site selection and suitability assessment specifically for hydropower development applying various approaches. An overview of some of these contributions will provide valuable indications for the design of an analysis model. Thirdly, micro hydropower in the context of rural development can be identified as an interdisciplinary field of research of its own, including – but not limited to – GIS-based approaches, that will be touched upon briefly. The main focus in terms of relevance for the purpose of this thesis lies on the former two subjects, while the latter is discussed briefly for the sake of completeness.

2.2 GIS-based Multi-Criteria Decision Analysis (GIS-MCDA)

The methodologic literature on GIS-MCDA is considerable. Comprehensive overviews of the existing GIS-MCDA approaches and their methodologic categorization can be found in Malczewski (2006) and in Malczewski and Rinner (2015). Boroushaki and Malczewski (2008) have developed an extension to ArcGIS based on analytical hierarchy process GIS-MCDA. Mendoza and Martins (2006) provide a review of MCDA methods with regard to natural resource management, while Wang et al. (2009) analyze MCDA approaches in sustainable energy decision-making. They describe MCDA as follows: “MCDA is a form of integrated sustainability evaluation. It is an operational evaluation and decision support approach that is suitable for addressing complex problems featuring high uncertainty, conflicting objectives, different forms of data and information, multi interests and perspectives, and the accounting for complex and evolving biophysical and socio-economic systems” (p. 2265). The concept of MCDA in general thus allows for a comprehensive inclusion of all relevant decision parameters of any kind. While the benefits and the necessity of a broad conceptualization of the decision environment especially in the field of energy infrastructure planning is undoubted, the focus of this thesis lies on the spatial aspects of the decision problem at hand. Therefore, the purpose of this section is to provide an overview of the prevailing GIS-MCDA approaches and their cornerstones in order to derive guidelines for the theoretical foundation of the study.

2.2.1 Classification of GIS-MCDA

In their taxonomy of GIS-MCDA, Malczewski and Rinner (2015) classify GIS-MCDA approaches based on GIS components and based on MCDA components. The classification scheme for GIS components (see Figure 2-1) is defined by the data structure used in the combination rules and by the explicit or implicit nature of the spatial criteria and the decision alternatives.

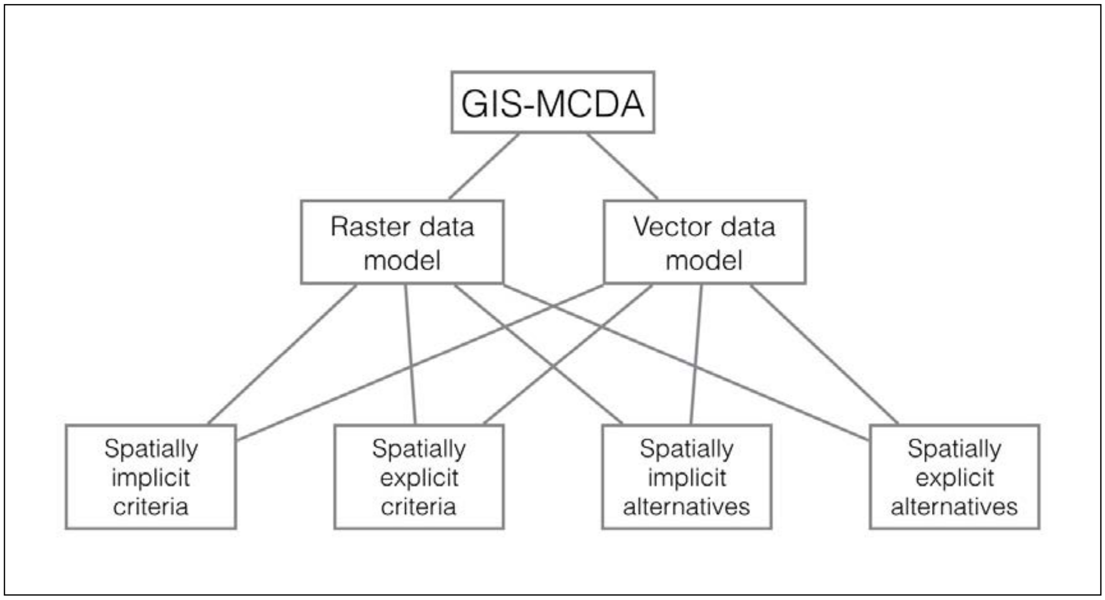

Figure 2-1: Classification of GIS-MCDA according to GIS components (Source: Malczewski and Rinner (2015), p. 63)

The MCDA components (see Figure 2-2) can be subdivided into the two categories of multi-objective decision analysis (MODA) and multi-attribute decision analysis (MADA), depending on the nature of the criteria to be considered in the decision process. According to Malczewski and Rinner (2015), "an objective is a statement about the desired state of a system under consideration (e.g., a spatial pattern of accessibility to primary schools). It indicates the directions of improvement of one or more attributes. The statement about dsired directions of improvement can be interpreted as either 'the more of the attribute, the better' or 'the less of the attribute, the better'. This implies a maximization or minimization of an objective function. Thus, the concept of an objective is made operational by assigning to each objective at least one attribute which directly or indirectly measures the level of achievement of the objective" (p. 25).

On the other hand, "an attribute can be described as a property of an element of a real-world geographic system (e.g., transportation system, location-allocation system, or land use pattern). More specifically, an attribute is a measurable quantity or quality of a geographic entity or a relationship between geographic entities. For example, the objective of maximizing physical accessibility to central facilities such as schools, health care clinics,

hospitals, or administrative centers can be operationalized by attributes such as total traveling distance, time, cost, or any other measure of spatial proximity" (ibid.).
With regard to the spatial character of the decision problem at hand, the GIS-MODA and GIS-MADA approaches can be further subdivided into discrete and continuous decision problems. Taking into account the decision makers' goal-preference structure, a further splitting into individual and group decision making can be made. Finally, the amount of information about the decision situation and the criteria to be analyzed define whether a decision problem can be characterized as deterministic, probabilistic or fuzzy.

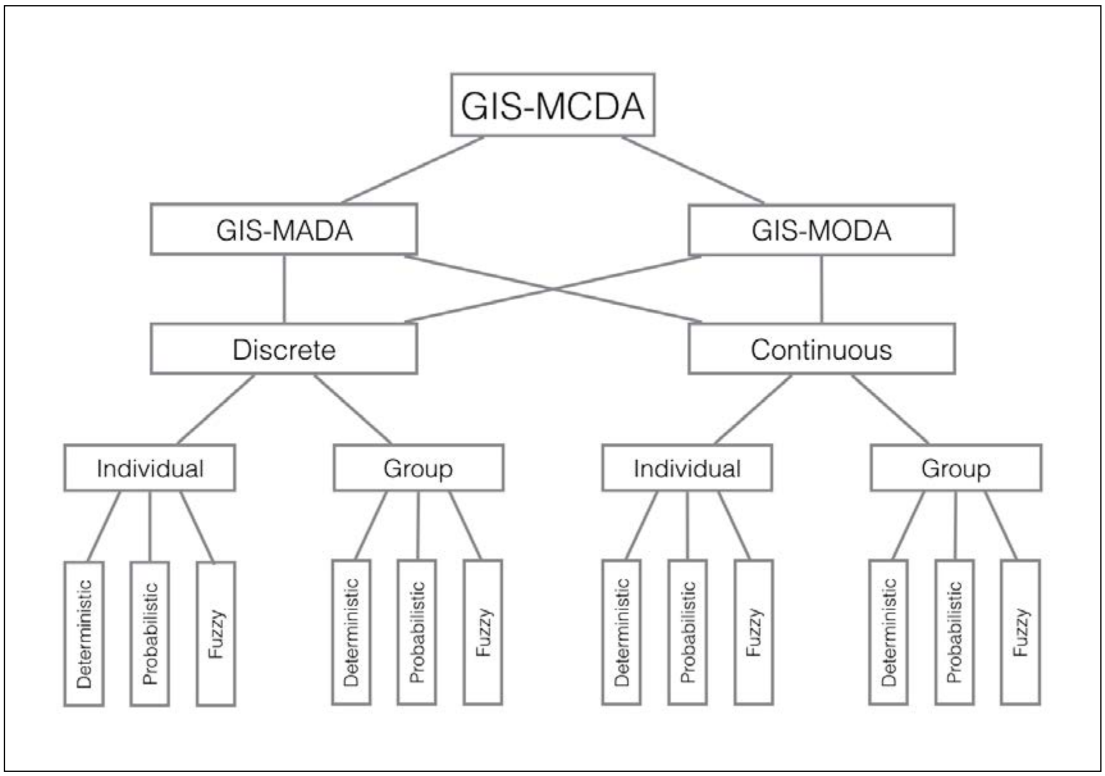

Figure 2-2: Classification of GIS-MCDA according to MCDA components (Source: Malczewski and Rinner (2015), p. 64).

2.2.2 Decision Makers

Decision makers can be individuals or groups of individuals. In terms of the above-mentioned taxonomy however, the number of actors is not the decisive criterion. Rather the degree of consensus among the decision-making agents is the defining aspect in terms of individual or group decision making. If the goal-preference structure among the agents is homogeneous, then one is dealing with individual decision making irrespective of the number of agents. If there is a conflicting goal-preference structure, one is dealing with group decision making (Malczewski and Rinner, 2015).

2.2.3 Criteria

The criteria are the most fundamental components of MCDA. They are the instruments that define the characteristics of the analysis results. According to Malczewski and Rinner (2015), a set of criteria must fulfill the following requirements:

- Completeness: Covering all aspects of a decision problem
- Operationality: Meaningfully usable in the analysis
- Decomposability: Decomposable into parts to simplify the process
- Minimality: Total number of criteria as small as possible

Moreover, criteria can be spatially explicit or spatially implicit. If a criterion directly contains or represents spatial concepts, such as distance, proximity, accessibility, elevation or slope, it is spatially explicit. If spatial data is needed to calculate the level of achievement of a criterion, it is said to be spatially implicit (ibid.).

2.2.4 Decision Alternatives

Decision alternatives are possible alternative courses of actions. In a geographic context, they must consist of at least two elements: action (what?) and location (where?). Decision alternatives can be sub-divided into feasible alternatives and infeasible alternatives. The latter are those that fall below a necessary minimal threshold of criteria-achievement. This threshold is to be specified during the process of model development. The former are those that fulfil the minimal threshold of achievement. They can be further specified into dominated and non-dominated feasible alternatives. The non-dominated feasible alternatives represent Pareto-optimal situations, where no increase in the value of a criterion is possible without decreasing the value of another criterion (Malczewski and Rinner, 2015). Thus, non-dominated feasible alternatives represent the most desirable decisions. When the decision problem requires finding the single-best or the n best solutions, non-dominated alternatives are the primary focus of the analysis. If the decision problem at hand requires finding as many as possible or all of the feasible alternatives, as necessary for a suitability analysis, the dominated feasible alternatives should also be considered.

2.3 MCDA-based site selection and suitability analysis for energy planning

Implementation examples of various forms of MCDA in the context of energy planning are tremendous, and there is a considerable number of publications dealing specifically with GIS-based site selection and suitability analysis for the development of hydropower stations. While some of them can be assigned to GIS-MCDA as outlined in Section 2.2, others are drawing on selected concepts from GIS-MCDA. This section's non-comprehensive overview will shed light on prevailing approaches in order to fall back on existing research. Kowalski et al. (2009) have applied multi-criteria analysis to comprehensively assess different renewable energy scenarios for Austria, while Omitaomu et al. (2012) have developed a GIS-MCDA approach for siting new power generating plants in the contiguous United States, taking into account a wide range of criteria, such as population, water availability, environmental and geological indicators. Khandekar et al. (2015) have shown the implementation of a fuzzy design MCDA methodology for small hydropower plant site selection in India based on the quantification of environmental, techno-commercial and socio-economic criteria through a nine-point fuzzy scale. Yi et al. (2010), doing a site location analysis for small hydropower in Korea, have pursued similar goals to the ones this study aims at. They have focused on "establishing the criteria and methodology for searching for alternative locations rather than selecting the most suitable site among the alternatives" (ibid., p. 852). Their case study based on raster overlay techniques included taking into account constraint criteria, such as national parks, agricultural and residential areas, and location criteria, such as water availability and natural head. A similar approach in terms of the objectives was pursued by Rojanamon et al. (2009), who conducted a comprehensive site selection analysis for small run-of-river hydropower plants including engineering, economic, environmental and social criteria in northern Thailand with a focus on iden-

tifying the feasible sites. It resulted in the identification of 89 technically and economically feasible sites which were further analyzed in terms of environmental and social impact.
Also in the European context, GIS-MCDA has been the basis for mini hydropower suitability mapping. Bódis et al. (2014) have conducted an analysis of the technical hydro potential in Europe based on the evaluation of hydrological, topographic and technological data resulting in suitable sites for hydropower development. Their model is based on the calculation of a gross head from elevation data and the river network.

2.4 Micro Hydropower in the Context of Sustainable Development

Within the research field of micro hydropower in the context of rural development, some contributions specifically apply a GIS-based methodology. These will be discussed in the following. For Uganda, a demand-side scenario supporting the planning process of rural electrification by identifying patterns of demand and priority areas of investment has been developed (Kaijuka, 2007). A very early example of implementing a GIS-based approach stems from Tanzania, where hydrological, demographic and economic factors have been considered in order to yield suitable sites for small-scale hydropower development (Gismalla, 1996). A situation very similar to Suriname has been analyzed in Ethopia, where a feasibility study partially based on GIS-data has been conducted in order to assess the possibility of replacing diesel-based electricity supply in remote areas by renewable energy (Bekele and Tadesse, 2012). An analysis of the theoretical hydro potential in South Africa has been made, based on the evaluation of elevation and hydrologic data (Ballance et al., 2000). Also in north-eastern India, elevation and hydrologic stream network data has been analyzed in order to assess the hydropower potential of a watershed, resulting in a model that includes carbon emission reduction potential and which has identified 107 suitable sites for run-of river hydropower plants.
Among the reviewed publications there are several studies with an interdisciplinary approach not focusing on GIS, some of them in the local context of Suriname, which will be briefly touched upon hereafter. Since the subject is covered very extensively in the litera-

ture[4] and is not of direct relevance to the research aims, this section has to be kept to a minimum. Faruqui (1994) has presented a general overview on chances and risks of small hydropower in the context of developing countries. Besides the benefits, such as economic development, low environmental impact and positive social side effects, he has pointed out that lack the of qualified staff, high capital costs and inadequate design of plants resulting in low load factors and thus economically unfavorable outcomes oftentimes pose serious challenges to hydropower development and operation. Such difficulties have also been experienced in Suriname. In the early 1980'ies, a first micro hydropower station was installed in Puketi in the southwest of Suriname's large hinterland district Sipaliwini (van Els, 2012). It was only operational for three years and its rehabilitation failed due to operational and financial obstacles (Alvares, 2007). In 2005, planning began for a new hydropower station, which as of March 2017 was equipped with the first of 3 planned turbines and has been operational only during tests for a couple of weeks so far[5]. Despite these drawbacks, the Surinamese government further pursues to implement micro and mini hydropower plants on a large scale for the electrification of its hinterland (Naipal, 2012).

2.5 Synthesis of Literature Review

The preceding chapter has given an overview of the state of research in the fields relevant to this study. It has been shown that GIS-MCDA is a widely-utilized methodology applied in various disciplines. A classification schema based on the type of data, the character of the criteria and the constitution of the decision environment has been introduced for categorizing the different methodological approaches within GIS-MCDA. The relevant concepts have been identified as decision makers, criteria and decision alternatives.
Subsequently, an overview has been provided on implementation examples of MCDA-based site selection and suitability analysis in the context of energy planning which resulted

[4] A search on Google Scholar for "micro hydro power for rural electrification" delivers approximately 24'400 papers.
[5] Personal communication with Sieuwnath Naipal (Anton de Kom University of Suriname) and Peter Donk (Energie Bedrijven Suriname N.V.) and personal field visit.

in the identification of some studies with similarities to the problem situation of the one at hand. Finally, the consideration of some contributions not strongly focused on a MCDA-based methodology has shed light on the wider chances and challenges related to the promotion of hydropower in the context of sustainable development.

3. METHODOLOGY AND DATA

3.1 Introduction

Based on the findings of the previous chapter, an assessment of the decision problem at hand in the theoretical context will be made and a specific GIS-MCDA approach will be chosen as the methodology to be applied in this study. After that, the concepts of the approach will be discussed based on the context of the suitability problem to be analyzed, before the software and data will be presented which builds the basis for the empirical analysis.

3.2 Theoretical Foundation and Methods Applied

The site requirements for the operation of VEPs can be classified into two groups: the physical preconditions necessary to generate electricity and demand-side prerequisites which determine where and by whom the produced electricity will be consumed. The former depend on given factors such as topography and hydrology. The latter depend on technical considerations about the transportation of the electricity to the consumer. These are determined by electro-technical and cost limitations. Thus, the demand-side prerequisites can be determined to a certain extent by the decision makers, whereas the physical preconditions are not flexible. Based on these considerations, a set of criteria for the analysis can be specified according to the criteria requirements mentioned in Section 2.2.3 as follows.

The physical preconditions in terms of topography mean that there must be a sufficient head, which will be analyzed by the criterion *slope*. In terms of hydrology there must be sufficient water available, which will be analyzed by the criterion *proximity to water body*. The requirement of *electricity demand* will be analyzed by the criterion *proximity to village*. An overview of the criteria set is given in Table 3-1. A detailed operationalization of the criteria follows in chapter 4.

Table 3-1: Requirements and Criteria

Requirement	Criteria
Head	Slope
Electricity demand	Proximity to village
Water availability	Proximity to water body

Based on the criteria set, the decision problem at hand can be classified according to the classifications shown in Section 2.2.1. The evaluation of the GIS components results in the classification depicted in Figure 3-1. Since slope is a characteristic that can only be represented adequately by raster data, the raster data model is to be used for the combination rules. Since the two proximity criteria are spatially explicit, the problem can thus be classified as such.

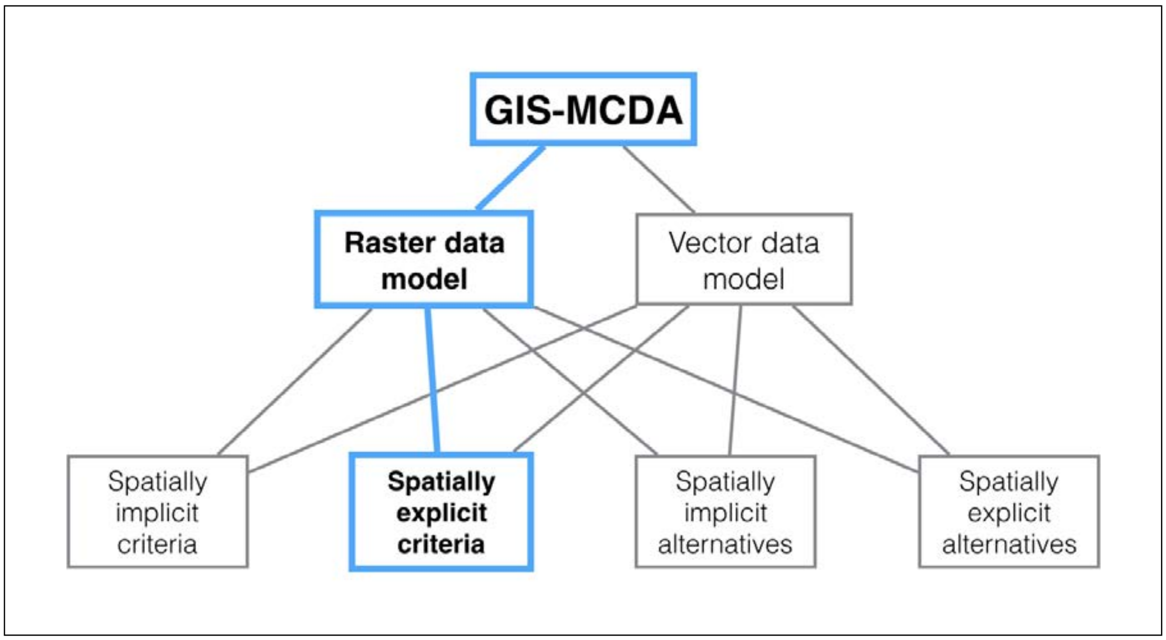

Figure 3-1: Classification of GIS components to be used in analysis (Source: Malczewski and Rinner (2015), p. 63)

The assessment of the MCDA components results in the classification shown in Figure 3-2. The MADA approach is most suitable for the problem at hand, since properties of real world geographic systems, namely topography and proximity, are to be analyzed (see Section 2.2.1). A continuous procedure is to be applied, since the criteria, above all slope, do not make sense to be modelled discretely. Furthermore, given the aims of the study (see Section 1.2), the goal-preference structure of the decision makers can be assumed to be homogenous. Therefore, the type of decision making is individual. Finally, since the information about the criteria taken into account is assumed to be complete, the problem falls into the category of deterministic decision problems.

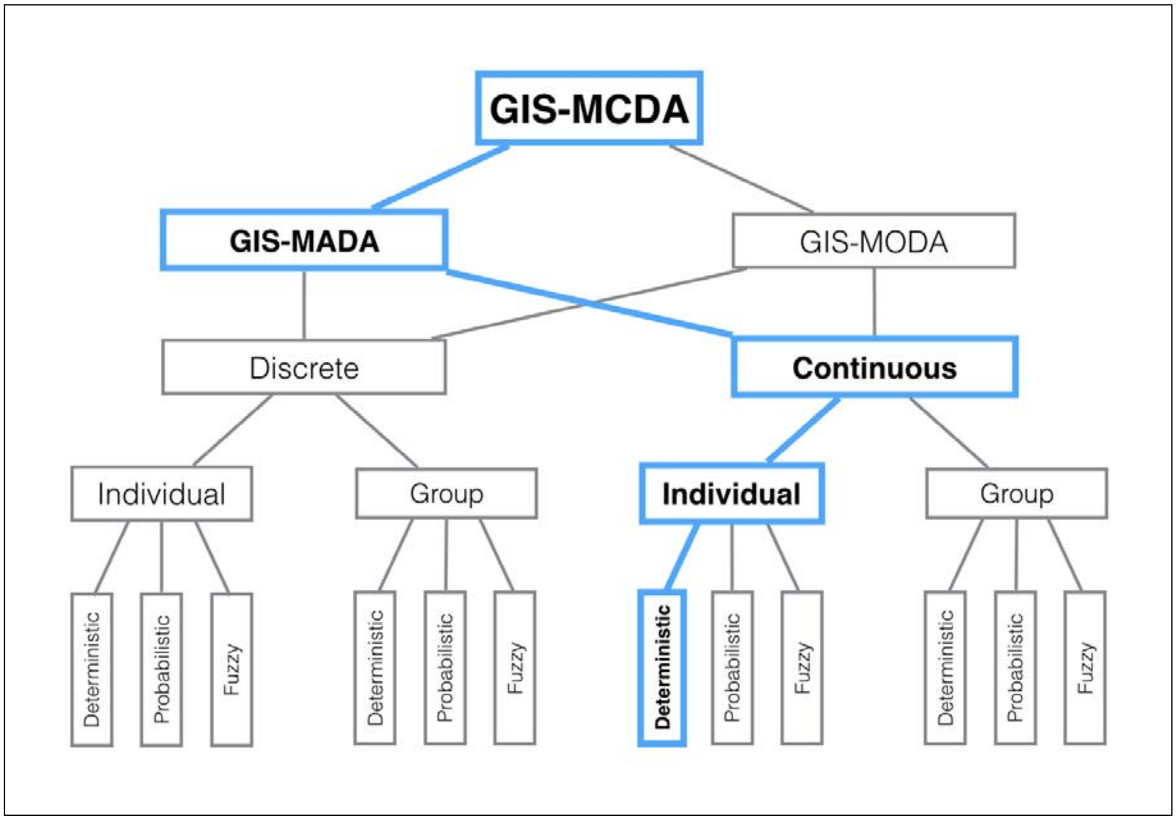

Figure 3-2: Classification of MCDA components to be used in analysis (Source: Malczewski and Rinner (2015), p. 64).

From the existing MADA approaches, Weighted Linear Combination (WLC) is the most suitable one for the problem at hand. It is the most frequently used GIS-MCDA approach and its intuitive appealing to decision makers as well as its ability to be implemented easily to GIS environments (Malczewski and Rinner, 2015) qualify it as approach to be used for the purpose of this study. WLC consists of criterion weights and value functions. It is a map combination procedure that associates a set of criterion weights with decision alternatives (i.e. locations) and combines the weights with the criteria's attribute values (ibid.). The criterion weights and value functions will be specified in the course of model development in chapter 4.

3.3 Software and Tools

3.3.1 Field Data Acquisition

3.3.1.1 Quadcopter Drone

For the acquisition of aerial image data, a Phantom 4 Pro quadcopter drone with a 20-megapixel camera manufactured by DJI has been used (DJI, 2017). It was used to sstematically capture aerial imagery of the pilot sites in order to produce high resolution elevation mdels. It proofed to be adequate for this purpose. However, the total flight time per day had to be limited to approximately 75 minutes, which equals the loads of 3 flight batteries. This limitation was due to the fact that it was not possible to recharge the batteries in the field due to lack of electricity and due to civil aviation regulations prohibiting the transport of more than 3 flight batteries, which prevented bringing more than 3 batteries. The limited flight time proved a big challenge and required sophisticated flight planning, involving some tradeoffs in terms of resolution of the outcome.

3.3.1.2 Flight Planning Software

In order to acquire systematic aerial imagery with a homogenous overlap, a flight planning software is necessary. Several options have been considered. Pix4DCapture and DroneDeploy were both dismissed, because they insufficiently fulfilled the requirement of being able to be used offline in remote locations without the possibility to connect to its servers. With DJI Ground Station Pro (GS Pro), a solution was found that adequately fulfilled all the requirements. A crucial function of GS Pro for the offline use is the ability to collect waypoints delimiting the area to be mapped by flying the drone to these locations and to manually adapt the generated waypoints. GS Pro runs on an iPad on iOS 8.1 or later as of March 2017.

3.3.1.3 Photogrammetric Software

For the calculation of digital elevation models (DEM) and orthomosaic aerial images, Pix4Dmapper 3.0.18 for Mac OS X was used. The very dense vegetation at the pilot sites turned out to be a major challenge. Pix4Dmapper's beta-version function to calculate a terrain model instead of a surface model based on generic point cloud classification was not capable of successfully removing vegetation without tedious manual editing.

3.3.1.4 GIS environment

ESRI's ArcMap 10.4.1 with Spatial Analyst extension is used as the main GIS environment. In addition, QGIS 2.12 is used for one step of elevation data pre-processing (see Section 3.4.1). ArcMap's Modelbuilder and the FME Data Interoperability extension are used to preprocess the necessary data and develop an analysis model. The WLC workflow is incorporated into the analysis model based on ArcMap's Raster Calculator (ESRI, 2017c) and Weighted Overlay (ESRI, 2017e) tools. For the creation of mosaic datasets based on Sentinel 2 satellite imagery, the Sentinel2 geoprocessing tool provided by ESRI is used (ESRI, 2017d).

3.4 Data and data pre-processing

3.4.1 Elevation

Since elevation data represent the most crucial basis for the analysis, careful consideration is required in order to choose a well-suited dataset. Wong et al. (2014) have assessed the accuracy of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Shuttle Radar Topography Mission (SRTM) elevation data in tropical conditions. They came to the conclusion that SRTM data is more accurate than ASTER data. Moreover, Bódis et al. (2014) have successfully based their assessment of new suitable locations for mini and small hydro power plants in Europe on SRTM elevation data. Thus, SRTM elevation data is used. Since a high resolution is crucial for the use-case, SRTM's 1 Arc-Second

Global dataset has been chosen. After the acquisition of the tiles for the whole area of Suriname through EarthExplorer (USGS, 2017), data pre-processing as described below has been conducted.

- Merging of tiles with QGIS Raster Merge function
- Import to Geodatabase with ArcGIS Raster to Geodatabase tool. The properties of the resulting raster are shown in Figure 3-3.

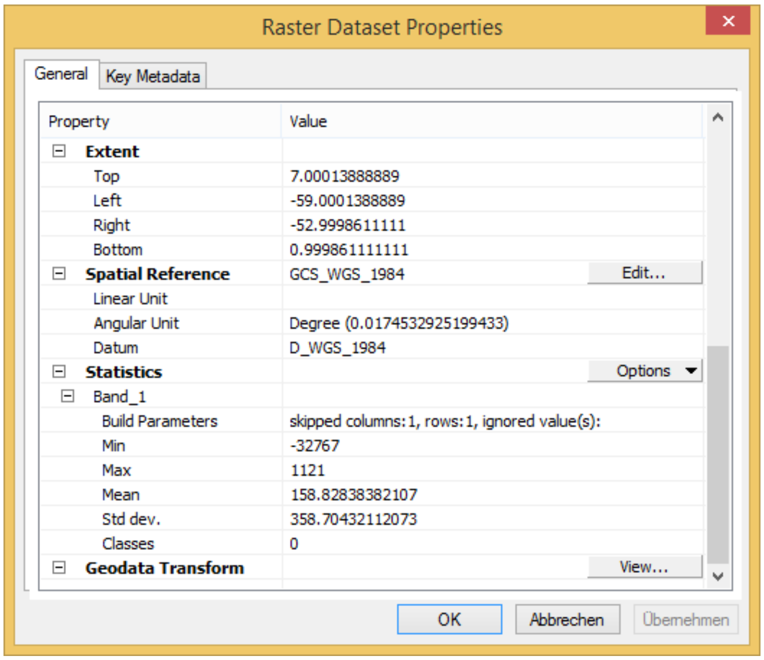

Figure 3-3: Properties of elevation raster dataset.

- As can be seen in Figure 3-3, the raster is unprojected in Datum D_WGS_1984. Thus, a projection to Suriname's standard Coordinate Reference System (CRS) Zanderij UTM Zone 21 N (EPSG 31121) is applied using ArcMap's Project Raster tool. This CRS will be used for all data. A grid size of 30 m x 30 m is chosen in oder to approximately maintain the dataset's initial resolution of 1 arc-second, which equals approximately 30 m near the equator. The bilinear resampling technique is chosen, since the incorporated bilinear interpolation algorithm (ESRI, 2017b) by determining the new value of a cell based on a weighted distance average of the four nearest surrounding cells is suitable for continuous data and most closely maintains the cells values of the original raster.

- As the statistics in Figure 3-3 show, there are values far below 0 m elevation. A closer look at the raster's histogram (see Figure 3-4) reveals, that there are approximately 65'000 cells with values below 0 m, with a pronounced cluster at -32'767 m. These values are apparently spurious and are eliminated.

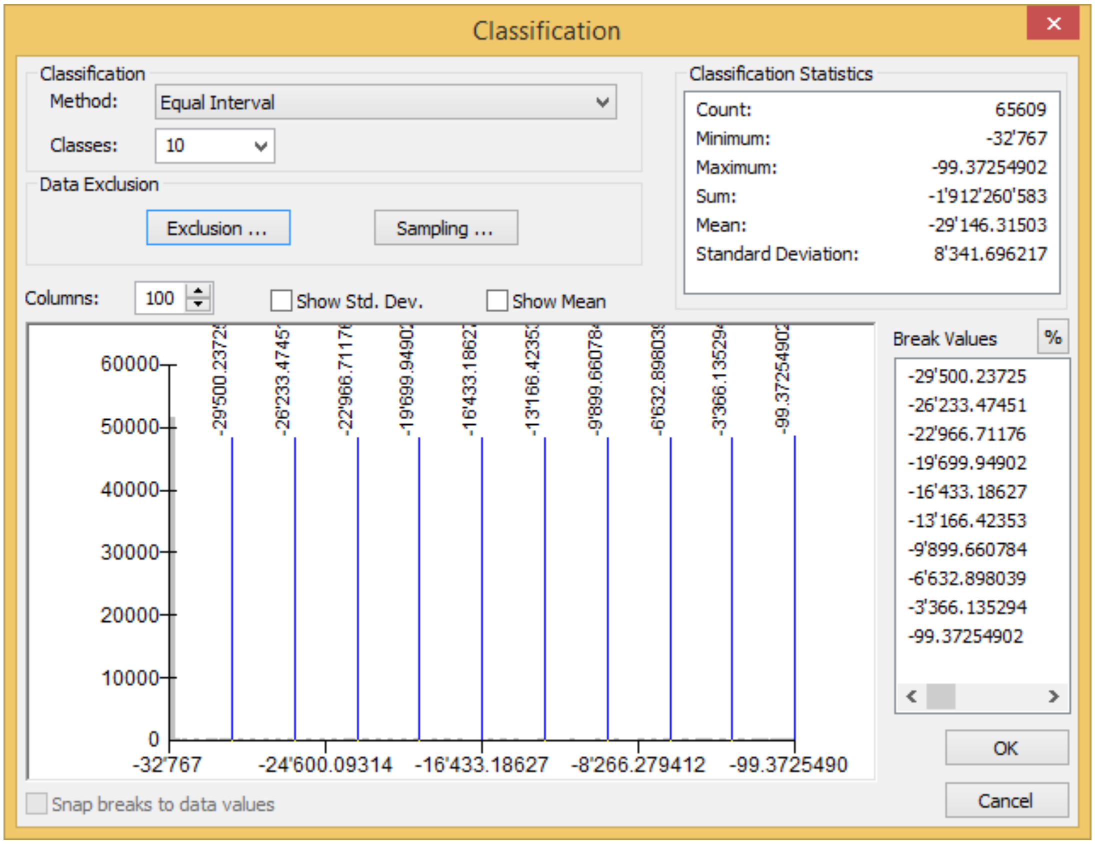

Figure 3-4: Spurious negative values with a cluster at -32'767.

- A closer examination of the elevation raster illustrates that the spurious values are found randomly, but spatially clustered all across the project perimeter with a width of the clusters not exceeding approximately 1'000 m, as is shown in Figure 3-5.

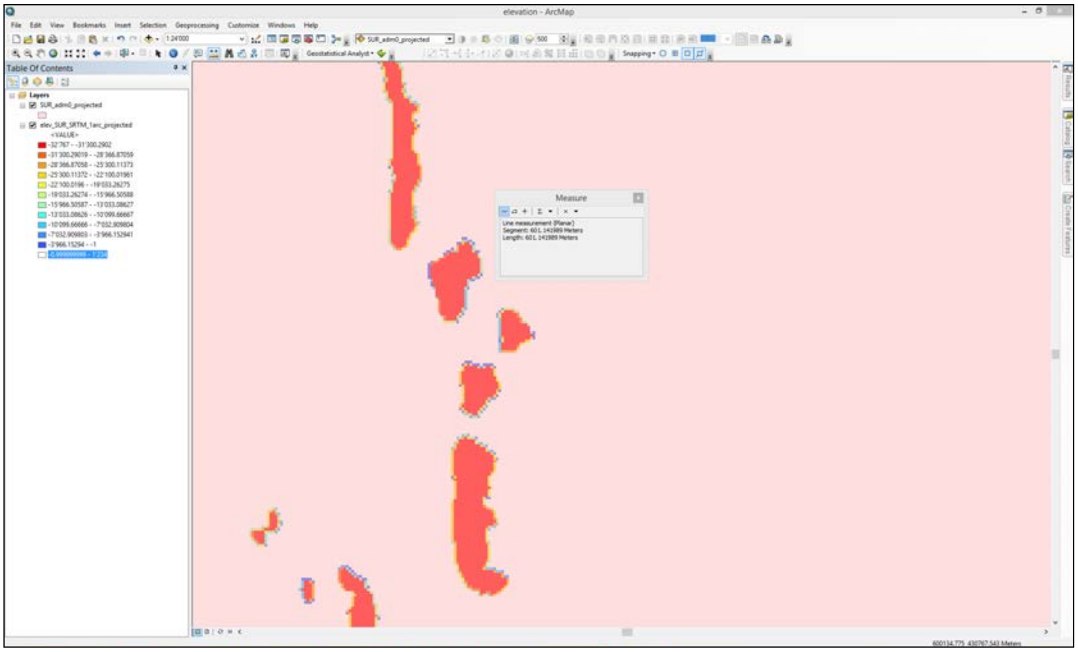

Figure 3-5: Visualization of spurious elevation raster values.

- In order to eliminate the spurious values and replace them with adequate interpolated values, the following procedure is applied:

a) Calculate a new raster with a cell size of 990 m with ArcGIS Aggregate tool, using the nearest interpolation technique for performance reasons and snapping to the input 30x30m elevation raster, using the MEDIAN aggregation technique. The results of this step reveal that not all spurious values have been eliminated, as Figure 3-6 shows. Therefore, step b) is necessary.

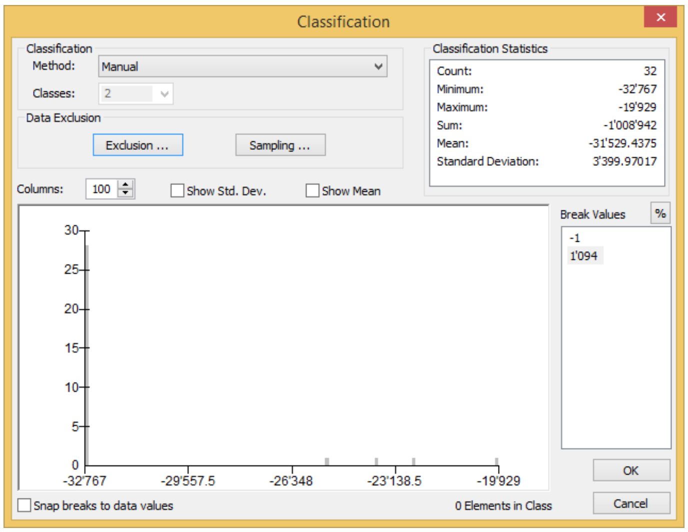

Figure 3-6: Distribution of negative elevation values after step a).

b) Calculate a new raster with a cell size of 1'980 m analogously to step a). Since after this step, not all strongly negative elevation values are eliminated yet, another raster with a cell size of 5'250 m is calculated using the same technique resulting in the elimination of all negative values.

c) In order to replace the original 30x30 m input elevation raster's negative values with interpolated values from the aggregated rasters, the model shown in Figure 3-7 is created. With the Raster Calculator, the conditions as stated in Table 3-2 are evaluated in order to assign the interpolated values to cells with negative values below -5 m[6].

[6] The lowest elevation in Suriname is an unnamed location in the coastal plain at -2 m, whereas the highest elevation is Juliana Top at 1'230 m (CENTRAL INTELLIGENCE AGENCY 2017. The World Factbook. Suriname.)

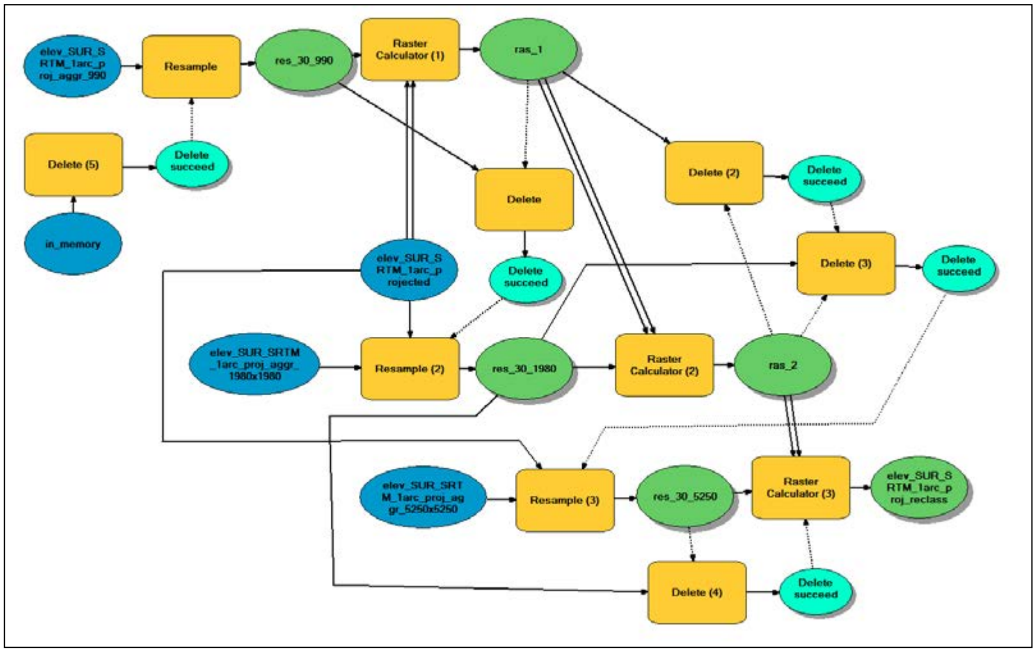

Figure 3-7: Model developed to replace negative values in original raster with interpolated values of aggregated rasters.

Table 3-2: Conditions evaluated inside model shown in Figure 3-7.

Raster Calculator (1)	Con("%elev_SUR_SRTM_1arc_projected%" < -5, "%res_30_990%", "%elev_SUR_SRTM_1arc_projected%")
Raster Calculator (2)	Con("%ras_1%" < -5, "%res_30_1980%", "%ras_1%")
Raster Calculator (3)	Con("%ras_2%" < -5, "%res_30_5250%", "%ras_2%")

The result as shown in Figure 3-8 indicates to be an adequate approximation of natural elevation values, although the interpolated values can clearly be identified as being artificial. From the final elevation raster depicted in Figure 3-8 a slope raster with a grid size of 90 m is calculated to be used for the analysis.

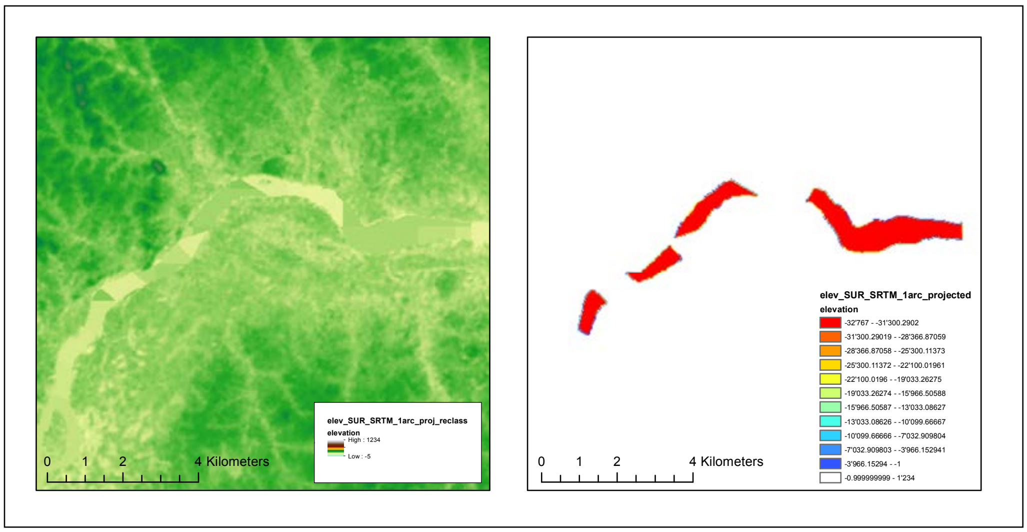

Figure 3-8: Visualization of interpolation results.

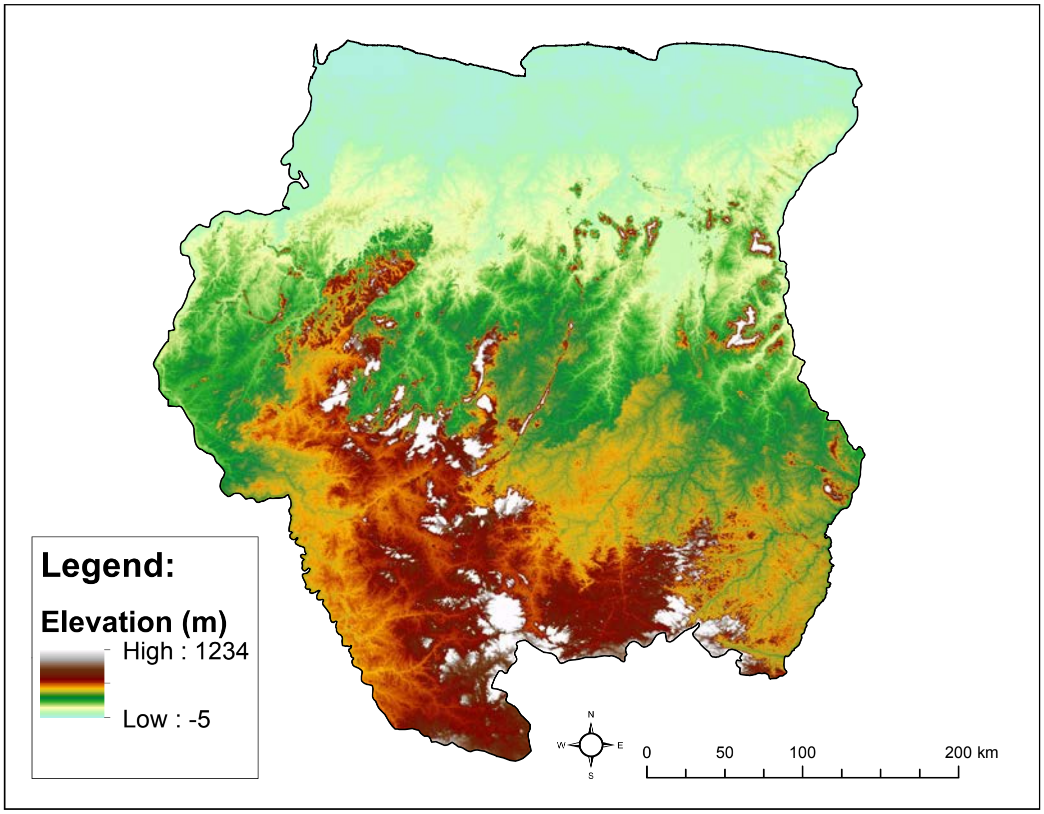

Figure 3-9: Final elevation raster.

3.4.2 Locations of Villages

A non-spatial list of 129 villages of interest regarding the electrification of the hinterland has been provided by EBS (see Appendix 8.1). An attempt was made to generically geocode this list with the ArGIS online geocoding service without producing useful results. Another attempt was made to manually geocode the list with Google Earth by taking into account place names and additional information, such as geolocated photos in Google Earth. Due to much inaccurate information and an amount of work not making up for the effort, this approach had to be abandoned as well. Therefore, OpenStreetMap was chosen as base data for village locations. A query for the key-value pairs place=town, place=village or place=hamlet delivered 116 nodes (see Figure 3-10). This result was complemented with airstrip locations also acquired from OSM data that are outside a 12 km buffer from the place nodes. The reason for the inclusion of these airstrip locations into the village location dataset for the analysis is that there were some airstrips found obviously servicing some dwelling or village which lack a corresponding place entry in the OSM data.

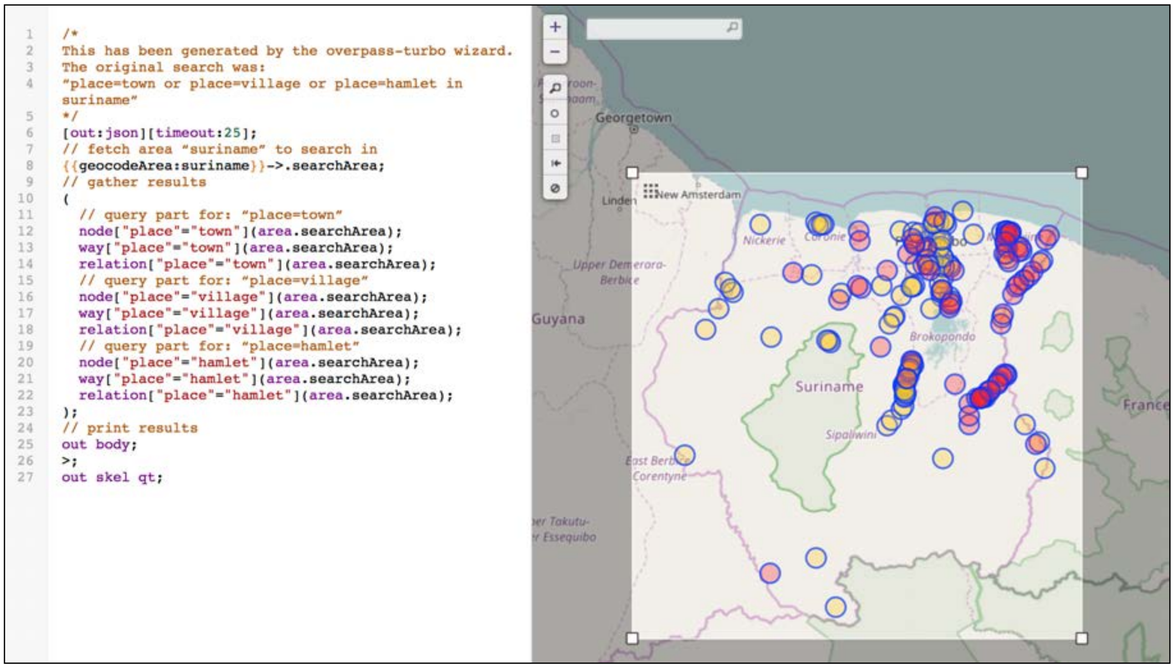

Figure 3-10: Query in OSM Overpass turbo API for village locations.

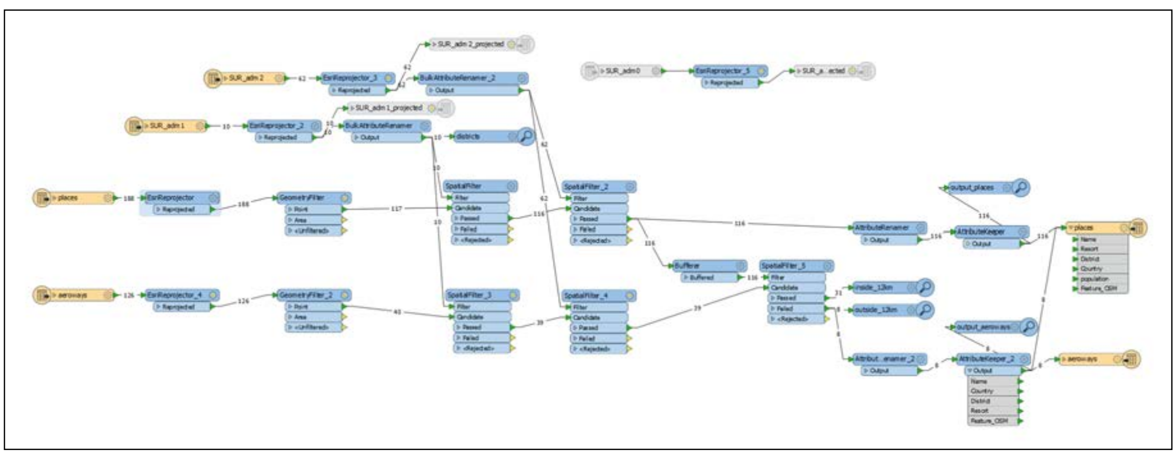

Figure 3-11: FME-workflow to generate final dataset of village locations.

The workflow shown in Figure 3-11 resulted in a total of 124 village locations to be included in the analysis, of which 116 stem from the OSM place key and 8 from the OSM aeroway key. The dataset is visualized in Figure 3-12 and the list of village names is provided in Annex 8.2[7]. Although joining the list provided by EBS with the list generated from OSM data based on the village name looking for exact matches only resulted in 8 successful matches, it is safe to assume that the OSM-based list adequately represents the locations of villages in the Surinamese hinterland. Although not empirically verifiable, the result coincides with personal communication with local experts regarding the existence of 120 to 130 villages. The lacking match to the village names provided by EBS is probably due the existence of a multitude of languages and dialects and the lacking of consistent spelling of place names. It can thus be assumed that the data quality is such as the data is fit for its purpose in the context of this study.

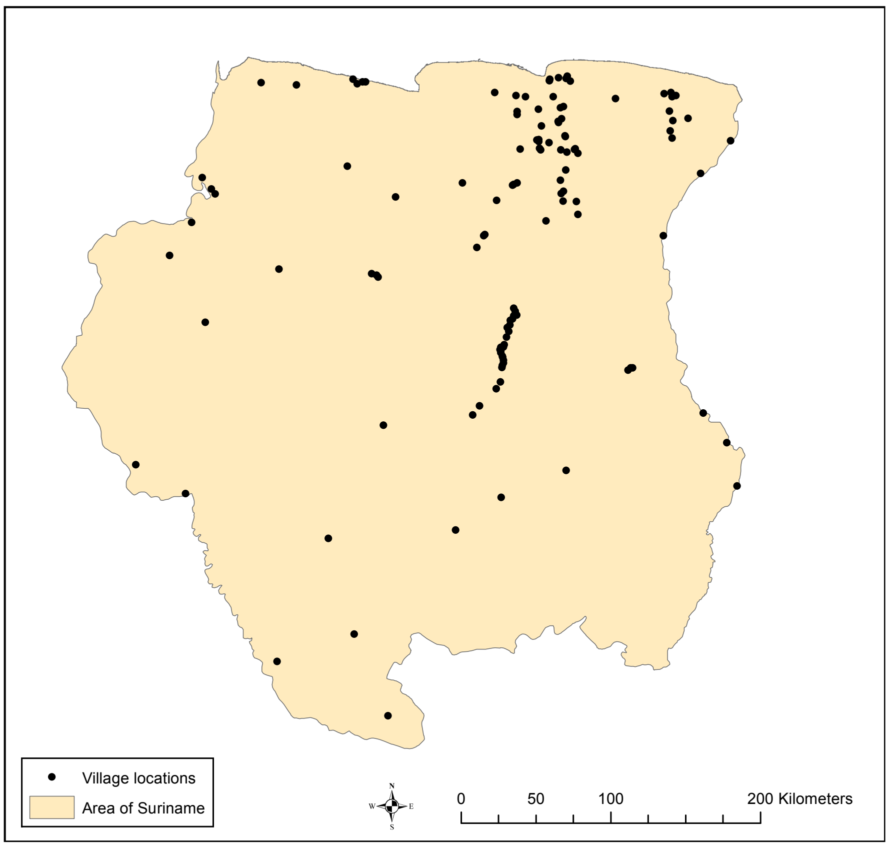

Figure 3-12: Village locations to be used in the analysis.

[7] The village of Puketi has been added manually, because it is not contained as a point in OSM data, but as an area. Therefore, the final village locations dataset consists of 125 villages.

3.4.3 Hydrology

The hydrological base data is acquired from OSM analogously to the village locations. All line elements with the values river, riverbank or stream in the waterway key are considered, as shown in Figure 3-13. This results in 4256 lines with a total length of 18’330 km.

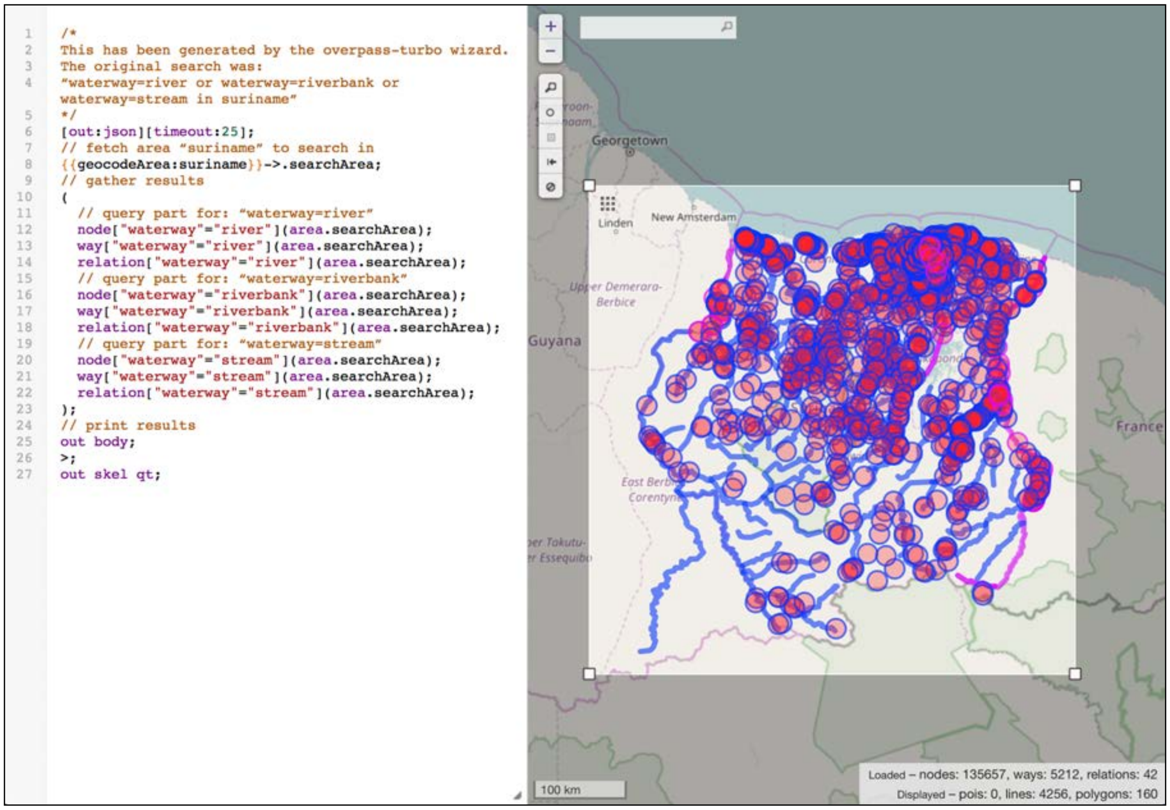

Figure 3-13: OSM Overpass turbo API query for waterways.

3.4.4 Administrative Areas

To support data visualization, a dataset of the administrative areas is utilized. It is acquired from the Database of Global Administrative Areas, version 2.8 (Global Administrative Areas, 2017).

4. MODEL DEVELOPMENT

4.1 Introduction

The basis for the final analysis model is compiled and the model is developed. First, the ground truth data which has been acquired on site is presented and discussed. Subsequently, the criteria's value ranges are defined based on theoretical considerations and a methodology for the interpretation of the result is presented. Finally, the model is formally developed in ArcGIS modelbuilder.

4.2 Ground Truth Data

4.2.1 Purpose of Ground Truth Data

Two specific sites assumed to meet the required suitability criteria had been previously identified by FOB and EBS. These sites were visited during a field trip in the course of this study in order to quantitatively reassess their suitability and to acquire empirical data to provide a basis for the design and calibration of the overlay model. The locations Gran Olo Sula and Tapawatra Sula[8] of these pilot sites are illustrated in Figure 4-1. They have been mapped according to the procedure described in Sections 3.3.1.1 to 3.3.1.3. The results of the field trips are presented in the following two sections and provide the basis for formalizing the model in Section 4.6. They will be used to test and calibrate the model.

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[8] „Sula" means rapid in a river in the local language.

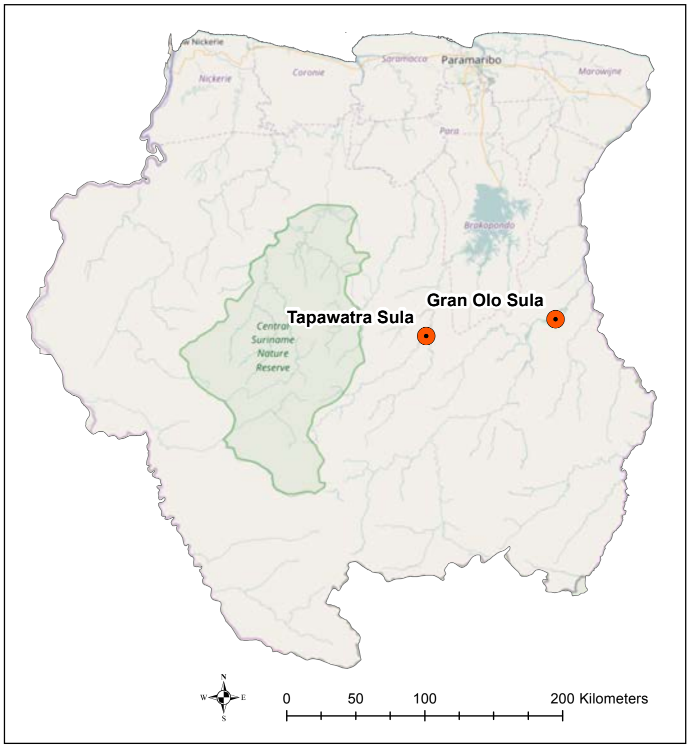

Figure 4-1: Locations of pilot sites (Source base data: OpenStreetMap and contributors CC-BY-SA).

4.2.2 Gran Olo Sula

Gran Olo Sula is one of Tapanahony River's largest rapids situated 500 m upstream of the small village of Puketi. It is the location of the two previous micro hydropower projects mentioned in Section 2.4. An overview of the situation is given in Figure 4-2.

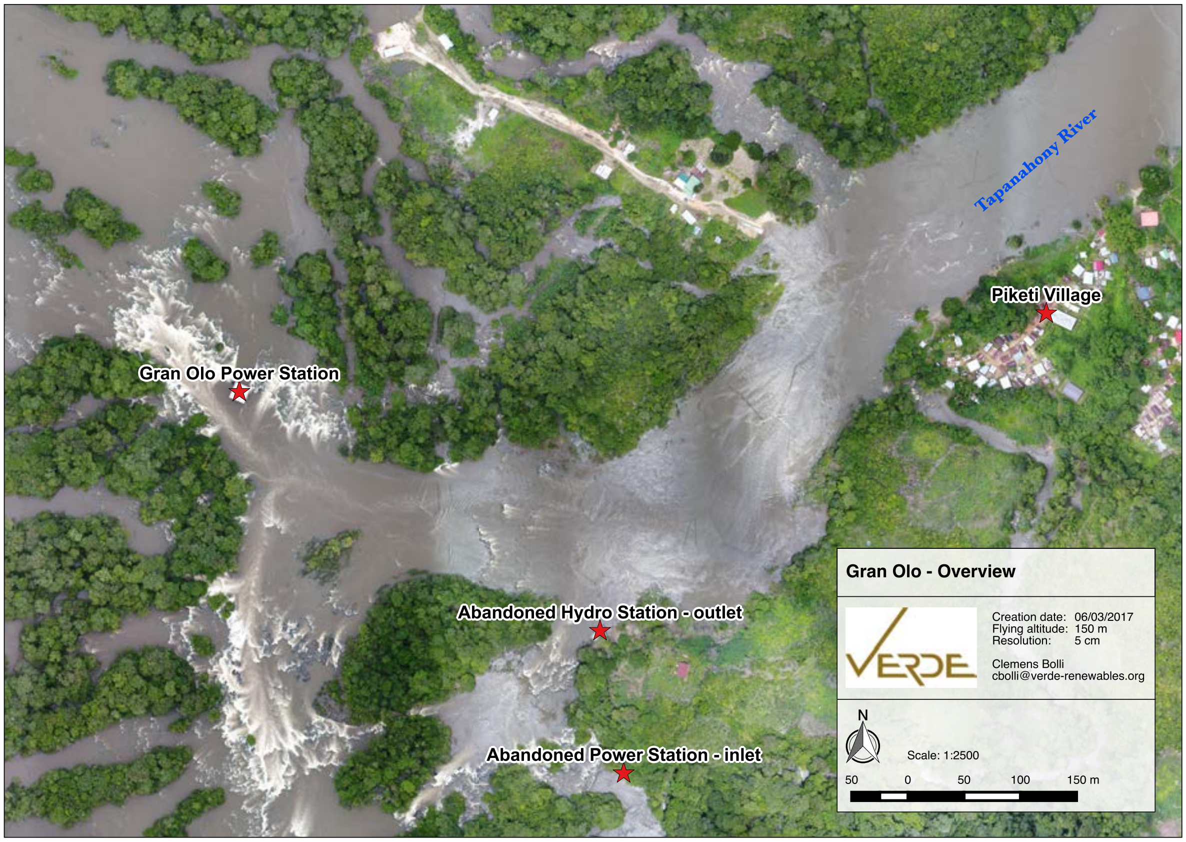

Figure 4-2: Overview of Gran Olo Sula and Puketi Village[9].

The site of the abandoned hydro station was chosen for closer analysis. The evaluation of the generated DEM revealed a head of approximately 8 m between the inlet and the outlet. With an abundance of water available throughout the year and a small village in close proximity as well as the larger village of Driettabbetje approximately 5 km upstream, the suitability of this location for the installation of VEPs could be confirmed. A possible configuration of several VEPs in a cascade is illustrated in Figure 4-4.

[9] A local spelling for the village name is "Piketi".

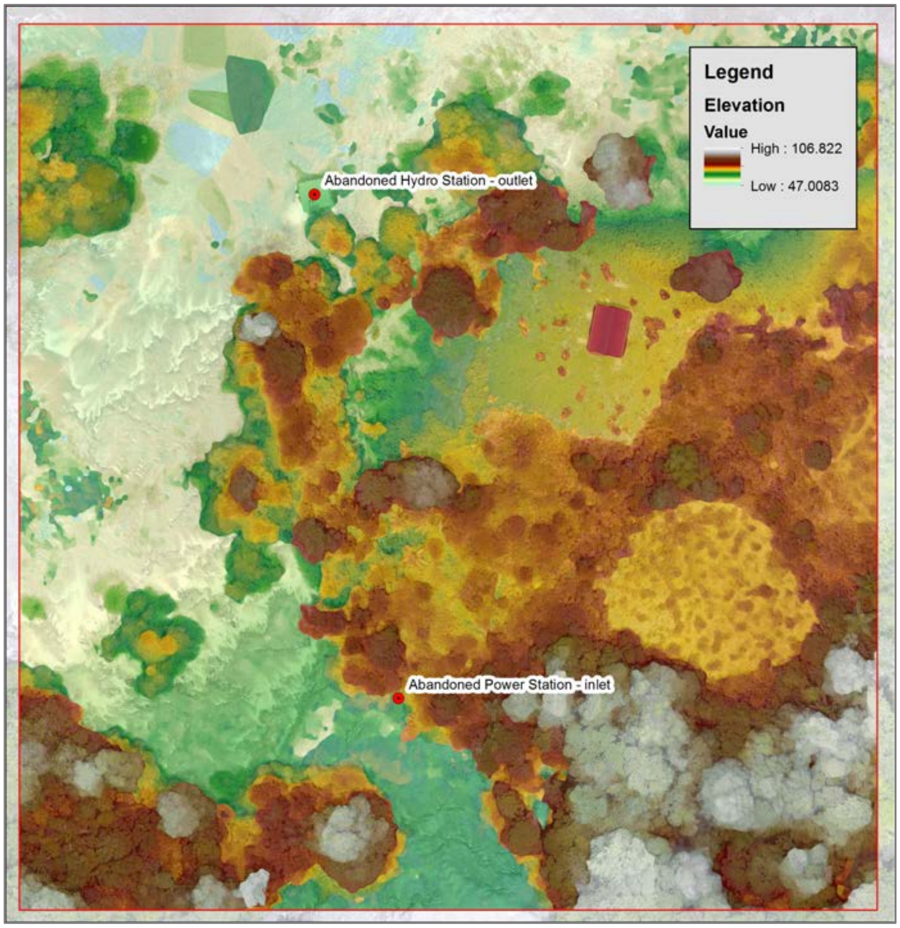

Figure 4-3: Illustration of generated elevation data at Gran Olo Sula.

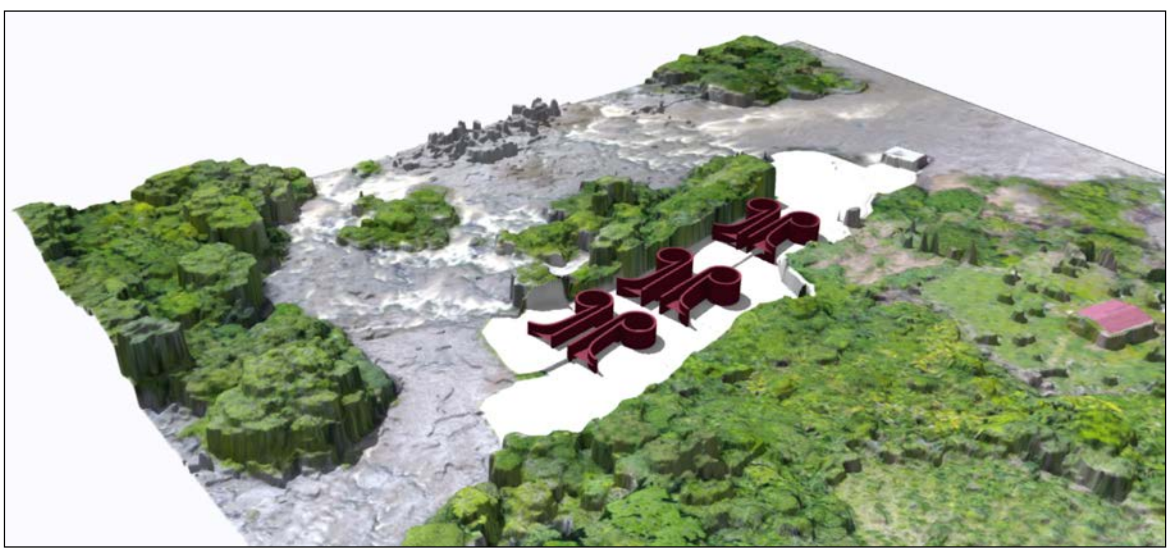

Figure 4-4: Illustration of possible arrangement of several VEPs.

4.2.3 Tapawatra Sula

Tapawatra Sula is a rapid located on the Upper Suriname river, which is the largest tibutary to the Brokopondo reservoir. It is situated in the village Asindo-Opo. An overview of the situation is given in Figure 4-5, where the red line indicates the location of the profile graph depicted in Figure 4-6. As can be seen in Figure 4-6, a head of approximately 3.6 m can be calculated from the elevation data. With the village and its residents as potential electricity consumers close by as well as the Upper Suriname river as source of water, the basic site requirements are fulfilled and the suitability of this site can be confirmed.

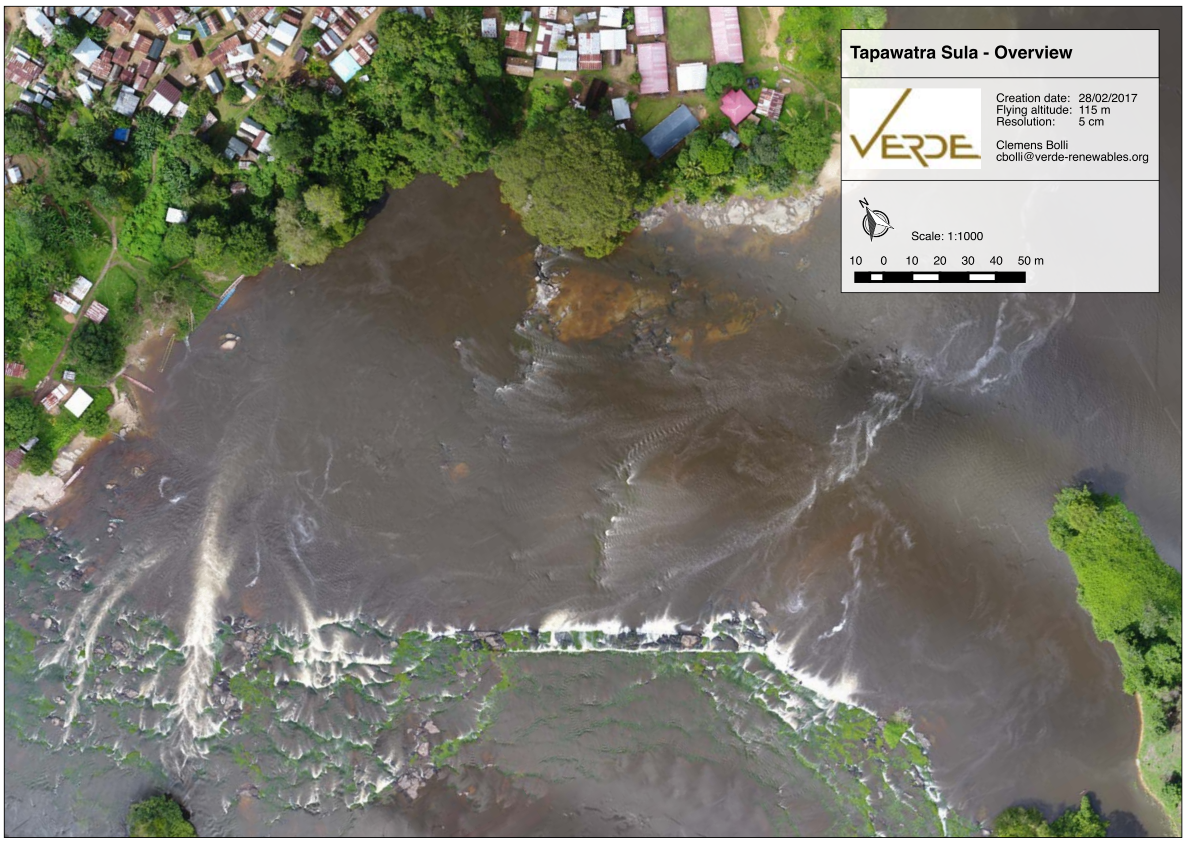

Figure 4-5: Overview of Tapawatra Sula.

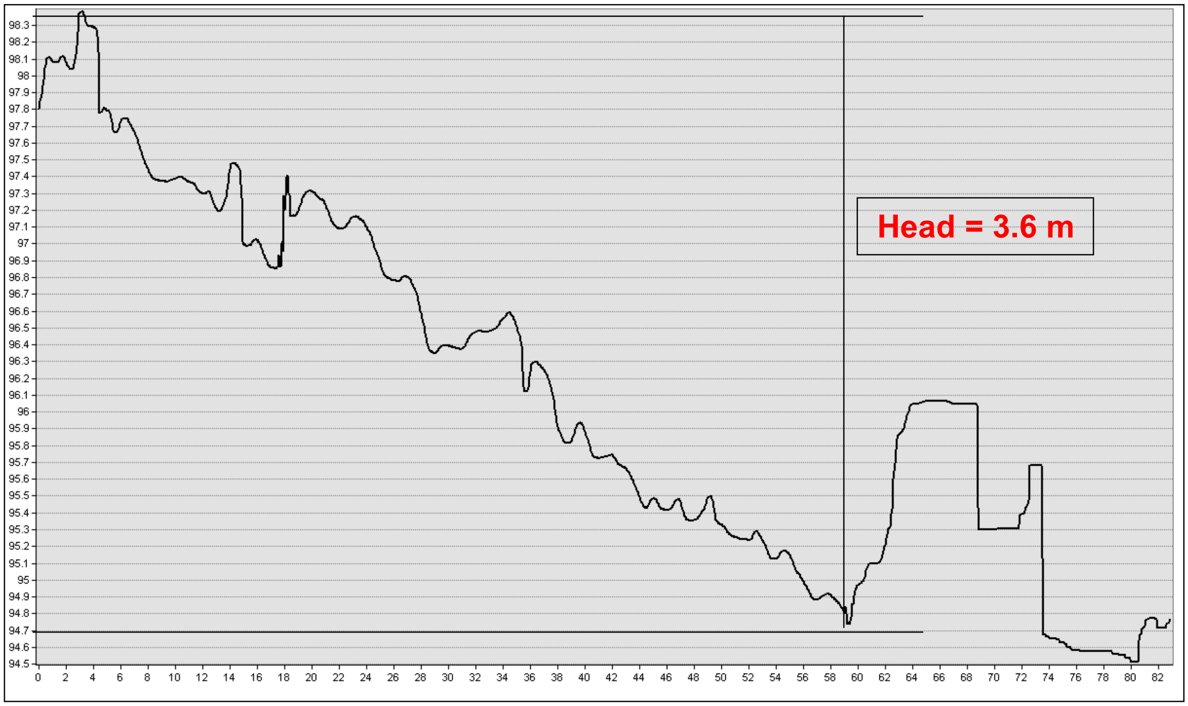

Figure 4-6: Elevation profile of Tapawatra Sula at location indicated in Figure 4-5.

4.3 Definition of Value Ranges

4.3.1 Head – Slope

Reconsidering the performance range of VEPs discussed in Section 1.7.5, it can be concluded that a minimum head of 1.5 m is a sensible assumption for one VEP. Taking into account the dimensions of the pilot VEP shown in Figure 1-3 and illustrated in more detail in Figure 4-7, it can be inferred that the elevation difference as defined by the minimum head should be given over a distance of approximately 30 m. As illustrated in Figure 4-8, this results in a theoretical minimum slope value of 2.9° given a raster grid size of 30 m. Given the laws of physics and the technical specifications of VEP, the suitability of a location increases with the available head. However, since VEPs are a low-head technology and not designed for a head of more than 3 m, the suitability decreases again with higher heads. Higher heads nevertheless do not per se inhibit the construction of VEPs, because corresponding construction measures can be taken in order not to utilize the total head. Therefore, suitability shall not be modelled to decrease with higher heads as drastically as with lower heads, where a physically possible minimum is approached. Based on these assumptions, a first test to reclassify slope values into a suitability raster according to Table 4-1 was made.

Figure 4-7: Dimensions of pilot VEP in Schöftland AG, Switzerland (Source: swisstopo).

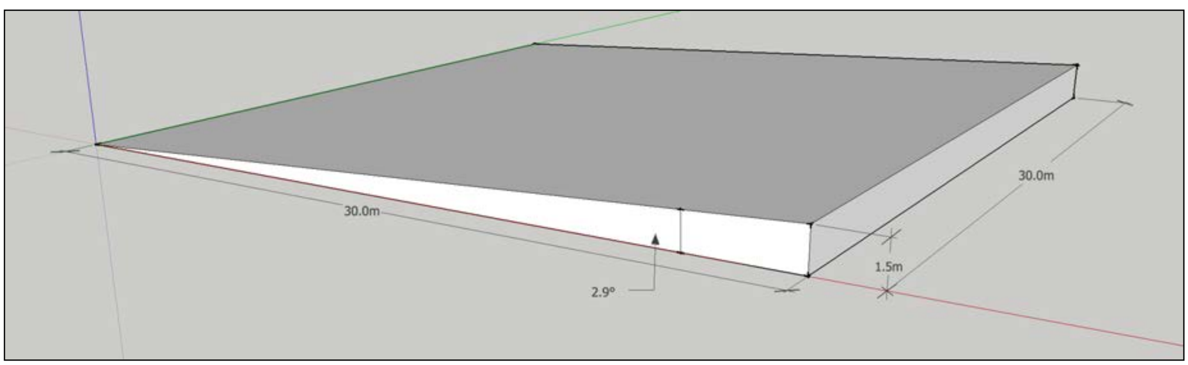

Figure 4-8: Minimum slope for achieving minimum head of 1.5 m on a 30m gridded raster.

Table 4-1: Reclassification of Slope Raster

Head:	Slope	Suitability
	< 2.5°	0 (infeasible)
1.5 m	2.50 - 3.59°	1
	3.60 - 4.19°	2
	4.20 - 4.79°	3
	4.80 - 5.39°	4
3 m	5.40 - 6.49°	5
	6.50 - 7.49°	4
	7.50 - 8.49°	3
	8.50 - 9.49°	2
5.6 m	9.50 - 10.49°	1
	> 10.5 °	0 (infeasible)

Although, a crosscheck with the empirical data gathered at test sites revealed that the results were not plausible enough. While for the case of Tapawatra Sula, the outcome looked quite reasonable (see Figure 4-9), the result for Gran Olo Sula made the impression of being rather coincidental (see Figure 4-10).

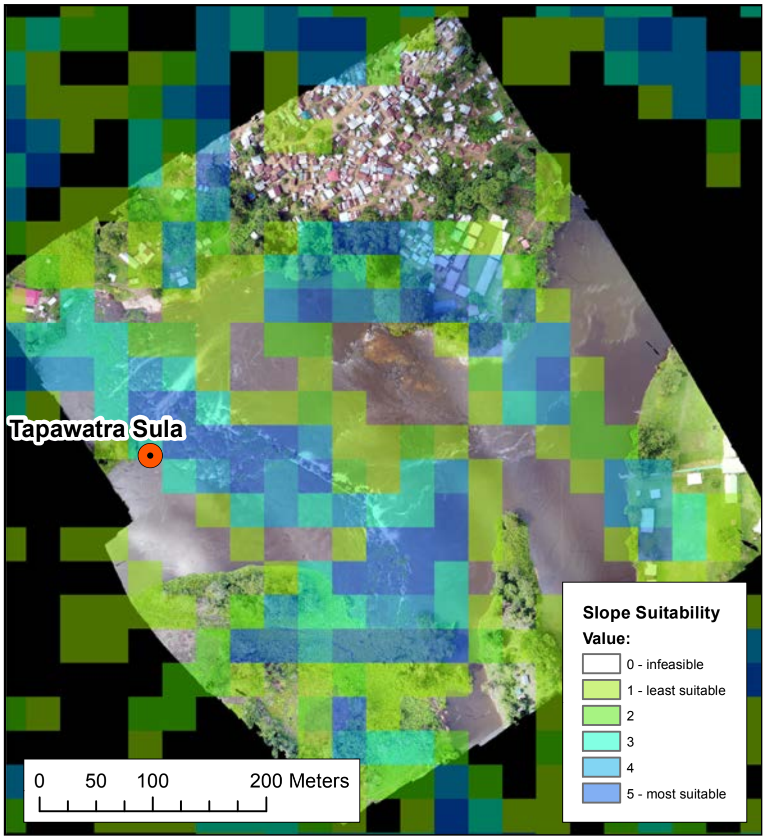

Figure 4-9: Slope suitability Tapawatra Sula based on 30 m elevation model according to suitability classification in Table 4-1.

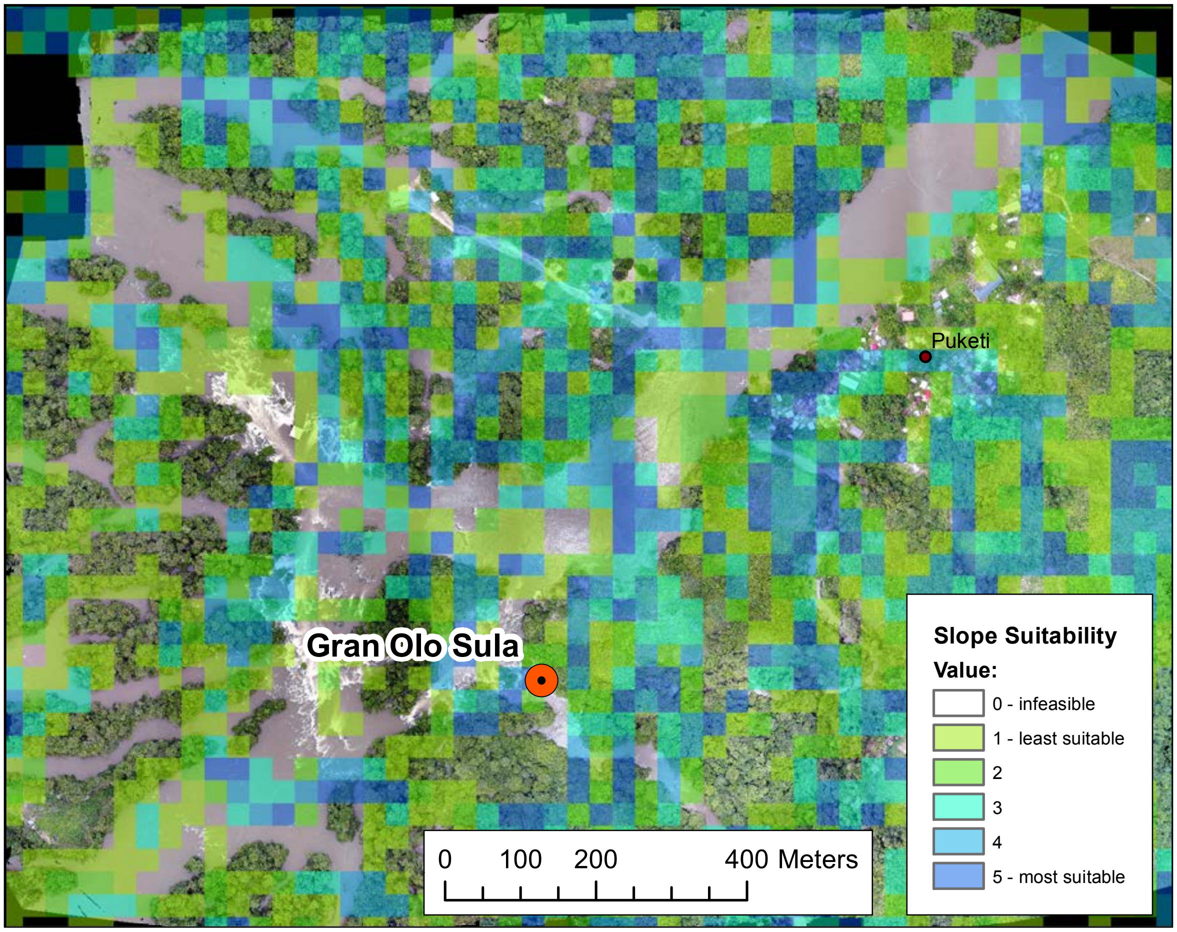

Figure 4-10: Slope suitability Gran Olo Sula based on 30 m grid elevation model according to suitability classification in Table 4-1.

Various unsuccessful attempts were made to optimize the result by applying focal filters to the slope suitability, such as mean and sum. The underlying problem is probably that the initial SRTM elevation dataset's accuracy is not perfectly suited for the scale range on which the first attempt was made, since very small elevation differences within the dataset's error range are already considered as suitable in terms of the head requirement. Therefore, the elevation dataset was resampled to a 90x90 m grid in order to flatten out the inaccuracies assumedly responsible for the random pattern observed in Figure 4-9 and Figure 4-10. Of the resampled elevation dataset, a new slope raster was calculated to be rclassified according to Table 4-1. As Figure 4-11 and Figure 4-12 indicate, this approach is more promising, since the modelled slope values better correspond to the high-resolution data gathered on site. The slope suitability raster calculated based on the 90x90 m grid elevation model will therefore be used for the suitability analysis.

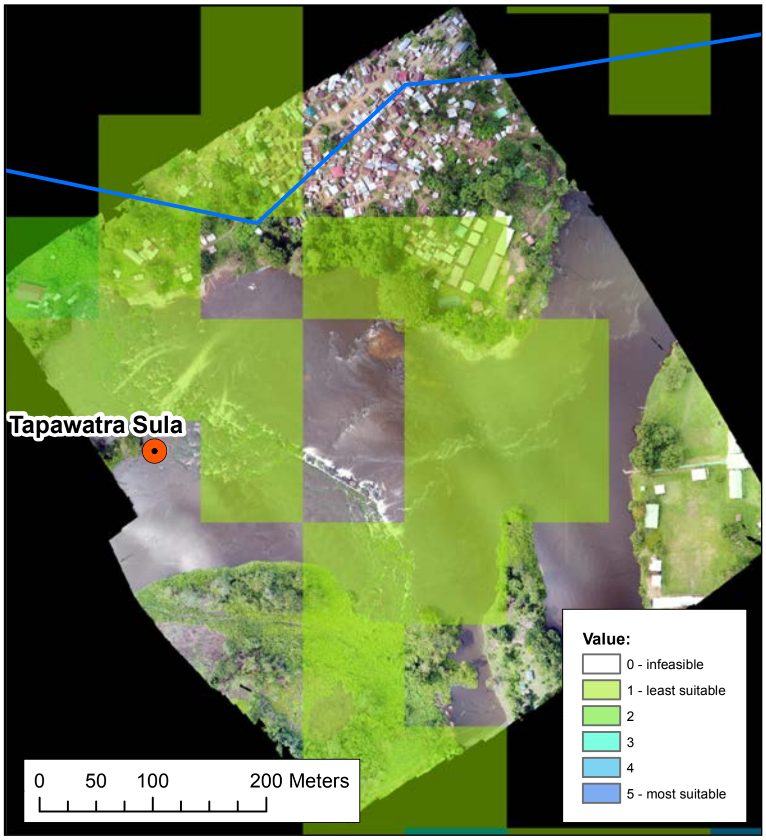

Figure 4-11: Slope suitability Tapawatra Sula based on 90 m elevation model.

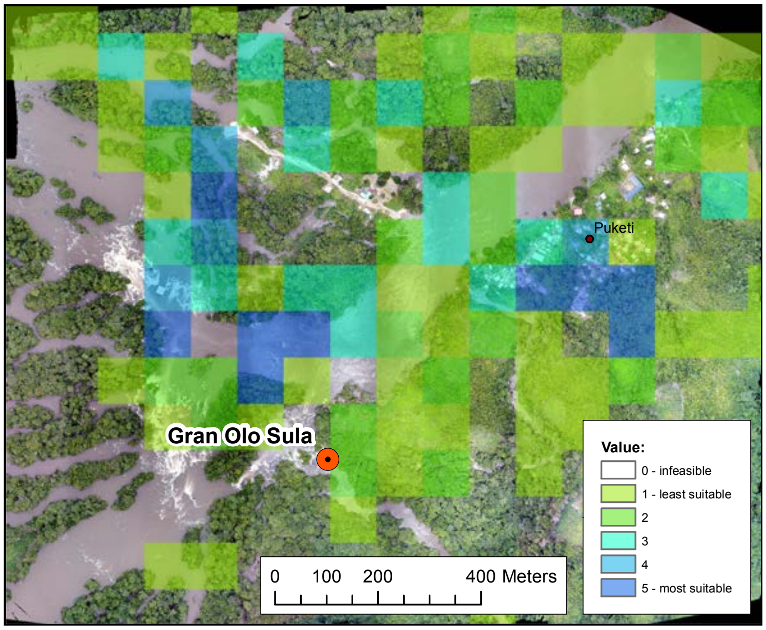

Figure 4-12: Slope suitability Gran Olo Sula based on 90 m elevation model.

4.3.2 Electricity Demand – Proximity to Village

Electricity demand shall be modelled in a binary way only considering the presence of any demand at all, which is to be operationalized by the criterion of the presence of a village. The location of electricity consumption is further relevant since the produced electricity will be distributed by small island grid systems. Therefore, the distance between production and consumption cannot be arbitrary, but is limited by electro-technical aspects and cost restraints. While within a distance of 3 km, the electricity can be distributed by means of low voltage systems, it must by stepped up to 12 kV for larger distances, which increases production costs and results in transmission losses. The maximum range of 12 kV systems is 12 km. The transmission over larger distances is technically possible, but due to economic considerations in the given context not possible[10]. Therefore, the feasible alternatives in terms of proximity to a village must be situated inside a radius of 12 km to the village to be supplied. The sites of highest suitability are modelled to be within 3 km, since the possibility of not having to install a high voltage system represents huge cost benefits. Therefore,

[10] Personal communication with Peter Donk (EBS) and Damian Staedeli (Verde Renewables AG).

suitability drops sharply outside a 3 km range, from where it decreases linearly due to larger construction and maintenance costs for larger distances. Based on these considerations, the suitability classification scheme shown in Figure 4-13 has been developed, where the values represent the level of suitability. This scheme is taken as a basis for a multiple ring buffer operation on the village locations to be used as input to generate the suitability raster for the criterion *proximity to village*. An illustration of the allocation of suitability values based on proximity to a village for the area of the village Puketi near Gran Olo Sula is shown in Figure 4-14. The suitability raster for the criterion proximity to a village, which is snapped to the slope suitability raster, is calculated with the model shown in Figure 4-15.

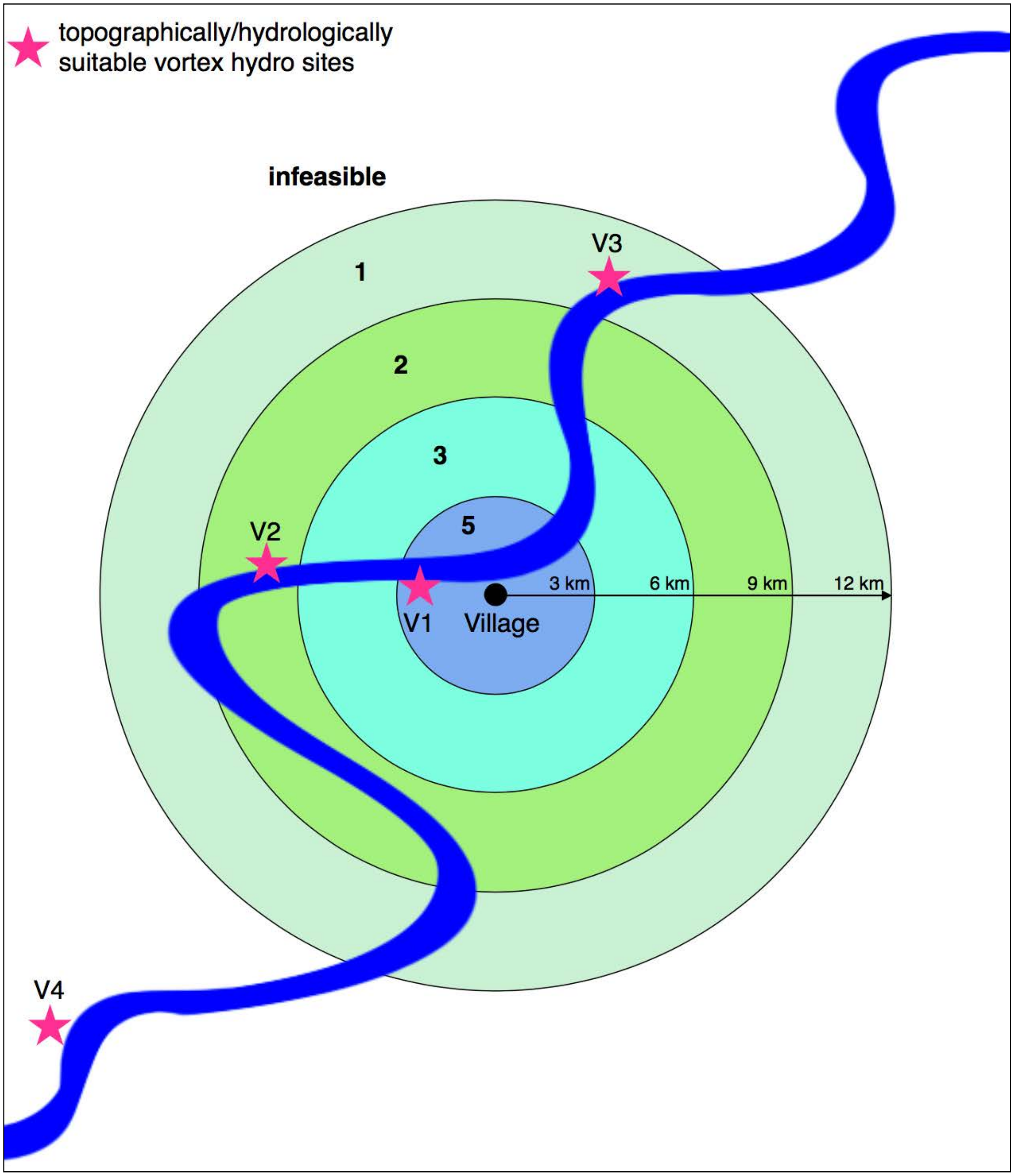

Figure 4-13: Suitability classification scheme for proximity to village.

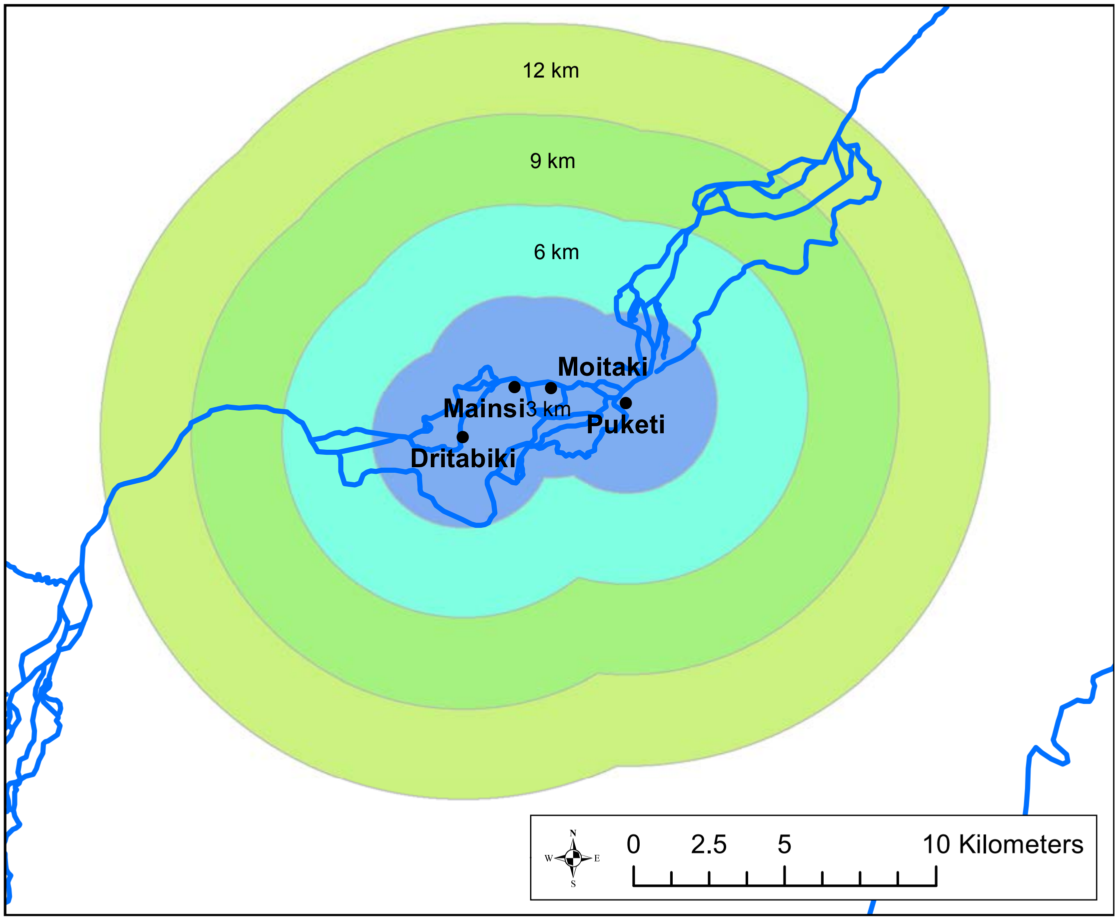

Figure 4-14: Allocation of suitability values based on proximity to village.

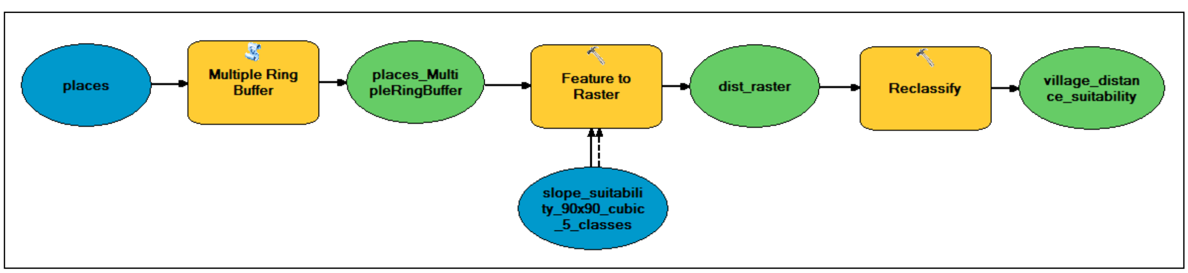

Figure 4-15: Calculation of proximity to village suitability raster.

4.3.3 Water Availability – Proximity to Water Body

As mentioned in Section 3.2, the requirement of *water availability* is operationalized by the criterion proximity to a water body. The generation of a hydrologic network from the SRTM elevation data has been considered and tested as an alternative to relying on OSM data. An ordered stream network has been calculated with the tools of ArcMap's Hydrology

Toolset (ESRI, 2017a). However, the result was not satisfying enough to be usable for the analysis. At Tapawatra Sula for example, no connected stream network could be calculated (see Figure 4-16).

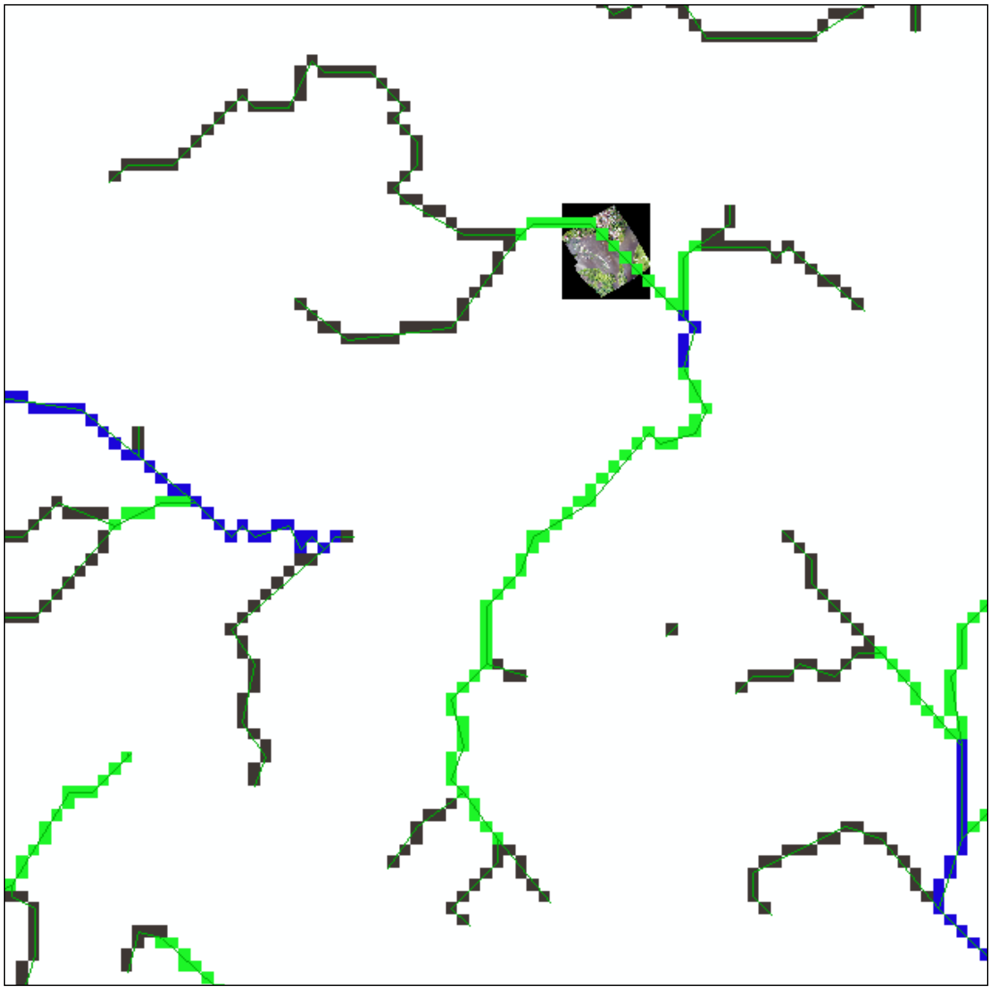

Figure 4-16: Fragment of stream network at Tapawatra Sula.

Therefore, the OSM hydrologic network is used as base data. Since the OSM data is not perfectly accurate and the line features do not take into account the width and the widely branched river system, the line features are buffered by 100 m. The resulting area is modelled as the best suitability in terms of water availability. With 4 ring buffers of 25 m each, a decreasing suitability is modelled with decreasing distance from the initial river system buffer, which means that sites outside a 200 m distance of the OSM hydrologic network are considered infeasible (see Figure 4-17).

This approach on the one hand, if considering some inaccuracy of the OSM dataset, models the likelihood of a site effectively being situated directly at the bank of a river as highest within 100 m from the OSM geometry, while this likelihood decreases with increasing distance. On the other hand it accounts for the fact that, supposing a perfect accuracy of the OSM data, riverbanks tend to be wide and the precise site location would be at the shore or even, with corresponding construction measures, some distance away from the shore.

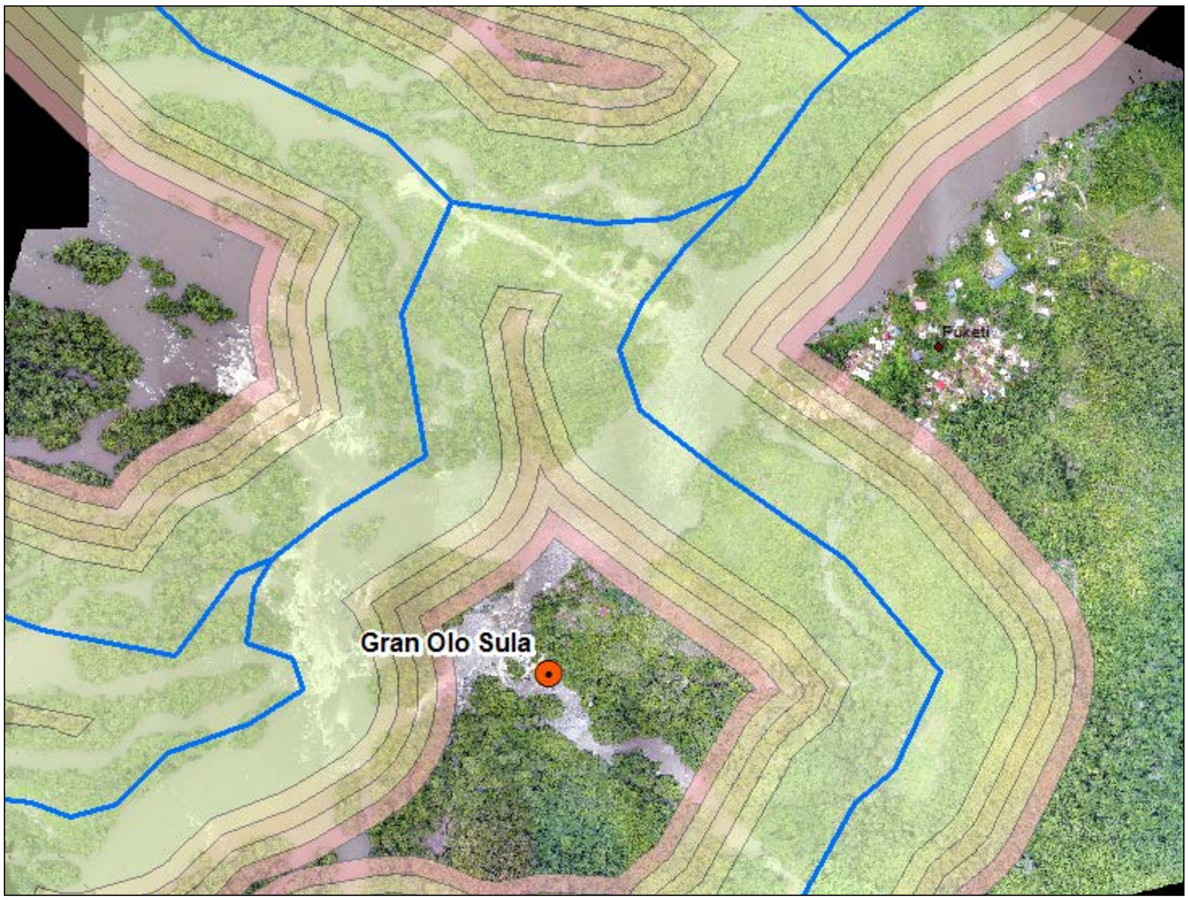

Figure 4-17: Buffers of OSM waterways geometries as a basis for the proximity to water body suitability raster.

The suitability raster for the criterion *proximity to water body* is generated based on the buffer distances according to Table 4-2. Since this raster's grid size will have to be 90 m, such as the slope suitability raster, the classification results in most values either belonging to the best suitability class or being classified as infeasible. This is desired, since the requirement *water availability*, as it is modelled, resembles a binary requirement. With the slight fuzzification achieved by the ring buffers of 25 m, the uncertainties and eventual constructional measures mentioned above are taken into account.

Table 4-2: Classification of Distance to Waterbody Raster

Buffer Distance	Suitability
< 100 m	5
100 – 124 m	4
125 – 149 m	3
150 – 174 m	2
175 – 200 m	1
> 200 m	0 (infeasible)

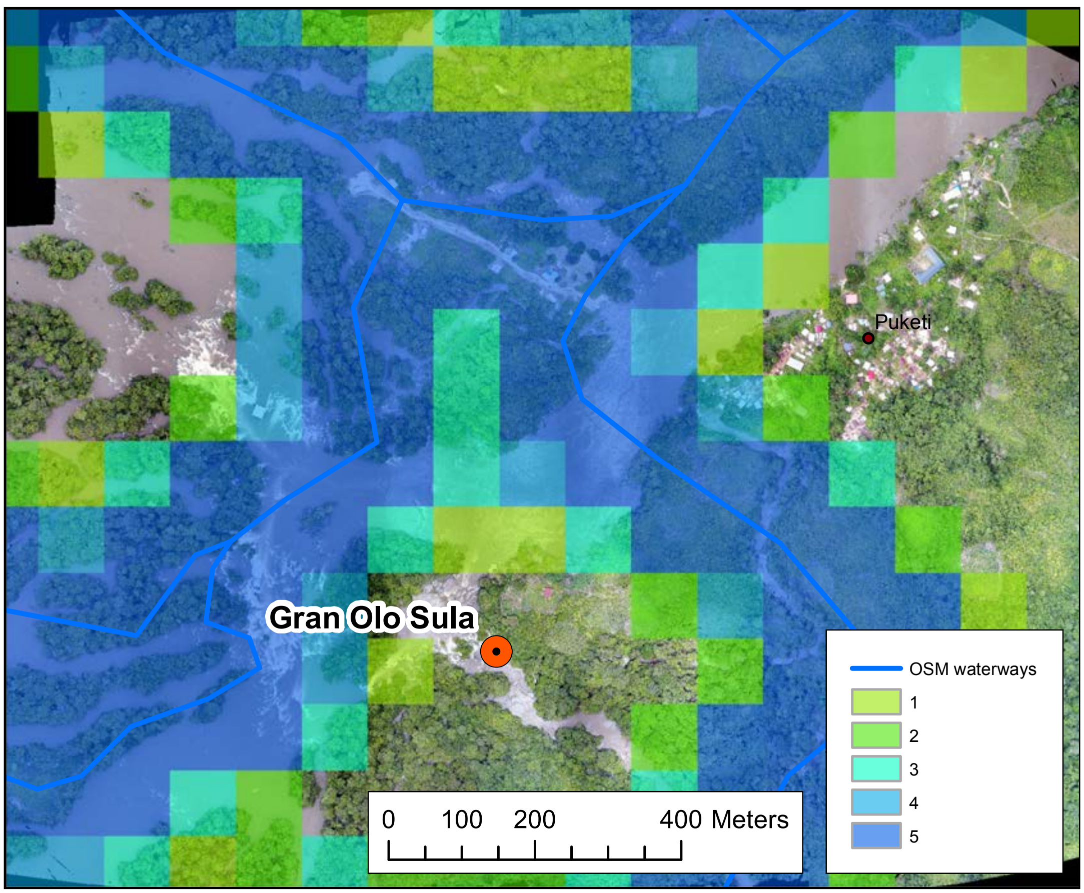

Figure 4-18: Proximity to waterbody suitability raster.

4.4 Definition of Criteria Weightings

The criteria set has been reduced to an absolute minimum of necessary criteria without the possibility of mutual payoff. However, regarding the requirement of *water availability*, the corresponding criterion's data basis in terms of locational accuracy has some drawbacks. With regard to the requirement of *electricity demand*, the model assumptions could be stretched in the state of project execution by technical means. The requirement of *head* however represents a physical restraint if it is not fulfilled adequately. Moreover, its criterion's data basis is the most robust of all the considered criteria. Therefore, a weight of 50 % is assigned to the criterion of *slope*, whereas weights of 25 % each are assigned to the criteria *proximity to water body* and *proximity to village*.

4.5 Methodology for Result Interpretation

Recalling the expected results of this study (see Section 1.4), a methodology must be defined in order to derive the expected results from the overall suitability raster generated by the weighted overlay analysis. For this purpose, suitability raster cell values within a 12 km distance of every village belonging to the dataset shall be summed up and assigned to the respective village as a new attribute (sum_suitability). These sums are then normalized, based on a range of 0 to $\text{sum\_suitability}_{max}$ as the attribute norm_suitability.
All village locations with a value of sum_suitability > 0 can be considered as feasible alternatives and will be the basis for a respective map. A rating of the level of fulfillment of the requirements can be made by comparing the normalized suitability values. It has to be emphasized that this rating will be a relative comparison of all feasible alternatives, and not an absolute statement on requirements fulfillment in relation to criteria value ranges. Nevertheless, it is meaningful, since higher values theoretically reflect more and better suitable raster cells in proximity of a village. Notwithstanding data and modelling inaccuracies, this effectively indicates a higher potential for VEPs, since more plants can be built, which is of importance in the context of larger villages. Considering eventual inaccuracies, higher val-

ues result in a higher probability of effectively finding a suitable location that is not a false positive produced by the model.

4.6 Model Formalization

Based on the findings of Sections 4.1 to 4.5, the model is formalized with ArcGIS Model-builder according to Figures Figure 4-19 to Figure 4-24 using the Weighted Overlay tool (ESRI (2017e)).

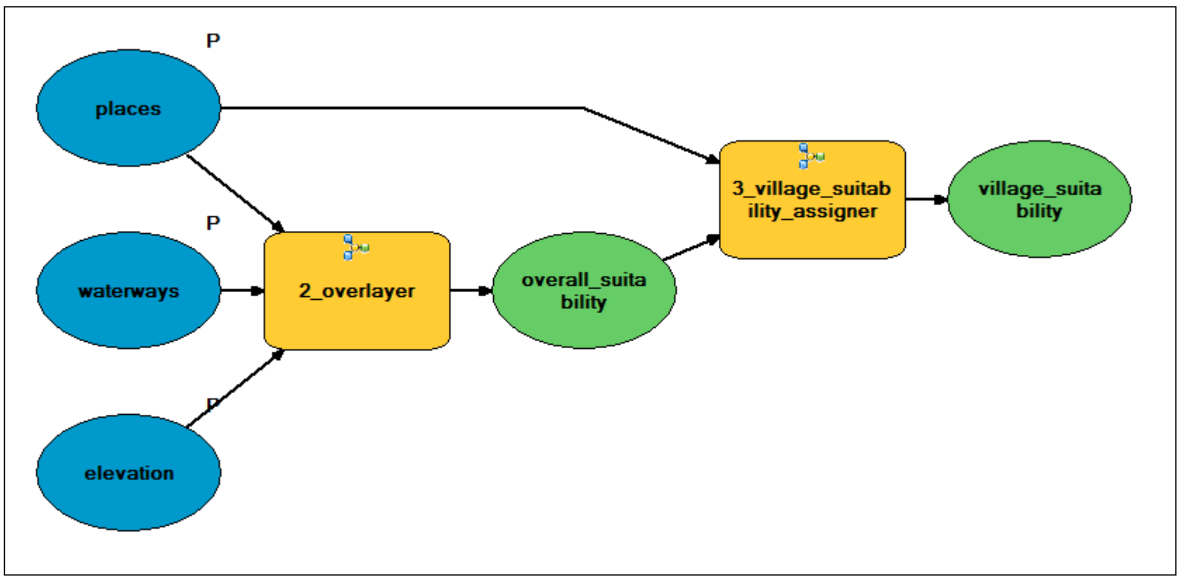

Figure 4-19: Model 1 – Master model outputting the final results.

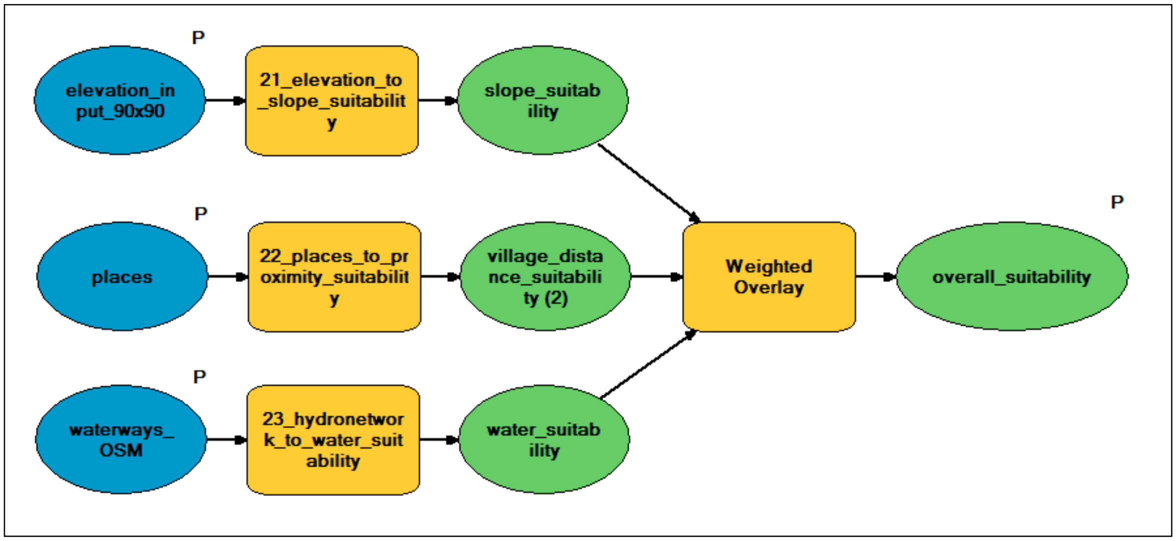

Figure 4-20: Model 2 – Weighted overlay of suitability rasters.

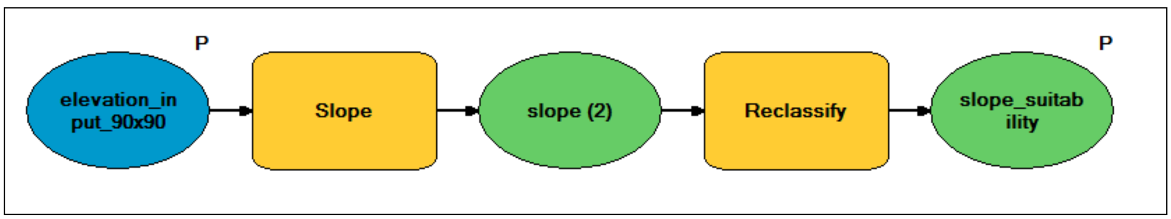

Figure 4-21: Model 21 – Calculating slope suitability raster.

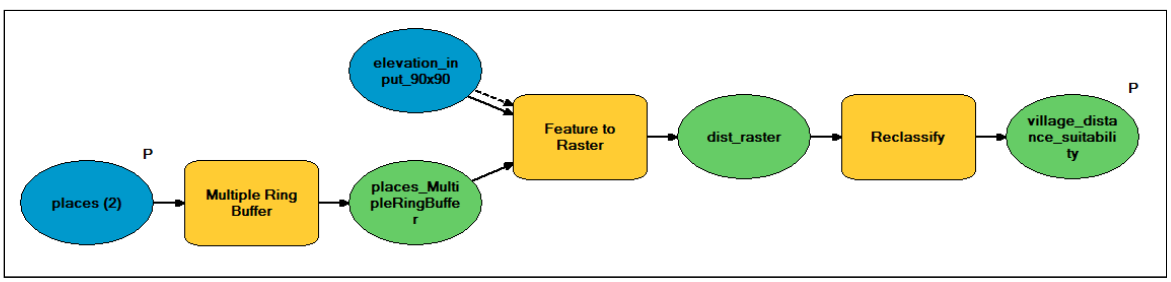

Figure 4-22: Model 22 – Calculating village proximity suitability raster.

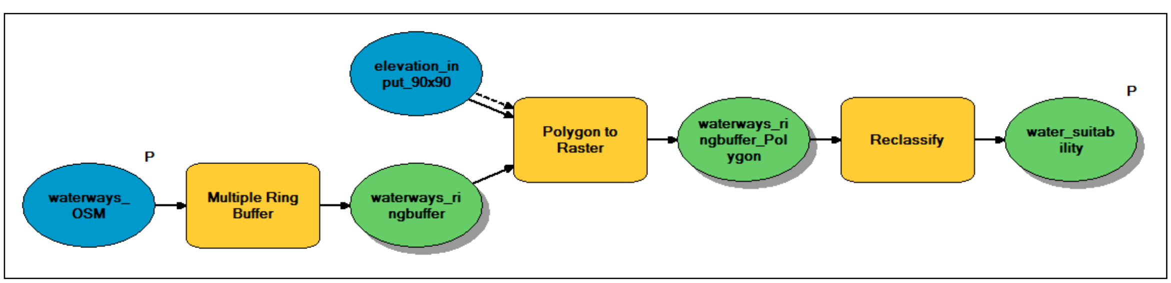

Figure 4-23: Model 23 – Calculating water body proximity suitability raster.

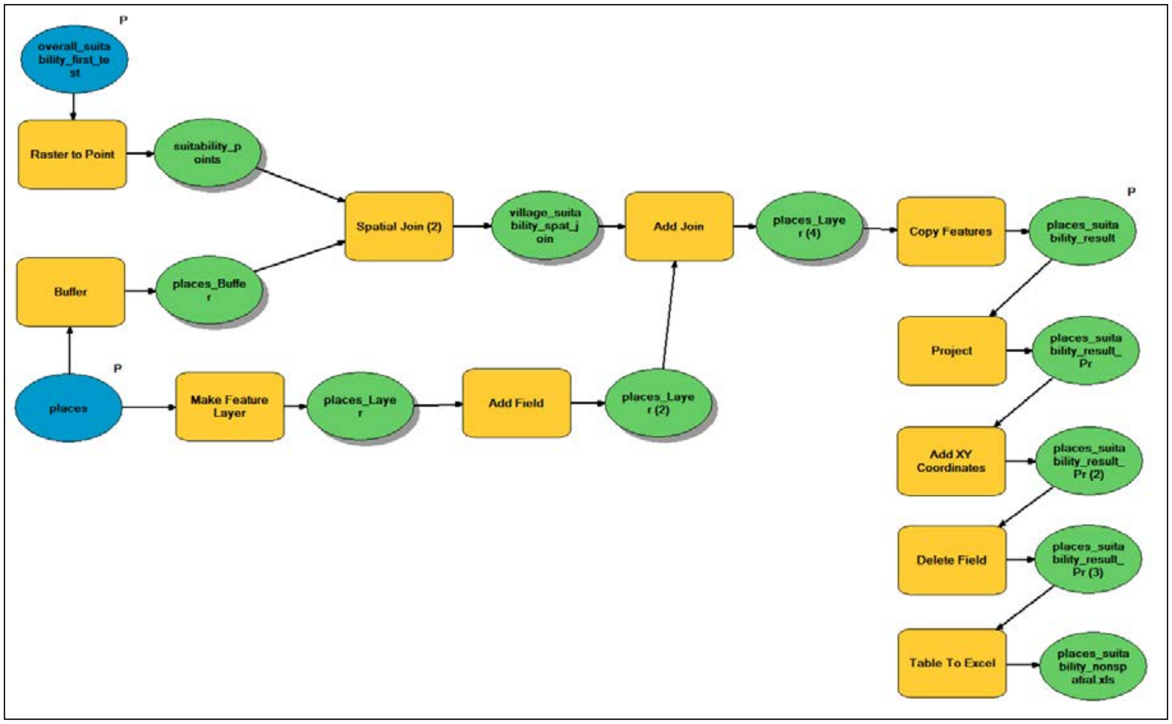

Figure 4-24: Model 3 – Generating village suitability attributes from suitability raster.

5. EMPIRICAL RESULTS

All of the village locations analyzed have been identified as feasible alternatives according to the model assumptions. The suitability map shown in Figure 5-1 gives an overview of the results. The villages of the districts Commewijne, Paramaribo and Wanica have been excluded from the results, since these regions are not of interest for micro hydro power development as they are already connected to the existing electricity grid. The remaining 110 villages cover the whole range of the normalized suitability scale, as Figure 5-2 indicates (see complete list in Annex 8.3). 3 outliers with exceptionally high suitability values can be identified. A closer look at the results reveals that these all represent the same area of Moeder Vallen, which is shown in figure Figure 5-3. A picture available on Google Earth, which is geolocated in that region and annotated as Raleighvallen, seems to confirm the high suitability (see Figure 5-4). Not surprisingly, the regions of the visited test sites also show high suitability values (see Figure 5-5 and Figure 5-6). Figure 5-7 and Figure 5-8 show 2 more regions with potentially highly suitable locations.

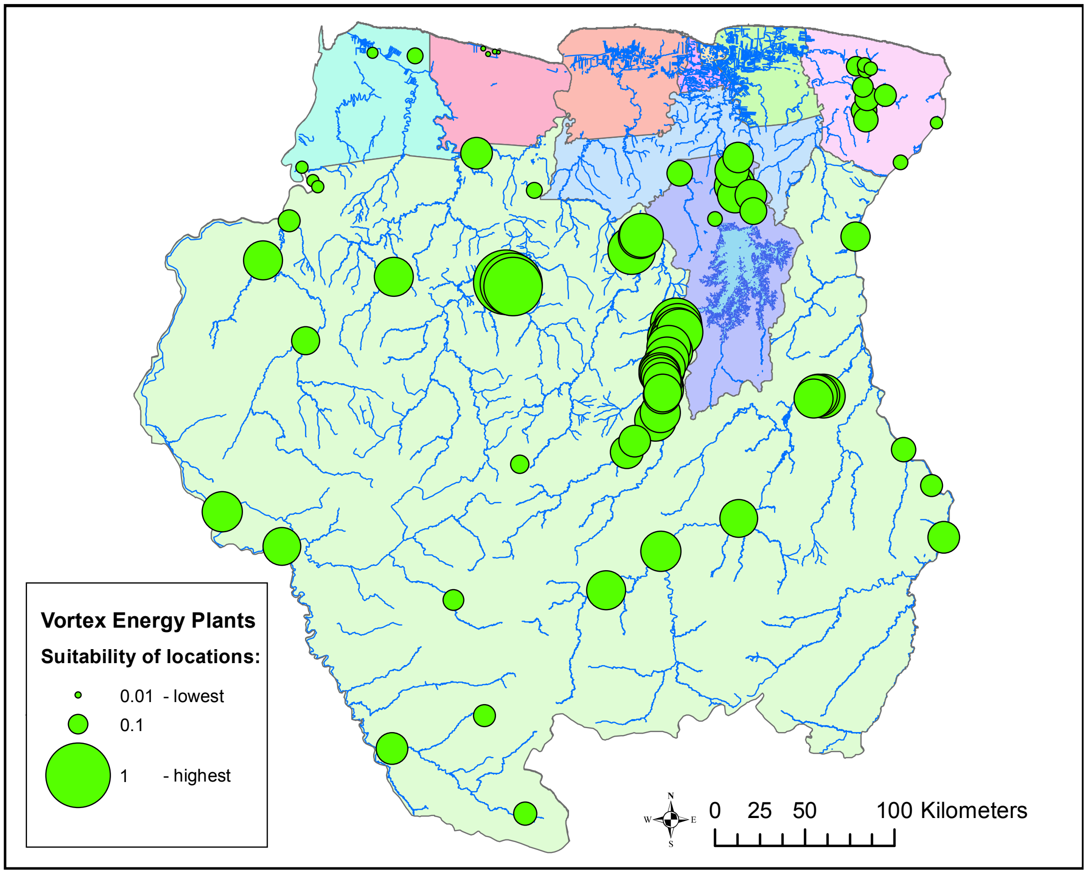

Figure 5-1: Suitability map of analysed locations.

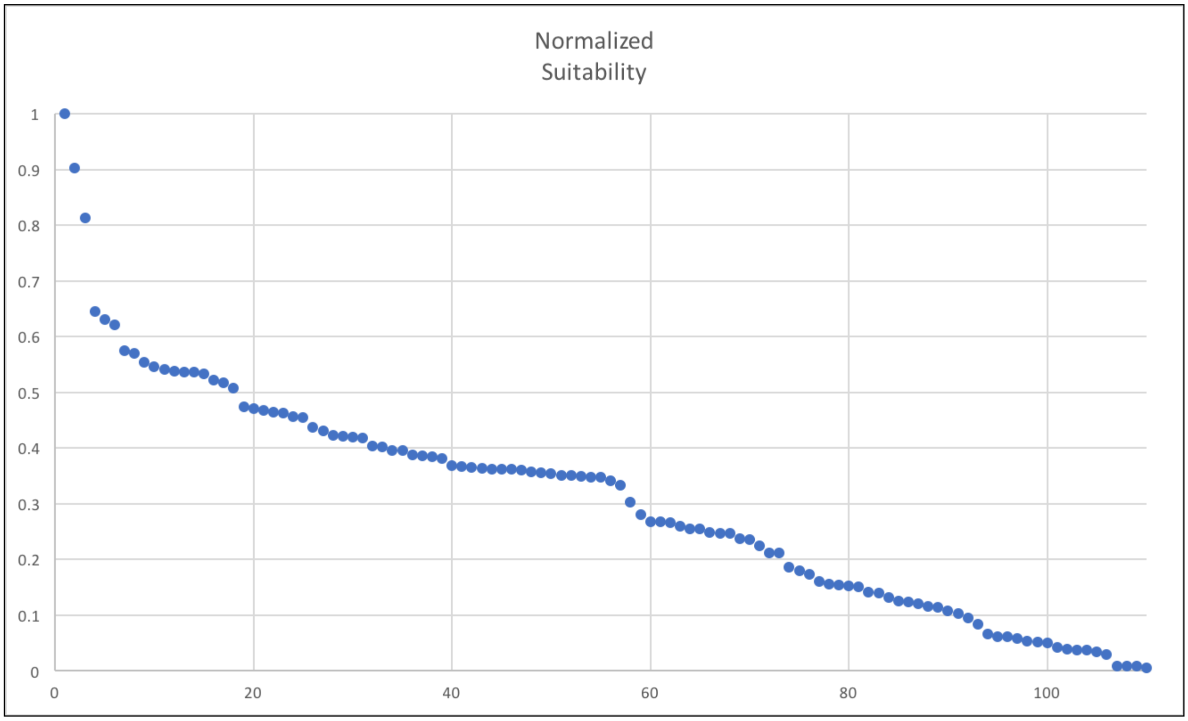

Figure 5-2: Normalized suitability distribution.

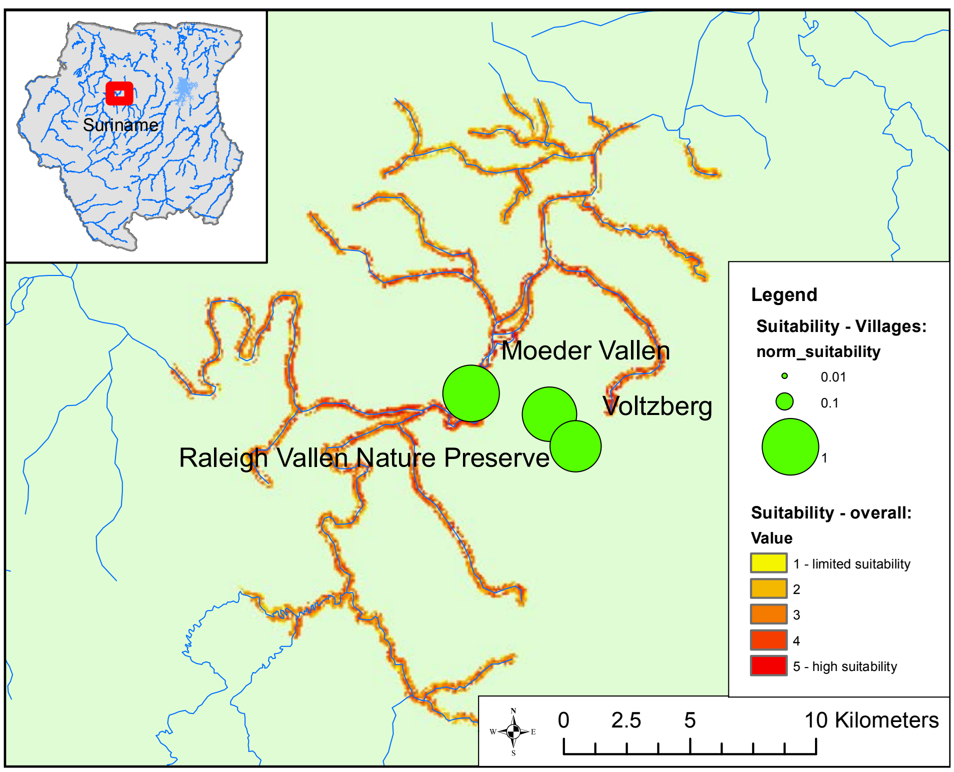

Figure 5-3: Suitability map of Moeder Vallen region.

Figure 5-4: Raleighvallen in the region of Moeder Vallen (Source: Google Earth).

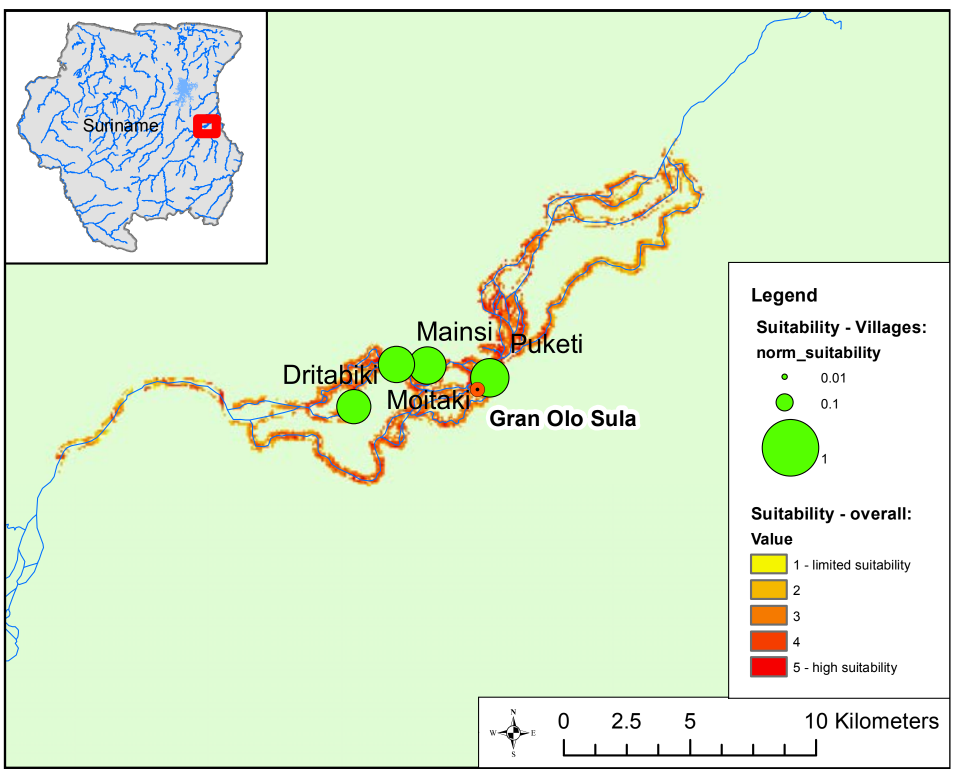

Figure 5-5: Suitability map of Gran Olo Sula region.

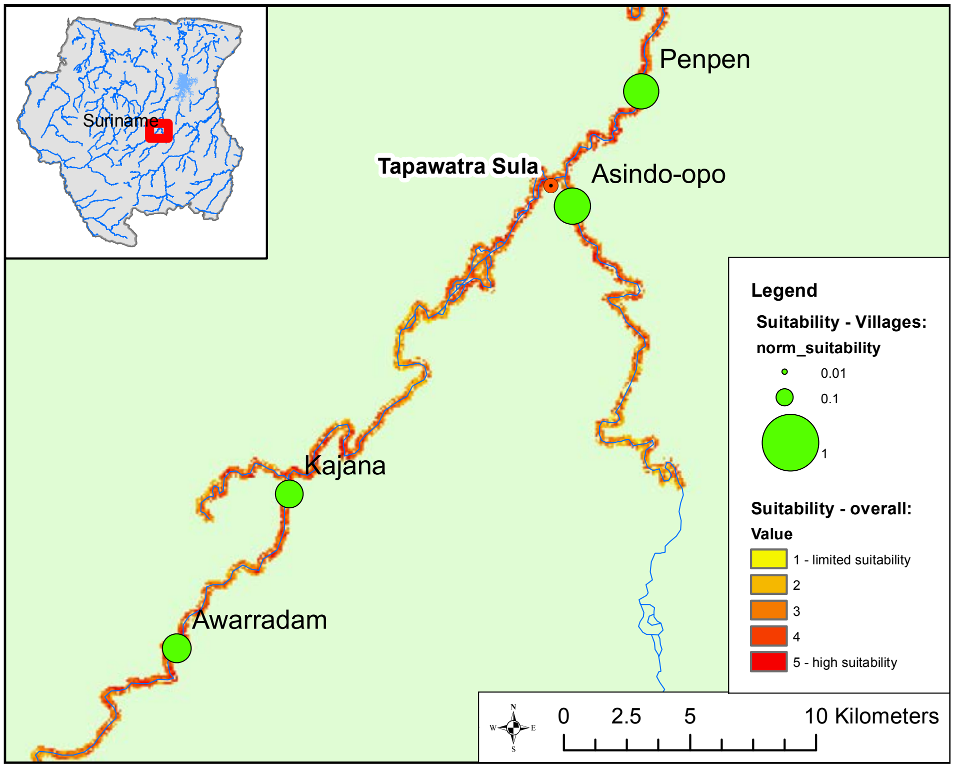

Figure 5-6: Suitability map of Tapawatra Sula region.

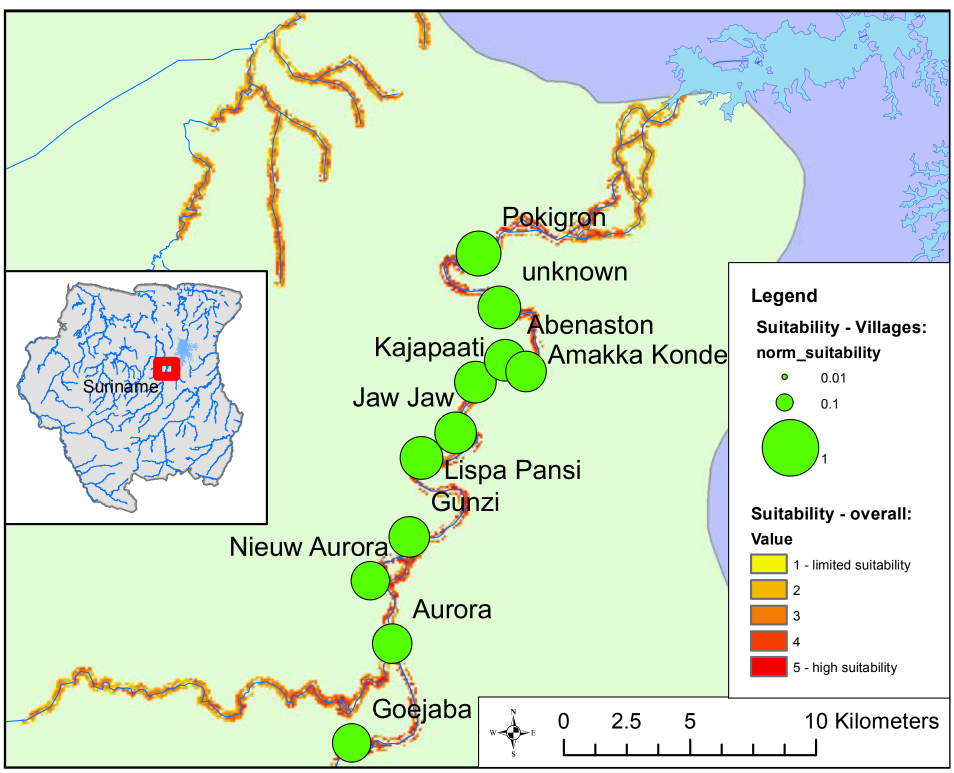

Figure 5-7: Suitability map of Upper Suriname region.

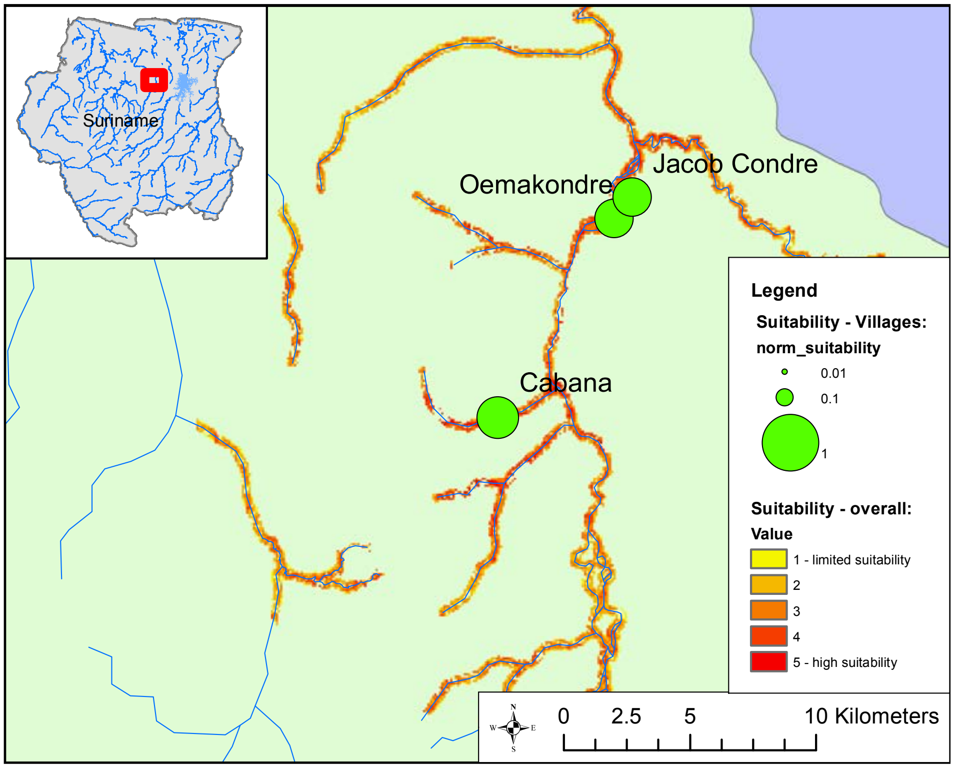

Figure 5-8: Suitability map of Upper Saramacca region.

6. CONCLUDING REMARKS

6.1 Interpretation of Empirical Results

The suitability rating based on the normalized suitability values shown in Figure 5-2 is a relative comparison of all feasible alternatives, where the value 1 represents the result with the highest score in terms of requirements achievement, which means a very high probability that several well-suited sites can be developed. A low score does not necessarily mean that no well-suited sites can be identified. It indicates a lower probability of the presence of a high number of well-suited sites.

The evaluation of the high-resolution ground-truth data gathered at the 2 field sites revealed a high suitability for these sites, as has been shown in Sections 4.2.2 and 4.2.3. The field sites also showed high suitability values in the suitability rating generated by the model, as is shown in Figure 5-5 and Figure 5-6. The village of Puketi, which is close to the field site Gran Olo Sula, scored 0.46 on the suitability rating (rank 33). This can be regarded as a strong indication for the validity of the model. However, no formal validation of the model was conducted. Therefore, the results have to be interpreted cautiously. They are to be taken as a coarse resolution starting position providing an overall impression over the whole perimeter of analysis. Based on the identified locations, further in-depth and high-resolution analysis of sites can be considered.

6.2 Discussion

The aim of this research was to develop a methodology for the GIS-based assessment of a project perimeter with regard to suitability for vortex energy plants, which produces a rated suitability assessment of sites (see Section 1.2). Such a methodology has been developed based on theoretic considerations of GIS-based Multi Criteria Decision Analysis. The methodology relies on the requirements of *head*, *electricity demand* and *water availability*. These requirements were operationalized by the criteria of *slope*, *proximity to village* and *proximity to water body* respectively. Value ranges for the criteria set were developed based on high-resolution ground truth data which had been gathered at two locations on site. Based on Weighted Linear Combination, a method to identify feasible alternatives in terms of suitability requirements and to rank these based on a comparative approach has been developed. The model has been formalized in ArcGIS modelbuilder. The procedure is therefore repeatable and can be reapplied with or without adjustments to the same or different project perimeters.

The model was successfully applied to the case study's perimeter located in Suriname. Suitable sites in terms of feasible alternatives were identified, ranked and presented in the form of a map (Figure 5-1) and in the form of a chart (Figure 5-2). Consequently, the research aim can be regarded as fulfilled.

However, a critical consideration of the chosen approach is indispensable, since several challenges had to be overcome in the course of the research. First and foremost, the availability of data and reliable information in general in the context of the case study was scarce. Since the application of the methodology in the case study and also possibly in the context of future projects was an inherent part of the research aim, these practical aspects had to be kept in mind during the development of the methodology. Inevitably, compromises had to be accepted therefore between the methodology's complexity and parsimony on the one hand and its applicability on the other hand. Focusing particularly on operationality and minimality as crucial requirements of a criteria set (Malczewski and Rinner (2015)), the decision model was designed in its present form, notwithstanding the fact that this might have implied some cutting back on the requirement of completeness.

The scarcity of available data further led to some scale discrepancy between the phenomena to be analyzed and the data used for the analysis. Regarding the *head* requirement, assessing the suitability of a site requires an accuracy of at least a few meters. Whether the chosen modelling approach based on terrain slope is able to accurately represent suitability in terms of available head cannot be ultimately confirmed. On the one hand, it is not necessarily guaranteed that locations identified as suitable in terms of head indeed possess the head of approximately 1.5 to 3 m required to be suitable due to the scale discrepancy and possible inaccuracies in the elevation data. On the other hand, the chosen modelling approach contains the representation of the *slope* criteria operationalizing the *head* requirement irrespective of aspect. This means that e.g. valley flanks within the slope range of interest are considered suitable in terms of the *head* requirement although in reality the modelled head does not exist along the river. Despite such false positives being mostly excluded from the final suitability assessment by taking account of the other two suitability criteria, they are contained in the isolated slope suitability raster, which is an intermediate product of the analysis. A promising approach to optimize modelling of the *head* requirement would be to accumulate the available head along the course of a river, as has been done by Bódis et al. (2014). This was not practicable in the given case due to two reasons: First, no river network dataset with a locational accuracy high enough to justify such an approach was available. Second, the identification of heads in the scale range of interest (i.e. a few meters) would have required a larger amount of high-resolution elevation data, which was not obtainable for the whole project perimeter due to cost restraints.

In terms of a critical consideration of the whole methodology, also the remaining two requirements and their operationalization shall be looked at in the following. Regarding the requirement of *electricity demand*, it must be mentioned that this requirement in fact involves the conceptualization of demand as a binary variable with a positive value in the case of a village present and a negative value in the case of no village present. Therefore, the methodology per se does not take into account the magnitude of the demand. Rather, it evaluates the presence of any demand whatsoever and simultaneously incorporates some aspects of technical feasibility for satisfying the demand by the chosen approach of operationalization by proximity to village and specification of the value range. Notwithstanding the constraints involved in the chosen approach, the validity of the assessment of the *electricity demand* requirement basically exclusively depend on the accuracy of the underlying village location dataset. Given the OSM dataset used for the analysis being the only option finally practicable, the results should be interpreted with some reservations in this respect. Should, however, an alternative data source for the locations of the villages of interest be available, the analysis can be repeated with acceptable efforts.

Finally, the hydrologic requirement of *water availability* was conceptualized similarly to *electricity demand* in a binary way by conceiving the presence of a river or creek as a fulfillment of the requirement. The definition of the value range was done exclusively based on distance to the river network, which is justified by the fact that in the given context no large-scale civil works can be considered due to cost and technical constraints and thus the plants necessarily will have to be placed in close proximity to the streams. Again, the available OSM base data does not allow for complete locational accuracy, but rather outlines suitable sites on a large scale. Further hydrologic characteristics, such as runoff volume and annual fluctuation of runoff, are per se excluded from the analysis.

The Weighted Linear Combination of the three criteria suitability raster datasets has resulted in a final suitability raster dataset. In order to compare and rank the results, an indicator summing up and normalizing suitability values has been developed. The validity of the indicator was not assessed comprehensively, but samples taken at the sites where high-resolution field data had been gathered indicate that the indicator values are meaningful.

To sum up, the developed methodology does not allow for the exact localisation and complete identification of single suitable sites for VEPs. Rather, it narrows down a large perimeter of interest to spatially explicit sub-perimeters where the feasibility of VEPs is likely and compares these with each other in terms of their suitability. The result can be regarded as a priority list on behalf of a project implementer for further site evaluation.

6.3 Future work

Since the present study is focused on applicability to a given context and available resources both in terms of manpower and finance were limited, several aspects well worth considering for future work had to be excluded. They can be grouped into the following categories:

- enhancements to the suggested methodology
- extension of the suggested methodology

The former comprise of adaptations to the modelling of the criteria, including those already touched upon above (Section 6.2), such as relying on alternative data bases or modelling approaches. Regarding the head requirement, introducing a second step of evaluation of the areas identified as suitable by the present methodology based on high-resolution elevation data could be promising. However, the acquisition of commercial high-resolution elevation products would involve major costs (Airbus Defence and Space (2017)).[11]

Furthermore, using LiDAR-based sensors for surveying test sites and gathering field data would be valuable, as the production of digital terrain models not including vegetation would be easier. Especially in combination with high-resolution satellite elevation data as mentioned above, this might be a promising approach for more accurate results due to better calibration and validation of the model.

The requirement of *electricity demand* could be modelled more comprehensively. Accounting for the actual demand instead of conceiving the demand as a binary concept would deliver more meaningful results. The demand could be modelled based on the demand forecasts calculated in a report on behalf of the Surinamese Fund for Regional Development FOB (Energy & Economics Consulting & ILACO (2015)).

Moreover, a more sophisticated modelling of the hydrologic requirement could be implemented. Considering actual runoff data would significantly increase the meaningfulness of the results. However, this would rather require a modelling approach based on physical process modelling than based on MCDA.

Generally, the suggested methodology could possibly be improved by broadening and intensifying the data acquisition. A possible source for high quality geodata especially in the context of the Suriname case that has not been consulted in the course of the study is Kadaster International. The international division of the Dutch national mapping agency is engaged in the provision of geographic data in the development context with a focus on former Dutch territories (kadaster (2017)).

The latter of the two categories mentioned above, namely the extension of the methodology, would involve complementing it by incorporating further requirements and criteria into the analysis. A very important aspect in the context of Suriname for example are transporta-

[11] The Elevation1 Digital Terrain Model provided by Airbus Defence and Space, a DTM with a grid spacing of 1 m and a vertical accuracy of 1.5 m, is available in bundles of 100 km^2 for 90 € per square kilometre as of July 2017.

tion costs and difficulties as well as socio-demographic considerations, which have been factored out and left for consideration at a later stage of project planning. The successful integration of the transportation cost aspect on the model level would probably enrich the suitability assessment and facilitate project planning. Likewise, an incorporation of possible benefits into the model would be valuable. Population figures, i.e. the number of people benefitting from enhanced electricity supply, could be taken as a starting point for modelling the possible benefits.

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8. APPENDIX

8.1 List of Villages provided by EBS

	Overzicht centrales te vervangen door solar sets	
volg #	Gebied	Centrale
1	Boven Suriname (Sipaliwinie)	Abenaston
2	Boven Suriname (Sipaliwinie)	Adawai
3	Boven Suriname (Sipaliwinie)	Amaka kondre
4	Boven Suriname (Sipaliwinie)	Asidonhopo
5	Boven Suriname (Sipaliwinie)	Baikutu
6	Boven Suriname (Sipaliwinie)	Bedi Watra
7	Boven Suriname (Sipaliwinie)	Bende kondre
8	Boven Suriname (Sipaliwinie)	Bendekwaai
9	Boven Suriname (Sipaliwinie)	Bofroekule school
10	Boven Suriname (Sipaliwinie)	Botopasie
11	Boven Suriname (Sipaliwinie)	Dan
12	Boven Suriname (Sipaliwinie)	Dan Gogo
13	Boven Suriname (Sipaliwinie)	Dawme
14	Boven Suriname (Sipaliwinie)	Duwatra/Bekio kondre
15	Boven Suriname (Sipaliwinie)	Futunakaba
16	Boven Suriname (Sipaliwinie)	Gengeston
17	Boven Suriname (Sipaliwinie)	Godo
18	Boven Suriname (Sipaliwinie)	Granslee
19	Boven Suriname (Sipaliwinie)	Grantatai
20	Boven Suriname (Sipaliwinie)	Gujaba
21	Boven Suriname (Sipaliwinie)	Gunzi
22	Boven Suriname (Sipaliwinie)	Hekoenoenoe
23	Boven Suriname (Sipaliwinie)	Jaw Jaw
24	Boven Suriname (Sipaliwinie)	Kajana
25	Boven Suriname (Sipaliwinie)	Kajapatie
26	Boven Suriname (Sipaliwinie)	Kambaloea
27	Boven Suriname (Sipaliwinie)	Kampoe
28	Boven Suriname (Sipaliwinie)	Ligorio
29	Boven Suriname (Sipaliwinie)	Lispansi
30	Boven Suriname (Sipaliwinie)	Malobi
31	Boven Suriname (Sipaliwinie)	Massiakreek
32	Boven Suriname (Sipaliwinie)	Nw. Aurora
33	Boven Suriname (Sipaliwinie)	Padanlafanti

	Overzicht centrales te vervangen door solar sets	
volg #	Gebied	Centrale
34	Boven Suriname (Sipaliwinie)	Pamboko
35	Boven Suriname (Sipaliwinie)	Pikinpada
36	Boven Suriname (Sipaliwinie)	Pikinslee
37	Boven Suriname (Sipaliwinie)	Pokigron
38	Boven Suriname (Sipaliwinie)	Semoisi
39	Boven Suriname (Sipaliwinie)	Stonhoekoe
40	Boven Suriname (Sipaliwinie)	Toemaipa
41	Brokopondo	Baku
42	Brokopondo	Phedra
43	Brokopondo	Rama
44	Brokopondo	Sarakreek
45	Brokopondo	Witsanti
46	Commewijne	Pomona
47	Coppename rivier	Corneliskondre
48	Coppename rivier	Donderskamp
49	Coppename rivier	Kaaimanston
50	Coppename rivier	Kalebaskreek
51	Coppename rivier	Tapoeripa(Nickerie)
52	Coppename rivier	Tottikamp
53	Coppename rivier	Witagron
54	Lawa (Tapanahony rivier)	Apetina
55	Lawa (Tapanahony rivier)	Benanu
56	Lawa (Tapanahony rivier)	Carmel
57	Lawa (Tapanahony rivier)	Clementie
58	Lawa (Tapanahony rivier)	Cottica a/d Lawa
59	Lawa (Tapanahony rivier)	Drietabbetje
60	Lawa (Tapanahony rivier)	Godo-olo
61	Lawa (Tapanahony rivier)	Goninikriki
62	Lawa (Tapanahony rivier)	Gonninikrikimoffo
63	Lawa (Tapanahony rivier)	Granbori
64	Lawa (Tapanahony rivier)	Jamaica
65	Lawa (Tapanahony rivier)	Jawsa
66	Lawa (Tapanahony rivier)	Kawemhakken
67	Lawa (Tapanahony rivier)	Kisai
68	Lawa (Tapanahony rivier)	Lincidede
69	Lawa (Tapanahony rivier)	Mainsie
70	Lawa (Tapanahony rivier)	Manlobi
71	Lawa (Tapanahony rivier)	Mooitakkie

	Overzicht centrales te vervangen door solar sets	
volg #	Gebied	Centrale
72	Lawa (Tapanahony rivier)	Peletepoe
73	Lawa (Tapanahony rivier)	Poeketie
74	Lawa (Tapanahony rivier)	Sanbendoemi
75	Lawa (Tapanahony rivier)	Sangamasoesa
76	Lawa (Tapanahony rivier)	Tabiki
77	Marowijne	Adjoemakondre
78	Marowijne	Akoloi kondre
79	Marowijne	Alfonsdorp
80	Marowijne	Anton Don school
81	Marowijne	Atemsa
82	Marowijne	Atemsa school
83	Marowijne	Badatabiki
84	Marowijne	Bigiston
85	Marowijne	Dantapoe
86	Marowijne	Gakaba
87	Marowijne	Galibi
88	Marowijne	Gosutu
89	Marowijne	Kasabaondro
90	Marowijne	Kraboe-olo
91	Marowijne	Krikimoffo
92	Marowijne	Langahoekoe
93	Marowijne	Langatabbetje
94	Marowijne	Lantiwee
95	Marowijne	Loka-Loka
96	Marowijne	Malokokondre
97	Marowijne	Manjabon
98	Marowijne	Moengotapoe
99	Marowijne	Mopikondre
100	Marowijne	Morakondre
101	Marowijne	Nason
102	Marowijne	Ovia-Olo
103	Marowijne	Pakira tabiki
104	Marowijne	Pakirakreek
105	Marowijne	Patamakka
106	Marowijne	Perica
107	Marowijne	Pikinsanti
108	Marowijne	Pinatjarimi
109	Marowijne	Pulugoedoe

	Overzicht centrales te vervangen door solar sets	
volg #	Gebied	Centrale
110	Marowijne	Ricanaumoffo
111	Marowijne	Skin tabiki
112	Marowijne	Stoelmanseiland
113	Marowijne	Tabikiede
114	Marowijne	Tamarin
115	Marowijne	Wanhatti
116	Para	Bigi Poika
117	Para	Carolina
118	Para	Cassipora
119	Para	Pierre Kondre
120	Para	Pikien Saron
121	Para	Powakka
122	Para	Redi-Doti
123	Sipaliwinie (Saramacca rivier)	Boslanti
124	Sipaliwinie (Saramacca rivier)	Commissaris kondre
125	Sipaliwinie (Saramacca rivier)	Kwakoegron
126	Sipaliwinie (Saramacca rivier)	Nw.Jacobkondre
127	Sipaliwinie (Saramacca rivier)	Padua
128	Sipaliwinie (Saramacca rivier)	Pijeti
129	Sipaliwinie (Saramacca rivier)	Pusugroenoe

8.2 List of Villages from OSM data

ID	Name	Resort	District
1	Brownsweg	Brownsweg	Brokopondo
2	Brokopondo	Centrum	Brokopondo
3	Victoria	Centrum	Brokopondo
4	Berg en Dal	Klaaskreek	Brokopondo
5	Kapsikele	Klaaskreek	Brokopondo
6	Reinsdorp	Klaaskreek	Brokopondo
7	Kwakoegron	Kwakoegron	Brokopondo
8	Marchallkreek	Marechalskreek	Brokopondo
9	Phedra	Marechalskreek	Brokopondo
10	Alkmaar	Alkmaar	Commewijne
11	Marienburg	Alkmaar	Commewijne
12	Margaretha	Margaretha	Commewijne
13	Nieuw-Amsterdam	Margaretha	Commewijne
14	Laarwijk	Meerzorg	Commewijne

ID	Name	Resort	District
15	Paranam	Meerzorg	Commewijne
16	Peperpot	Meerzorg	Commewijne
17	Stolkertsijver	Tamanredjo	Commewijne
18	Totness	Totness	Coronie
19	Bellevie	Welgelegen	Coronie
20	Hamilton	Welgelegen	Coronie
21	Haque	Welgelegen	Coronie
22	Albina	Albina	Marowijne
23	Mason	Moengo	Marowijne
24	Moengo	Moengo	Marowijne
25	Ricanau Mofu	Moengo	Marowijne
26	Toekoppie	Moengotapoe	Marowijne
27	Apaye Kampou	Patamacca	Marowijne
28	Ovillanhollo	Patamacca	Marowijne
29	Langa Hoekoe	Wanhatti	Marowijne
30	Lantiwei	Wanhatti	Marowijne
31	Tamarin	Wanhatti	Marowijne
32	Wanhatti	Wanhatti	Marowijne
33	Groot Henarpolder	Groot Henar	Nickerie
34	Wageningen Airport	Wageningen	Nickerie
35	Wakai	Westelijke Polders	Nickerie
36	Bigi Poika	Bigi Poika	Para
37	Commisariskondre	Bigi Poika	Para
38	Loksi Hattie	Bigi Poika	Para
39	Makakriki	Bigi Poika	Para
40	Gelderland	Carolina	Para
41	Redi Doti	Carolina	Para
42	Carolina	Oost	Para
43	La Simplicite	Oost	Para
44	Overbridge	Oost	Para
45	Powakka	Oost	Para
46	Smal Kalden	Oost	Para
47	White Beach	Oost	Para
48	Wiesawinie	Oost	Para
49	Bersaba	Zuid	Para
50	Hanover	Zuid	Para
51	Hollandse Kamp	Zuid	Para
52	Matta	Zuid	Para
53	Onverwacht	Zuid	Para
54	Republiek	Zuid	Para
55	Vierkinderen	Zuid	Para
56	Zanderij	Zuid	Para
57	Bridj Village	Blauwgrond	Paramaribo
58	Greenview Lake	Blauwgrond	Paramaribo
59	Tourtonne garden	Blauwgrond	Paramaribo
60	Groningen	Groningen	Saramacca
61	Uitkijk	Jarikaba	Saramacca

ID	Name	Resort	District
62	Abenaston	Boven Suriname	Sipaliwini
63	Amakka Konde	Boven Suriname	Sipaliwini
64	Asindo-opo	Boven Suriname	Sipaliwini
65	Aurora	Boven Suriname	Sipaliwini
66	Awarradam	Boven Suriname	Sipaliwini
67	Boto Pasi	Boven Suriname	Sipaliwini
68	Boto Pasi	Boven Suriname	Sipaliwini
69	Dan	Boven Suriname	Sipaliwini
70	Debike	Boven Suriname	Sipaliwini
71	Funutakaba	Boven Suriname	Sipaliwini
72	Goejaba	Boven Suriname	Sipaliwini
73	Gunzi	Boven Suriname	Sipaliwini
74	Jaw Jaw	Boven Suriname	Sipaliwini
75	Kajana	Boven Suriname	Sipaliwini
76	Kajapaati	Boven Suriname	Sipaliwini
77	Kamaloea	Boven Suriname	Sipaliwini
78	Koemboe	Boven Suriname	Sipaliwini
79	Lispa Pansi	Boven Suriname	Sipaliwini
80	Mallobi Lobi pisa	Boven Suriname	Sipaliwini
81	Marechalkriki	Boven Suriname	Sipaliwini
82	Nieuw Aurora	Boven Suriname	Sipaliwini
83	Penpen	Boven Suriname	Sipaliwini
84	Pikin Slee	Boven Suriname	Sipaliwini
85	Pokigron	Boven Suriname	Sipaliwini
86	Puketi	Boven Suriname	Sipaliwini
87	unknown	Boven Suriname	Sipaliwini
88	unknown	Boven Suriname	Sipaliwini
89	unknown	Boven Suriname	Sipaliwini
90	Cabana	Bven Saramacca	Sipaliwini
91	Jacob Condre	Bven Saramacca	Sipaliwini
92	Oemakondre	Bven Saramacca	Sipaliwini
93	Alalapadi	Coeroeni	Sipaliwini
94	Amatopo	Coeroeni	Sipaliwini
95	Coeroenie Airstrip	Coeroeni	Sipaliwini
96	Kayser Airport	Coeroeni	Sipaliwini
97	Kwamalasoemoetoe Airport	Coeroeni	Sipaliwini
98	Sipaliwini Airport	Coeroeni	Sipaliwini
99	Donderkamp	Coppename	Sipaliwini
100	Moeder Vallen	Coppename	Sipaliwini
101	Raleigh Vallen Nature Preserve	Coppename	Sipaliwini
102	Rudi Kappel Airport	Coppename	Sipaliwini
103	Voltzberg	Coppename	Sipaliwini
104	Witagron	Coppename	Sipaliwini
105	Apoera	Kabalebo	Sipaliwini
106	Avanavero	Kabalebo	Sipaliwini

ID	Name	Resort	District
107	Bakhuis	Kabalebo	Sipaliwini
108	Kabalebo Airport	Kabalebo	Sipaliwini
109	Malapi	Kabalebo	Sipaliwini
110	Washabo	Kabalebo	Sipaliwini
111	Apetina	Tapanahony	Sipaliwini
112	Benzdorp	Tapanahony	Sipaliwini
113	Bonnidoro	Tapanahony	Sipaliwini
114	Cottica	Tapanahony	Sipaliwini
115	Diitabiki	Tapanahony	Sipaliwini
116	Kawemhaken	Tapanahony	Sipaliwini
117	Mainsi	Tapanahony	Sipaliwini
118	Moitaki	Tapanahony	Sipaliwini
119	Tepoe Airstrip	Tapanahony	Sipaliwini
120	Vincent Fayks Airport	Tapanahony	Sipaliwini
121	Domburg	Domburg	Wanica
122	Koewarasan	Koewarasan	Wanica
123	Haarlem	Lelydorp	Wanica
124	Lelydorp	Lelydorp	Wanica
125	Santigron	Lelydorp	Wanica

8.3 Village Suitability

#	Normalized Suitability	Name	Resort	District	Summed Suitability	Latitude (WGS1984)	Longitude (WGS 1984)
1	1.00	Moeder Vallen	Coppename	Sipaliwini	13336	4.699144387	-56.21970651
2	0.90	Raleigh Vallen Nature Preserve	Coppename	Sipaliwini	12029	4.691633787	-56.19165731
3	0.81	Voltzberg	Coppename	Sipaliwini	10849	4.680175087	-56.1823058
4	0.65	White Beach	Oost	Para	8609	5.635269984	-55.07421231
5	0.63	Smal Kalden	Oost	Para	8412	5.618405283	-55.09500361
6	0.62	Pokigron	Boven Suriname	Sipaliwini	8284	4.489887587	-55.36432021
7	0.58	unknown	Boven Suriname	Sipaliwini	7673	4.470611287	-55.3568565
8	0.57	Onverwacht	Zuid	Para	7597	5.590504083	-55.19500081
9	0.55	Lispa Pansi	Boven Suriname	Sipaliwini	7385	4.416614587	-55.38484541
10	0.55	Bersaba	Zuid	Para	7276	5.508267784	-55.21150601
11	0.54	Cabana	Bven Saramacca	Sipaliwini	7214	4.857506886	-55.58685911
12	0.54	Jaw Jaw	Boven Suriname	Sipaliwini	7169	4.425651987	-55.37260551
13	0.54	Kajapaati	Boven Suriname	Sipaliwini	7152	4.443762687	-55.36562001
14	0.54	Vierkinderen	Zuid	Para	7151	5.505456783	-55.22265891
15	0.53	Abenaston	Boven Suriname	Sipaliwini	7103	4.451703987	-55.35481821
16	0.52	Republiek	Zuid	Para	6955	5.498122084	-55.21245461
17	0.52	Gunzi	Boven Suriname	Sipaliwini	6899	4.388428787	-55.38934711
18	0.51	Amakka Konde	Boven Suriname	Sipaliwini	6771	4.447566487	-55.34735851
19	0.47	Aurora	Boven Suriname	Sipaliwini	6325	4.350120887	-55.3955368
20	0.47	Nieuw Aurora	Boven Suriname	Sipaliwini	6273	4.372591487	-55.40321741

#	Normalized Suitability	Name	Resort	District	Summed Suitability	Latitude (WGS1984)	Longitude (WGS 1984)
21	0.47	Oemakondre	Bven Saramacca	Sipaliwini	6245	4.928881986	-55.54503961
22	0.46	Goejaba	Boven Suriname	Sipaliwini	6200	4.314474588	-55.41009751
23	0.46	Puketi	Tapanahony	Sipaliwini	6178	4.12292262	-54.62837965
24	0.46	Hanover	Zuid	Para	6098	5.489117084	-55.15039381
25	0.46	Jacob Condre	Bven Saramacca	Sipaliwini	6075	4.936519886	-55.53849701
26	0.44	Moitaki	Tapanahony	Sipaliwini	5840	4.127538687	-54.65075381
27	0.43	Pikin Slee	Boven Suriname	Sipaliwini	5740	4.253603787	-55.44453631
28	0.42	Botopasi	Boven Suriname	Sipaliwini	5639	4.252132888	-55.44050651
29	0.42	unknown	Boven Suriname	Sipaliwini	5611	4.256022921	-55.42688535
30	0.42	Mainsi	Tapanahony	Sipaliwini	5601	4.127806187	-54.66166501
31	0.42	unknown	Boven Suriname	Sipaliwini	5572	4.270228487	-55.4229939
32	0.40	Funutakaba	Boven Suriname	Sipaliwini	5390	4.238395988	-55.44771371
33	0.40	Asindo-opo	Boven Suriname	Sipaliwini	5358	4.002781388	-55.4709446
34	0.40	La Simplicite	Oost	Para	5277	5.531272784	-55.05301631
35	0.40	Debike	Boven Suriname	Sipaliwini	5271	4.232370888	-55.44345271
36	0.39	Overbridge	Oost	Para	5169	5.526585583	-55.05145961
37	0.39	Amatopo	Coeroeni	Sipaliwini	5158	3.544767593	-57.6416528
38	0.38	Vincent Fayks Airport	Tapanahony	Sipaliwini	5126	3.345279891	-55.4425011
39	0.38	Penpen	Boven Suriname	Sipaliwini	5081	4.043992188	-55.4463323
40	0.37	Avanavero	Kabalebo	Sipaliwini	4911	4.810657289	-57.43959611
41	0.37	unknown	Boven Suriname	Sipaliwini	4886	4.174964388	-55.4272337
42	0.36	Zanderij	Zuid	Para	4863	5.455615183	-55.20600091
43	0.36	Dritabiki	Tapanahony	Sipaliwini	4849	4.112876887	-54.67705631
44	0.36	Bakhuis	Kabalebo	Sipaliwini	4839	4.728111388	-56.7801778
45	0.36	Boto Pasi	Boven Suriname	Sipaliwini	4826	4.221067188	-55.44248241
46	0.36	Tepoe Airstrip	Tapanahony	Sipaliwini	4821	3.150000092	-55.7169991
47	0.36	Hollandse Kamp	Zuid	Para	4814	5.447306184	-55.19922941
48	0.36	Mallobi Lobi pisa	Boven Suriname	Sipaliwini	4763	4.158507788	-55.42720711
49	0.36	Dan	Boven Suriname	Sipaliwini	4745	4.192895388	-55.4327811
50	0.35	Apetina	Tapanahony	Sipaliwini	4715	3.50950099	-55.0522873
51	0.35	Kapsikele	Klaaskreek	Brokopondo	4685	5.197073484	-55.06251151
52	0.35	Reinsdorp	Klaaskreek	Brokopondo	4682	5.182656085	-55.07690151
53	0.35	Kamaloea	Boven Suriname	Sipaliwini	4663	4.200962288	-55.43553401
54	0.35	Koemboe	Boven Suriname	Sipaliwini	4646	4.132393988	-55.4370988
55	0.35	Coeroenie Airstrip	Coeroeni	Sipaliwini	4643	3.369955993	-57.3423783
56	0.34	Marechalkriki	Boven Suriname	Sipaliwini	4561	4.142351988	-55.433946
57	0.33	Uitkijk	Jarikaba	Saramacca	4439	5.776221883	-55.34751611
58	0.30	Berg en Dal	Klaaskreek	Brokopondo	4046	5.137140884	-55.06581051
59	0.28	Marchallkreek	Marechalskreek	Brokopondo	3732	5.263469384	-55.08099811
60	0.27	Powakka	Oost	Para	3571	5.445400984	-55.07793341
61	0.27	Wiesawinie	Oost	Para	3563	5.432791484	-55.04247601
62	0.27	Groningen	Groningen	Saramacca	3548	5.793791984	-55.47640751
63	0.26	Awarradam	Boven Suriname	Sipaliwini	3460	3.844469289	-55.6127568
64	0.26	Gelderland	Carolina	Para	3407	5.451898184	-54.99142091
65	0.26	Carolina	Oost	Para	3405	5.449281684	-54.99688901
66	0.25	Kwamalasoemoetoe Airport	Coeroeni	Sipaliwini	3308	2.354973295	-56.7911649
67	0.25	Victoria	Centrum	Brokopondo	3292	5.134633485	-54.98634701

#	Normalized Suitability	Name	Resort	District	Summed Suitability	Latitude (WGS1984)	Longitude (WGS 1984)
68	0.25	Kajana	Boven Suriname	Sipaliwini	3286	3.899753889	-55.5724478
69	0.24	Kawemhaken	Tapanahony	Sipaliwini	3162	3.411488689	-54.0253275
70	0.24	Donderkamp	Coppename	Sipaliwini	3155	5.350685986	-56.36555341
71	0.23	Phedra	Marechalskreek	Brokopondo	3005	5.325253684	-55.04965211
72	0.21	Redi Doti	Carolina	Para	2825	5.424722683	-54.97608991
73	0.21	Bonnidoro	Tapanahony	Sipaliwini	2825	4.925709284	-54.46270811
74	0.19	Kabalebo Airport	Kabalebo	Sipaliwini	2475	4.40600009	-57.22299961
75	0.18	Brokopondo	Centrum	Brokopondo	2407	5.056771285	-54.97669161
76	0.17	Matta	Zuid	Para	2319	5.452475884	-55.32336981
77	0.16	Kwakoegron	Kwakoegron	Brokopondo	2151	5.247956584	-55.34317941
78	0.16	Mason	Moengo	Marowijne	2088	5.558116383	-54.41833281
79	0.15	Makakriki	Bigi Poika	Para	2065	5.233349885	-55.36946241
80	0.15	Cottica	Tapanahony	Sipaliwini	2026	3.854047288	-54.2273095
81	0.15	Commisariskondre	Bigi Poika	Para	2019	5.237799084	-55.36388731
82	0.14	Ovillanhollo	Patamacca	Marowijne	1879	5.514075683	-54.40794251
83	0.14	Moengo	Moengo	Marowijne	1870	5.619561282	-54.40317531
84	0.13	Sipaliwini Airport	Coeroeni	Sipaliwini	1758	2.025704996	-56.1237467
85	0.13	Malapi	Kabalebo	Sipaliwini	1673	5.011660987	-57.30635961
86	0.12	Bigi Poika	Bigi Poika	Para	1650	5.247556885	-55.67270851
87	0.12	Alalapadi	Coeroeni	Sipaliwini	1606	2.519531994	-56.3266311
88	0.12	Benzdorp	Tapanahony	Sipaliwini	1544	3.673956288	-54.0852132
89	0.11	Toekoppie	Moengotapoe	Marowijne	1520	5.634361482	-54.31034351
90	0.11	Ricanau Mofu	Moengo	Marowijne	1447	5.677714782	-54.42376171
91	0.10	Kayser Airport	Coeroeni	Sipaliwini	1368	3.099999893	-56.4830017
92	0.10	Wanhatti	Wanhatti	Marowijne	1267	5.783246982	-54.45533091
93	0.08	Rudi Kappel Airport	Coppename	Sipaliwini	1114	3.78299999	-56.1500015
94	0.07	Witagron	Coppename	Sipaliwini	881	5.163674386	-56.07599821
95	0.06	Langa Hoekoe	Wanhatti	Marowijne	827	5.765912182	-54.40706811
96	0.06	Wageningen Airport	Wageningen	Nickerie	819	5.841667985	-56.67446241
97	0.06	Lantiwei	Wanhatti	Marowijne	780	5.789847382	-54.41211931
98	0.05	Apaye Kampou	Patamacca	Marowijne	710	5.300017583	-54.23608941
99	0.05	Brownsweg	Brownsweg	Brokopondo	693	5.017695785	-55.16890361
100	0.05	Tamarin	Wanhatti	Marowijne	675	5.771578082	-54.38434261
101	0.04	Washabo	Kabalebo	Sipaliwini	571	5.211804587	-57.18653871
102	0.04	Wakai	Westelijke Pol-ders	Nickerie	523	5.281198687	-57.24239291
103	0.04	Apoera	Kabalebo	Sipaliwini	502	5.182652787	-57.16477281
104	0.04	Albina	Albina	Marowijne	501	5.497552182	-54.05522991
105	0.03	Loksi Hattie	Bigi Poika	Para	464	5.140993285	-55.46596931
106	0.03	Groot Henarpolder	Groot Henar	Nickerie	403	5.855821585	-56.88680981
107	0.01	Totness	Totness	Coronie	112	5.877131384	-56.33077621
108	0.01	Bellevie	Welgelegen	Coronie	110	5.848594184	-56.30605291
109	0.01	Haque	Welgelegen	Coronie	110	5.861073484	-56.27359501
110	0.01	Hamilton	Welgelegen	Coronie	79	5.859707284	-56.25511911