Locating Optimal sites for Small Hydropower Plants in Western Cape Province, South Africa.

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Research report submitted in partial fulfilment of the requirements for the Degree of Bachelor of Science Honours in Geographical Information Systems at the University of Cape Town

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AUTHORSHIP DECLARATION

I, Dibanisa Fakude, declare that:

1. This research report and the work presented in it, is my own.

2. I know that plagiarism is wrong. Plagiarism is to use another's work and pretend that it is one's own.

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RESEARCH ETHICS DECLARATION

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PRE-SCREENING QUESTIONNAIRE OUTCOME LETTER

STU-EBE-2023-PSQ000371

2023/05/08

Dear Dibanisa Fakude,

Your Ethics pre-screening questionnaire (PSQ) has been evaluated by your departmental ethics representative. Based on the information supplied in your PSQ, it has been determined that you do not need to make a full ethics application for the research project in question.

You may proceed with your research project titled:

Finding Optimal Locations Of Hydropower Stations In South African Dams.

Please note that should aspect(s) of your current project change, you should submit a new PSQ in order to determine whether the changed aspects increase the ethical risks of your project. It may be the case that project changes could require a full ethics application and review process.

Regards,

Faculty Research Ethics Committee

ABSTRACT

This research investigates the suitability of sites for Small Hydropower (SHP) development in the Western Cape region, focusing on seven key parameters: flow accumulation, slope, soil type, elevation, drainage density, rainfall, and distance to Powerlines. Using a Geographic Information Systems (GIS) and Analytic Hierarchy Process (AHP) methodology, the study analyses various data sets and integrates them to generate a comprehensive suitability map. The map serves as a decision support tool for stakeholders involved in SHP project planning and development. The results indicated that only 0.002% of the watershed is classified as "extremely suitable" for SHP, while 41,024% falls into the "highly suitable" category. The study emphasizes the untapped SHP potential in the region and its significance for rural electrification. To validate the results, existing SHP dams in the Western Cape region are examined, revealing a noteworthy consistency between their locations and the identified suitability categories. In proposing dam sites for SHP development, the research identifies existing dams that meet specific criteria, including stream order > 3, elevation < 109m, and extremely and high suitability level. The study suggests repurposing these dams for SHP, considering their alignment with the established criteria, which is deemed cost-effective and environmentally sustainable. The research concludes with a call for on-site geotechnical investigations at the identified potential sites to further assess their suitability for dam construction. The findings contribute to sustainable energy practices, aligning with Sustainable Development Goals related to affordable and clean energy, industry and infrastructure, and climate action.

Keywords: GIS; AHP; Site Selection; Western Cape

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DEDICATION

This Thesis is dedicated two extraordinary souls who are the heart and soul of this journey. My father Khanyakwezwe Zeeken Dlamini, a diligent farmer And to my dearest mother Nondumiso.

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GLOSSARY

AHP	Analytical Hierarchy Process
BWM	Best Worst Method
CI	Consistency Index
CN	Curve Number
CR	Consistency Ratio
DEM	Digital Elevation Model
DWS	Department of Water and Sanitation
EIA	Environmental Impact Assessment
ESRI	Environmental Systems Research Institute
GCS	Geographic Coordinate System
GHG	Greenhouse Gas
GIS	Geographic Information System
IDW	Inverse Distance Weighting
ISRIC	International Soil Reference and Information Centre
MCD	Multicriteria Decision Making
MCDA	Multicriteria Decision Analysis
MHPP	Mini Hydropower Plant
MLP	Multilayer Perceptron
MRVBF	Multiresolution Valley Bottom Flatness
OSM	OpenStreetMap
PHS	Pumped Storage Hydropower
RI	Random Index
RS	Remote Sensing

SHP	Small Hydropower
STRM	Shuttle Radar Topography Mission
SWAT	Soil and Water Assessment Tool
TPI	Topographic Position Index
UTM	Universal Transverse Mercator
VHA	Visual Habitat Assessment
VRD	Valley Ridges and Depressions
WGS	World Geodetic System
WSM	Weighted Sum Model

1 INTRODUCTION

1.1 Background

In the past decade, there has been significant growth in the development of new energy sources, particularly variable renewable energy. As renewable energy penetration increases, there is a growing need for electricity systems to be more flexible to mitigate volatility and intermittency (Joel Jaeger, 2021). To achieve high levels of renewable energy penetration, it becomes necessary to store electricity over longer durations, spanning days, weeks, or even months. Electricity storage plays a crucial role in providing these essential services, enabling substantial decarbonization of the electricity sector and facilitating the transformation of the entire energy industry. By complementing the expansion of solar and wind power generation, energy storage technologies can drive significant decarbonization in key sectors of the energy market (Irena & Costs, 2017). Looking ahead to 2030, the growth in the electricity storage market is expected to be diverse and multifaceted. Currently, the most advanced methods of energy storage include pumped hydro energy storage (PHS), flywheel energy storage, air compression energy storage, and chemical batteries. These technologies contribute to enhancing the reliability and stability of the electricity grid while enabling the integration of higher levels of renewable energy sources.

The global focus on mitigating carbon emissions has led to an increasing interest in renewable energy production, and small hydropower (SHP) has emerged as a prominent option. SHP projects play a significant role in reducing greenhouse gas emissions by generating low-carbon electricity, (Jhi et al., 2016). While the initial costs of installing SHP systems can be significant, the ongoing operational expenses tend to be relatively low. Additionally, SHP technology is well-established and offers greater reliability in terms of generating base load power compared to other renewable sources such as wind and solar. SHP with capacities of up to 10 megawatts are widely implemented and feasible in various regions, particularly in Europe. In South Africa, De Wet, Brent & Kroger, (2018) investigated the viability of SHP systems in the Eastern Cape Province and found that they could provide a reliable and affordable source of electricity.

While SHP schemes are often regarded as environmentally friendly in terms of greenhouse gas emissions, their installation can have negative impacts on ecosystems, particularly on fish populations and river ecosystems (Bednarek, 2001; O'Hanley & Tomberlin, 2005). The construction of SHP dams creates physical barriers that frequently disrupt the natural connectivity of rivers, obstructing the transfer of water and sediment. This disruption can have significant consequences on geomorphological processes and fragment habitats within river systems. Additionally, it can impede the access of fish to crucial breeding and rearing areas, leading to reduced fish productivity and alterations in the composition of aquatic communities (Lucas & Baras, 2001). Changes to the landscape and the loss of land are further concerns (Sundqvist, 2002; Ponce et al., 2011) .

As a result, decisions regarding the implementation of SHP dams often involve a trade-off between renewable energy production and the preservation of healthy rivers. This emphasizes the significance of decision support tools in the planning of SHP locations, which can effectively balance these conflicting objectives. The availability of such tools would greatly assist river management organizations in formulating well-informed and efficient strategies for SHP development while considering the preservation of river ecosystems.

Various studies have been conducted to evaluate SHP potential at regional and national scales. Some of these studies have utilized hydrological modelling, flow-duration curves, and alternative methods to estimate streamflow in unmonitored rivers (Rojanamon, Chaisomphob & Bureekul, 2009; Coskun et al., 2010; Nguyen-Tien, Elliott & Strobl, 2018). However, these approaches typically require a significant amount of input data. Therefore, in regions with limited, scarce, or unevenly distributed data, employing a robust methodology becomes crucial.

1.2 Problem Statement

The increasing concerns regarding the environmental impact of fossil fuel-based energy production, coupled with depleting reserves and rising energy demands, have led to a heightened focus on the development and exploration of alternative and sustainable energy sources (Avtar et al., 2019).Within this context, the challenges posed by load shedding and the reliance on fossil fuels have emerged as significant issues. Load shedding directly results from the absence of a dependable backup power supply in the Western Cape region, which subsequently necessitates the increased use of fossil fuels to compensate for the energy deficit. Moreover, when considering the electricity supply situation in the Western Cape, these pressures on the backup renewable energy system not only jeopardize the well-being of residents but also impose financial burdens on businesses. This situation ultimately has negative implications for the public.

Exciting opportunities have opened for evaluating SHP potential due to advancements in remote sensing, satellite data, and improvements in Geographic Information Systems (GIS) tools (Kayastha, Singh & Dulal, 2018). This study utilized GIS to help identify suitable SHP locations, which effectively combine various factors that influence the choice of the right spot (Punys et al., 2011). By gathering data on factors like soil type, Digital Elevation Model (DEM), Rainfall, and powerlines, pre-processing and geoprocessing tools can offer valuable insights into finding the ideal locations for SHP, along with providing geographic context and solutions to the research problem.

1.3 Aim

The aim of this research is to identify suitable locations for SHP in the Western Cape Province, South Africa.

1.4 Objectives

Objectives	Research questions
1. To identify suitable criteria for siting SHP.	a. What criteria have been used by other researchers doing similar studies? b. Which of these criteria is relevant to the Western Cape context?
2. To define a suitable method for siting SHP.	a. What methods have other researchers doing similar studies used? b. Which of these methods is suitable for this study given the available data and resources?
3. To source suitable data for analysis according to the defined criteria.	a. What data sources have other researchers doing similar studies used? b. Which of these data sources are relevant to the Western Cape context? c. Are these data sources freely available, or are there suitable substitutes?
4. To analyse the data using the chosen method and according to the defined criteria.	
5. To validate the results against existing SHP locations.	a. How do the results compare to existing SHP locations? b. Where there are differences, how can these be explained?

1.5 Scope And Limitations

1.5.1 Scope

The scope of this study encompasses the identification of suitable locations for SHP installations in the Western Cape Province of South Africa. It will centre its attention only on the specific geographic and technical conditions unique to this region. The study aims to determine relevant criteria for siting SHP through a review of criteria employed by other researchers in similar studies and their adaptation to the local context. Data sourcing will be a pivotal aspect, and the research will investigate existing data sources employed by other researchers while emphasizing the accessibility of freely available or cost-effective data. Methodology selection will rely on those successfully utilized in analogous studies, carefully chosen to align with the available data and resources. Data analysis will be conducted according to the chosen methodology, assessing potential SHP locations in adherence to the defined criteria. Finally, the study will validate its findings by comparing them to the existing SHP sites within the Western Cape, offering explanations for any disparities encountered.

1.5.2 Limitations

Several limitations should be acknowledged in this study. Firstly, its geographic focus is restricted to the Western Cape Province of South Africa, rendering the findings less applicable to regions with differing geographical and environmental characteristics. The accessibility and completeness of data pose potential limitations, as any difficulty in acquiring certain data sources may jeopardize the precision of results. Resource constraints, such as budgetary and time limitations, could impact the thoroughness of data analysis and limit fieldwork or data collection efforts. Additionally, the study primarily concentrates on technical and geographic aspects only, thus not extensively addressing the legal, regulatory, and policy considerations that significantly influence SHP project implementation.

2 LITERATURE REVIEW

2.1 Introduction

The aim of this literature review is to develop a thorough comprehension of the current knowledge and research surrounding the selection of sites for hydropower projects, with a specific emphasis on SHP site selection projects. The review seeks to identify and examine the essential parameters that should be analysed and considered during the site selection process. By synthesizing the existing literature, this review intends to contribute to the identification of criteria, data and methodology that other authors have used that successfully influenced the optimal siting of SHP projects.

2.2 Small Hydropower

SHP is a type of renewable energy producing tool that utilize the flow of water to produce electricity. SHP has long been recognized as an appealing and historically significant environmentally friendly energy option (Balser, 2002) . Another aspect is their labour-intensive nature during the construction phase, along with their ability to offer long-term employment opportunities (Yuksel, 2008). Due to its renewable nature and environmental friendliness, this energy source is considered less harmful compared to fossil fuels, which release dangerous gas emissions (Dursun & Gokcol, 2011). There are three different categories of SHP plants (Okot, 2013). Figure 2-1 , shows a representation of a storage type SHP.

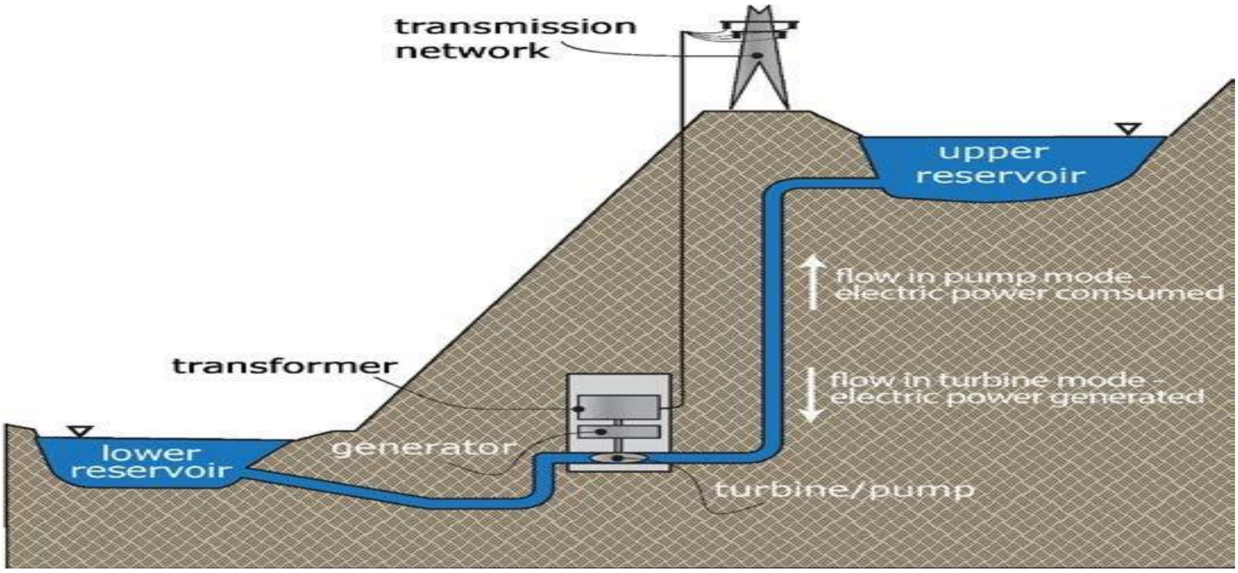

Figure 2-1 SCHEMATIC ILLUSTRATION OF A STORAGE SMALL HYDROPOWER, SOURCED FROM (Viadero, Rehbein & Singh, 2017)

The diagram above (see Figure 2-1) illustrates how a storage SHP system generates energy. The process starts with water being diverted from a dam and directed onto a turbine. The turbine's job is to convert the potential energy of the water into the mechanical energy through rotation (Paish, 2002). When the water interacts with the runner blades on the turbine, it creates a twisting force known as torque. This torque is then transferred to the runner, which is connected to a shaft that drives an electric generator (Lajqi, Lajqi & Hamidi, 2016). The amount of energy produced in this system depends on two main factors: the flow rate of the water and the elevation at which it enters the system (Nasir, 2013).

2.2.1 Types Of SHP

Run-Of-River

This type of SHP produces electrical power by harnessing the natural flow of the river without creating a significant reservoir. The river's water flow is influenced by factors such as rainfall, groundwater movement, and runoff, and these elements can exhibit significant fluctuations on a daily, monthly, or seasonal basis. Consequently, for a river with varying flow rates, an ideal Run-of-River (RoR) SHP system would generate power in a way that closely mirrors the fluctuations in the river's flow pattern(Kaunda, Kimambo & Nielsen, 2012).

Storage

In a storage SHP project, there is a reservoir created by a dam to store water for future power generation and various other uses. This reservoir serves to control the flow of water, giving storage SHP plants a higher level of power reliability when compared to RoR SHP plants (Kaunda, Kimambo & Nielsen, 2012).

Diversion

A diversion facility directs a portion of a river's flow through either a canal or a penstock. This system might not necessitate the construction of a dam (Okot, 2013).

2.2.2 Difficulties In Siting SHP

Assessing the SHP potential of a river basin poses a unique challenge compared to individual hydropower projects. Individual projects where the site is known and boundary conditions are defined, the locations of projects in a river basin are uncertain. Additionally, the energy output at each site depends on other planned reservoirs in the same basin and their capacity for flow regulation. This complexity requires integrated environmental and technical assessments that consider multiple criteria and spatially distributed data (Kurse et al., 2010).

The dominance of technical factors alone no longer determines the success of a SHP project. Additional factors, including environmental, social, and economical aspects, must be considered. Inaccurate design or improper selection of projects and parameters will significantly impact the overall cost and efficiency, resulting in lower power generation at a higher cost-per-watt (Adhikary, Roy & Mazumdar, 2015).

2.3 Site Selection Processes

In the context of SHP site selection, it is essential to begin by understanding the fundamental role of Geographic Information System (GIS) as an invaluable tool for spatial analysis. Rikalovic, Cosic & Lazarevic, (2014), defined GIS as a robust tool specifically developed for spatial analysis, as it offers various functionalities for capturing, storing, querying, analysing, displaying, and communicating geographic information. Consequently, GIS plays a significant role in the spatial decision-making process. Ji et al., (2022),also highlighted that GIS utilizes computer technology to facilitate automatic screening and precise analysis based on selected constraints such as terrain and area. This enables the identification of suitable locations and the visualization of map positions. By leveraging GIS capabilities, the process of finding appropriate locations becomes more efficient and accurate, allowing for informed decision-making.

A key aspect of a GIS is its ability to utilize data layers that represent various characteristics within a specific area. By creating distinct criteria for each layer and overlaying them, GIS can generate an optimal area that satisfies all criteria. Due to this capability, GIS is extensively employed in site selection problems for various purposes (Atici et al., 2015). In GIS, various methods are employed to analyse geographic data. These methods encompass both the analysis of geographic data and the analysis of attribute data. Regarding geographic data, analyses are conducted on both vector data and raster data (Rikalovic, Cosic & Lazarevic, 2014).

The most used spatial analysis techniques in GIS include:

- Analysis of attributive (tabular) data
- Overlapping layers (i.e., query of spatial data)
- Analysis of distance
- Network analysis and
- Nonparametric techniques

2.3.1 Multicriteria Decision Analysis

Multiple Criteria Decision Analysis (MCDA) is a widely recognized field within operational research that addresses decision problems involving multiple conflicting criteria (Atici et al., 2015). This approach involves evaluating and considering several criteria to arrive at informed decisions. Numerous MCDA methods are available in this literature, serving different purposes like selection, ranking, sorting, or description of options. The choice of a specific method is typically made by the decision maker, considering the nature and characteristics of the problem at hand (Atici & Ulucan, 2011). Multi-criteria decision-making procedures establish a relationship between "input maps" and "output maps" (Malczewski, 2006).

Utilizing MCDA, Bayazıt, Bakış & Koç, (2021) developed a GIS-based model to identify a suitable location for a second reservoir and converted an existing dam into a pumped hydroelectric storage (PHS) system. This model incorporated data on reservoirs, dams, terrain, and land use restrictions. Through a multi-criteria decision analysis, they generated a map indicating the suitability of the second reservoir location based on criteria such as slope, aspect, geology, transportation infrastructure, villages, and rivers.

Jafari et al., (2021) developed a location-based model for sustainable energy development, focusing on the installation of RoR hydropower facilities in Gilan. The data used was categorized into four groups – physical, environmental, socio-economic, and technical aspects and eleven sub criteria to assess the significance of each criterion within its respective category in the study area. With these parameters, they utilized the BWM (Best-Worst Method) developed by Rezaei, (2015), which is a robust comparison-based MCDA approach, to determine optimal weights and consistency ratios through a straightforward linear optimization model employing an expert questionnaire. This method offers two key advantages, which was the primary reasons for its selection in their research, firstly it requires less pairwise comparison data, and secondly it yields more consistent results compared to other methods.

2.3.1.1 Fuzzy-Based Multi Criteria

The Fuzzy-MCDA method has been developed based on the principles of fuzzy logic and the MCDA approach. It offers a rational and systematic process for identifying both the best solution and a compromise solution to address the renewable energy problem (Adhikary, Roy & Mazumdar, 2015) .

Shimray et al., (2018) developed a neuro-fuzzy multi-criteria framework that combined Neural Network and Fuzzy approaches for decision-making in the SHP domain. The framework evaluated criteria such as ecology, hostility, cost of energy delivery, water quality, and air quality with 19 sub-criteria. These sub-criteria were classified using a Multi-layer Perceptron neural network that is trained by Genetic Algorithm. Lastly utilizing fuzzy reasoning, a scoring system was employed to rank and prioritize various existing and future sites for the installation of the SHP.

Ghumman et al., (2020) employed a fuzzy-based multi-criteria decision-making method (Fuzzy-MCDA) to prioritize a large set of potential SHP sites. Considered factors such as safety concerns, social aspects, hydrological factors, economic viability, technical feasibility, environmental impacts, and climate change impact for their analysis. For screening of potential sites, they used a screening technique established by Tavakkoli-Moghaddam, Hassanzadeh & Zhang, (2010). This approach included subjective ratings, provided by a panel of decision-makers for each of the sustainability criteria. The fuzzy-based subjective judgment approach proved effective in ranking SHP sites during the initial screening phase of the project.

Kucukali, Al Bayatı & Maraş, (2021) utilized a fuzzy logic-based multi-criteria scoring method to identify the most favourable existing irrigation dams for the development of SHP. A set of parameters which include dam's purpose, years of operation, normal water level, reservoir capacity, distance to grid connection, and the requirement for an Environmental Impact Assessment were utilized to find suitable SHP dams. Incorporating a scoring system, scoring of chosen parameters relied on fuzzy logic membership functions and employing geo-database queries that considered the technical criteria for dams and substations, as well as the spatial criterion of proximity to the nearest substation. Using ArcGIS spatial analyst tools, they identified a significant number of potential SHP dam sites.

2.3.1.2 Analytical Hierarchy Process

The Analytic Hierarchy Process (AHP) approach, developed by Satty, (1980), is among the most widely utilized methods in MCDA (Chen, 2006). This method is based on three key principles: analysis, binary comparison, and the processes of summarizing, prioritizing, and selecting among alternatives. The developed AHP model comprises four phases, namely problem structuring to create a hierarchy, data collection through pair-wise comparison, priority determination, and analysis for problem resolution (Chen, 2006; Vaidya & Kumar, 2006).

The AHP offers an analytical approach that allows for the integration and consolidation of evaluations of alternatives and criteria, whether conducted by an individual or a group involved in the decision-making task (CROUCH & RITCHIE, 2005). The importance of criteria and sub criteria in the decision-making process can vary at different levels of the hierarchy, and each alternative may have different ratings on each criterion. Figure 2-2 below shows an AHP model structure.

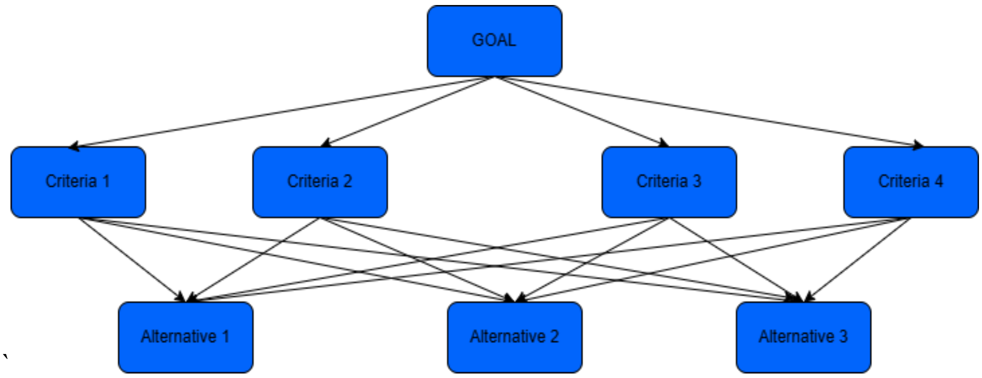

Figure 2-2 AHP MODEL STRUCTURE ADAPTED FROM (BADRI, 2001)

The first step in AHP is identifying the issue at hand and specifying the type of information needed. The problem under scrutiny is selected from a pool of significant or sufficiently intricate challenges warranting examination. The act of choosing this problem may itself pose a multifaceted dilemma necessitating a specialized analysis. When defining and opting for a problem, it is crucial to openly articulate all the assumptions and the viewpoint that led to this decision.

The second step is organizing the decision hierarchy. This hierarchical structure is constructed, starting at the highest level with the primary decision objective, followed by overarching objectives, then intermediate levels representing criteria, and finally, the lowest level encompassing a range of alternatives. In essence, once the primary goal or objective is established, the process of seeking a solution to a related problem can be approached in two ways: top-down (beginning with criteria and moving to alternatives) or bottom-up (starting with alternatives and moving to criteria) (Satty, 1980). It is imperative to construct a model that facilitates the identification of truly pertinent criteria and alternatives.

The third step is to create matrices for conducting pairwise comparisons as in Equation 2-2. These comparisons are executed using a scale to indicate how much more significant or dominant one element is compared to another in terms of the criterion or attribute under consideration (Russo & Camanho, 2015). This scale, applicable for both quantitative and qualitative criteria, spans from "equal" (assigned the value of 1) to "significantly more important than" (assigned the value of 9), refer to Table 2-1. The preferred cell within the criterion's matrix holds the assigned value, while the corresponding cell holds the inverted value (1 divided by the value). The redundancy of these pairwise comparisons enhance the precision of the analysis and contributes to a deeper understanding of the problem's elements. The scales from the decisions must be assessed, so the consistency ratio check of the pairwise comparison judgement is employed (see Equation 2-1).

Equation 2-1

$$\boldsymbol{CR = \frac{CI}{RI}}$$

CR is the consistency ratio used to assess the consistency of judgements made during pairwise comparison of criteria, CI is the consistency index, which is a numerical value calculated during the AHP to quantify the level of inconsistency in the pairwise comparisons. RI is the random index which is a predefined set of values used to assess whether the level of inconsistency observed is acceptable or if it exceeds a random level of inconsistency.

The matrix of pairwise comparisons is a square matrix of size n × n, where each element **aij** represents the preference expressed as a numerical value of the element in row **i** when compared with the element in column **j**. In other words**, aij = wi/wj,** where **wi** and **wj** are the weights or preferences assigned to the elements being compared. If there are n elements to be compared, the comparison matrix A is defined as follows: (Fuentes-Bargues & Ferrer-Gisbert, 2015)

Equation 2-2 **(1)**

$$\mathbf{A} = \left\langle \begin{matrix} \boldsymbol{w_1/w_1} & \boldsymbol{w_1/w_2} & \cdots & \boldsymbol{w_1/w_n} \\ \boldsymbol{w_2/w_1} & \boldsymbol{w_2/w_2} & \cdots & \boldsymbol{w_2/w_n} \\ \boldsymbol{w_n/w_1} & \boldsymbol{w_n/w_2} & \dots & \boldsymbol{w_n/w_n} \end{matrix} \right\rangle$$

$$= \begin{bmatrix} \mathbf{1} & \boldsymbol{a_{12}} & \cdots & \boldsymbol{a_{1n}} \\ \boldsymbol{a_{21}} & \mathbf{1} & \cdots & \boldsymbol{a_{2n}} \\ \cdots & \cdots & \cdots & \cdots \\ \boldsymbol{a_{n1}} & \boldsymbol{a_{n2}} & \cdots & \mathbf{1} \end{bmatrix} \qquad \mathbf{(2)}$$

The final step involves consolidating a set of priorities to arrive at the ultimate decision. The alternative that attains the highest priority concerning the overarching goal becomes the definitive choice. This is achieved by combining the scores assigned to each option with their respective criterion weights, resulting in a final score for each option.

Table 2-1 9-POINT INTENSITY OF RELATIVE IMPORTANCE SCALE (FROM SATTY (1980))

Magnitude of the significance	**Description**	**Explanation**
1	Equal Importance	Two activities make an equal contribution to objective 1.
3	Moderate Importance	Experience and judgment slightly favour one activity over another.
5	Strong Importance	One activity is strongly favoured over another based-on experience and judgment.
7	Demonstrated importance	One activity demonstrates strong favouritism, and its dominance is evident in practice.
9	Extreme Importance	The evidence strongly affirms the favouring of one activity over another at the highest possible level.
2,4,6,8	Intermediate Values	When a compromise is necessary

In the context of SHP site selection using AHP, Nzotcha, Kenfack & Blanche Manjia, (2019) proposed a decision-making tool aimed at selecting the best alternative among several preselected sites for Pumped Hydro Energy Storage plants within the context of sustainable development. To accomplish this, they developed a MCDA methodology that integrates three criteria, techno-economic factors, social factors and environmental factors, each applied to a specific step in the decision-making process, assigning weights to decision factors and criteria using the pairwise comparison approach of the AHP. In addition, the performance of the alternatives was assessed based on a set of sixteen diverse sub-criteria from all the three criteria. To address the uncertainty arising from human preferences expressed in linguistic variables, a scoring system was employed that combines fuzzy membership functions and rating scales, allowing for the standardization of the assessed performance of the alternatives.

In the upper Benue River watershed in Nigeria, the identification of suitable locations for a SHP dam was accomplished through the integration of ten thematic data layers, which include land use, Rainfall, geology, soil, slope, elevation, stream power index, topographic wetness index, drainage density, and flow. Utilizing GIS and AHP to weigh these criteria and combining them with weighted overlay, a composite suitability map was generated to assess the suitability index of SHP in different areas. In addition to the suitability map they developed a semi-automatic approach, which involved intersecting contour lines with overlayed stream order and the suitability layer to identify narrow valleys. This approach was employed to select the most favourable site for the SHP dam (Odiji et al., 2021).

Ali et al., (2023) identified potential sites for small run-of-river hydropower in the Songkhla Lake Basin in Thailand. Their research employed an integrated approach that integrated GIS and the Soil and Water Assessment Tool (SWAT), along with AHP to assess technical, economic, and environmental factors for the small run-of-river siting. Various data were used, including a DEM, road data and transmission networks, information on national parks, and population density. Their analysis was done using ArcGIS software and these analyses aimed to identify suitable locations for SHP based on all the pre-defined criteria.

Othman et al., (2020) utilized remote sensing and GIS techniques in the Kurdistan Region of Iraq to identify eleven potential dam locations. Their analysis integrated fourteen different data layers, including average Rainfall, curve number (CN), distance to lineaments, distance to major roads, distance to towns and cities, distance to active faults, distance to villages, hypsometry, land cover, lithology, slope gradient, soil type, stream width, and tectonic zones. This approach allowed them to assess and identify suitable sites for potential dam construction based on the data used and their spatial information then combining them with weighted sum model (WSM) and AHP for the analysis. Similarly, Chen, (2006), used GIS and AHP to assess potential dam locations. Geographic data, such as slope, Rainfall, geology, soil type, drainage, and land use and land cover, were considered in their analysis. The study aimed to identify suitable sites for dam construction based on the integrated analysis of these data.

Al-Ruzouq, Shanableh, Yilmaz, et al., (2019) utilized a hybrid algorithm that integrates GIS, AHP, and machine learning techniques to identify optimal locations for constructing new dams in a major city in the United Arab Emirates. Nine thematic layers were used to generate a dam site suitability map. These layers included Rainfall, Digital Surface Model, geomorphology, geology, curve number, total dissolved solids, elevation, slope, and major fracture. To determine the influence of each factor, two approaches were employed, the first approach involved using previous literature and expert opinion based. The second approach involved utilizing machine learning techniques and ground truth groundwater mapping. The weighting assigned to each factor was based on these two approaches which was then combined to create a new revised weighting.

2.3.1.3 Weighted Sum Model

The Weighted Sum Model (WSM) is a straightforward and commonly employed multi-criteria decision approach. It relies on the weighted average using arithmetic means. To determine an evaluation score for each alternative, one can calculate it by multiplying the scaled value assigned to that alternative for a specific attribute with the weights of relative importance assigned directly by the decision makers. Afterward, the products for all criteria are summed together (Chourabi et al., 2019). One benefit of the WSM method is that it involves a linear transformation of the raw data that maintains the relative order of magnitude in the standardized scores (Jaberidoost et al., 2015).

The fundamental principle of the WSM method is to calculate a weighted sum of performance ratings for each alternative across all attributes (Chourabi et al., 2019). The first step is to compute the decision matrix X, each cell (X_{ij}) in the matrix contains a value that quantifies how well a specific alternative (row) performs on a particular criterion (column). These values are typically based on data or assessments.

(3)

Equation 2-3

$$\mathrm{X} = \begin{bmatrix} \boldsymbol{X_{11}} & \boldsymbol{X_{12}} & \cdots & \boldsymbol{X_{1n}} \\ \boldsymbol{X_{21}} & \boldsymbol{X_{22}} & \cdots & \boldsymbol{X_{2n}} \\ \cdots & \cdots & \cdots & \cdots \\ \boldsymbol{X_{m1}} & \boldsymbol{X_{m2}} & \cdots & \boldsymbol{X_{mn}} \end{bmatrix}$$

The second step is to compute the normalized decision matrix R

(4)

Equation 2-4

$$\mathbf{R} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}$$

Then third step is to compute the weighted normalized decision matrix R'

Equation 2-5

$$\mathbf{R'} = \begin{bmatrix} w_1 * r_{11} & w_2 * r_{12} & \cdots & w_n * r_{1n} \\ w_1 * r_{21} & w_2 * r_{22} & \cdots & w_n * r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ w_1 * r_{m1} & w_2 * r_{m2} & \cdots & w_n * r_{mn} \end{bmatrix} \qquad \textbf{(5)}$$

The fourth step is calculating the score S_i^{WSM} of each alternative.

Equation 2-6

$$\boldsymbol{S_i^{WSM} = \sum_{j=1}^{n} w_j\, r_{ij}\, for\ i = 1, 2, 3, \ldots, m.} \qquad \textbf{(6)}$$

Where S_i^{WSM} represents the weighted sum for a specific alternative **i** in the decision-making process and $\boldsymbol{w_j}$ are the weights assigned to each criterion **j.** The weights reflect the relative importance or significance of each criterion in the decision-making process. Higher weights indicate greater importance. $\boldsymbol{r_{ij}}$ are the performance ratings or scores of each alternative **i** with respect to each criterion **j**. These ratings represent how well each alternative satisfies or performs on each criterion.

2.3.2 Other Approaches

In selecting a suitable site for SHP, Tamm & Tamm, (2020) utilized GIS capabilities to develop a reliable method for estimating and identifying SHP potential. They employed a virtual hydropower assessment system to determine appropriate size and location of SHP sites for generating hydroelectric power along a river, utilizing a DEM and specific discharge maps to determine suitable areas for SHP production. Their study findings offered a dependable approach for assessing SHP potential, particularly in countries with limited access to meteorological and hydrological data. Yi, Lee & Shim, (2010) introduced a novel methodology for analysing potential sites for SHP plants that incorporates constraint criteria and location criteria. The constraint criteria were employed to eliminate unsuitable locations that either have legal restrictions or are prone to potential disputes. The remaining search points were assessed and scored based on location criteria, including factors such as natural head (slope), storage capacity, dam width limitation, runoff contributing area and stream network grid for the searching process of the potential sites for SHP.

Rojanamon, Chaisomphob & Bureekul, (2009) selected run-of-river SHP sites, incorporating a comprehensive approach that integrated engineering, economic, and environmental criteria, along with an evaluation of social impact. The engineering analysis encompassed the estimation of discharge models and GIS analysis to identify potential project sites. The discharge models, specifically flow duration curves, are developed by utilizing recorded data from nearby gauging stations within the river basin. The GIS analysis involves a series of steps, including setting criteria for site location, delineating and calculating watershed areas, estimating designed discharge, searching for powerhouse locations, and identifying surge tank, headrace, and penstock locations. In the environmental analysis, a weighted linear combination is applied to calculate the total weighted scores for all environmental parameters. For the examination of social impact, a public participation process is implemented, incorporating interview questionnaires and focus group discussions. The identified locations were then compared with potential sites gathered from previous reports.

Larentis et al., (2010) developed an automated sequence of steps using a GIS-based computational tool called Hydrospot, which utilized remote sensing and regional streamflow data for hydropower spotting. The program integrated two key modules as part of methodology: survey and selection. Within the survey module, the process entails identifying the dam site, pinpointing the powerhouse location, assessing the gross natural potential, and ultimately developing a dam and reservoir lake. The selection module involves evaluating the site's potential, ranking and pre-selection of options, and conducting interference tests. These two modules collectively contribute to the comprehensive approach employed by the program in its decision-making and planning processes for hydropower dam construction projects.

(Fesalbon & Blanco, 2019) employed a combination of Interferometric Synthetic Aperture Radar and a DEM, GIS-based hydrology tools, and terrain characterization techniques to locate natural reservoirs and identify potential dam building sites for hydropower. The process involved the utilization of criteria such as valley determination, landform classification, and flow accumulation. Various algorithms for identifying valleys were included in the comparative analysis. These algorithms comprise Multi-Resolution Valley Bottom Flatness

(MRVBF), Topographic Position Index (TPI), Valley and Ridge Detection (VRD), and Geomorphons. After identifying the valleys in the study area, elevation and slope data were integrated to pinpoint sections of these valleys with elevated terrain and relatively level topography was suitable for accommodating the reservoir's volume. The outcome was presented as an index ranging, with higher values indicating valleys with greater suitability.

Ghazal and Salman identified the most suitable locations for small dams through the analyses of drainage patterns, slope maps, geological maps, and extracting lineament structures from Landsat satellite imagery. These lineaments were identified as potential obstacles in the development of dam sites and were avoided. Their selection criteria for determining suitable dam sites encompassed areas with minimal slope to facilitate efficient water collection, as well as streams of high order to accommodate a larger volume of water (Ghazal & Salman, 2015).

2.4 Conclusion

In conclusion, this literature review aimed to develop a comprehensive understanding of the current knowledge and research related to site selection for SHP projects. The review identified and examined essential parameters that should be considered during the site selection process for SHP siting.

The literature review highlighted the importance and benefits of SHP as an environmentally friendly energy option. SHP was found to have advantages such as low operating costs, minimal environmental impact, and potential for long-term employment opportunities. Various methodologies and techniques were discussed in the literature for site selection, including the use of GIS and AHP. Studies showcased the integration of multiple criteria and spatial information layers to identify suitable sites for dam construction. These criteria encompassed factors such as Rainfall, slope, elevation, soil type, drainage density, flow accumulation and proximity to powerlines. The methodologies utilized in these studies provided valuable insights into assessing potential sites and generating suitability maps for SHP projects. Additionally, fuzzy-based multi-criteria decision-making approaches were explored, offering a rational and systematic process for identifying suitable sites for renewable energy projects. These approaches combined fuzzy logic and MCDA techniques to evaluate attributes such as ecology, cost, safety, and social aspects.

This portion of the literature review addressed objective 1 and research question 1a and objective 2 research question 2a (refer to section 1.4) by contributing to the identification of key criteria and methods influencing the optimal siting of SHP projects. It lays the groundwork for understanding the criteria used in similar studies, which is a crucial step in determining the relevant criteria for the Western Cape context.

3 METHODOLOGY

3.1 Study Area And Data Collection

By collecting comprehensive data, the project identified suitable sites for SHP siting and assessed their potential for electricity generation. This robust methodology ensured that the project is well-informed and equipped to make informed decisions regarding renewable energy infrastructure in the Western Cape region.

This chapter focused primarily on addressing research objective 3 on sourcing suitable data for analysis according to defined criteria. It delves into the description of the Western Cape region as the study area and the processing of data collected, shedding light on the methods and sources used to obtain accurate and reliable information concerning terrain variations within the Western Cape region. This chapter also thoroughly addresses research question 3a by explaining how original datasets were sourced from open-access platforms and various datasets were explored. Additionally, it provides insights into research question 3b by elaborating on the relevance of the data sources to the Western Cape context. The mention of specific datasets and how they were utilized in the study area underscores their relevance to the research's geographical focus.

Moreover, also research question 3c is implicitly addressed as this chapter discusses the nature of data sources, including whether they were derived from open-access platforms. This information hints at the accessibility and availability of these data sources, which is a key aspect of this research question.

3.1.1 The Study Area

The Western Cape Province of South Africa extends north and eastward from the Atlantic Ocean. Its spans around 400 kilometres along the Atlantic coast and 500 kilometres along the southern coast, reaching the Southern Indian Ocean. This Province shares borders with the Northern Cape to the north and the Eastern Cape to the east. Encompassing a total land area of approximately 129 462 square kilometres, it constitutes approximately 10.6% of the country's overall land area.

Several notable rivers flow through the province. The Berg and Olifants rivers empty into the Atlantic Ocean, while the Breede and Gourits rivers drain into the Indian Ocean. The province’s topography and the influence of nearby ocean currents contribute to a diverse climate. The warm Agulhas Current moves southward along the eastern coast, while the cold Benguela Current emerges from the depths of the South Atlantic Ocean along the western coast, resulting in distinct micro- and macroclimates. This leads to significant climatic variations over short distances. A large part of the province experiences a Mediterranean climate, characterized by cool, rainy winters and warm, dry summers. Figure 3-1 shows the study are area of Western Cape.

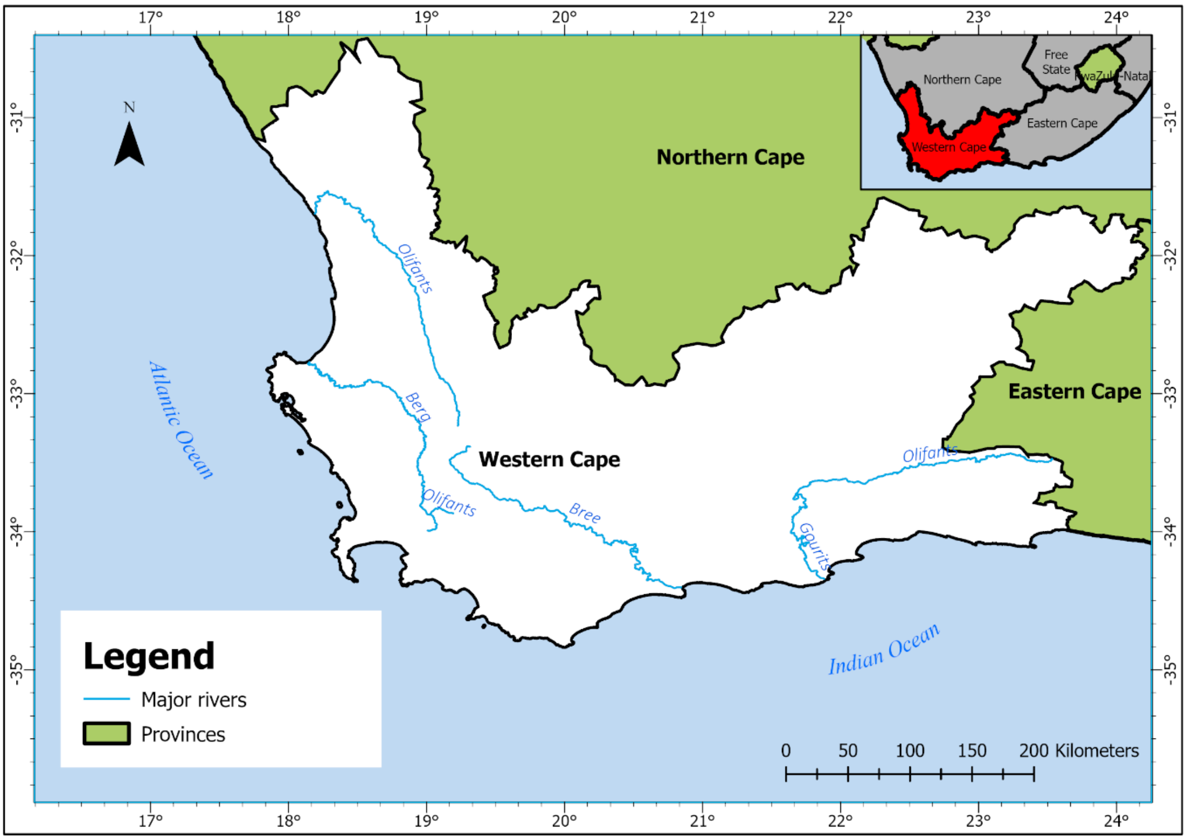

Figure 3-1 STUDY AREA OF WESTERN CAPE REGION IN SOUTH AFRICA

3.1.2 Data Collection

In this research, original datasets were sourced from open-access platforms, and a variety of datasets were explored. When it came to pinpointing suitable sites for SHP installations, all analyses were carried out using ArcGIS 3.1.0 by Esri, a leading geographic information system software. Several datasets as outlined in Table 3-1 underwent preliminary processing. Additionally, certain datasets were derived from existing data sources; including, parameters like slope and stream order, as well as flow accumulation, were generated from the DEM. To facilitate subsequent data manipulation, all datasets were converted into raster format as the GIS methods employed in this study necessitated rasterization for easier reclassification. Prior to conducting the weighted overlay analysis, each dataset underwent reclassification. The input rasters for the weighted overlay analysis included elevation, average rainfall, distance to powerlines, flow accumulation, slope, soil type, and drainage density data. Ultimately, through the application of the weighted overlay method, diverse categories of suitable locations were identified and categorized.

Table 3-1 DATA COLLECTION TABLE

Data Used	**Format**	**Scale/Resolution**	**Source**
STRM-DEM	Raster	30m	OpenTopography
Rainfall	Raster	2.5 arc minutes	WorldClim
Soil Map	Raster	1km	International Soil Reference and Information Centre (**ISRIC**)
Powerlines	Vector	-	Open street Map (**OSM**)
Rivers	Vector	-	Department of water and Sanitation (**DWS**)
Existing Dams	Vector	-	Department of water and Sanitation (**DWS**)

The flowchart depicts a comprehensive sequence of actions, beginning with data collection on various factors such as soil type, proximity to power lines, average Rainfall, and DEM. The DEM is then analysed to generate flow accumulation, stream order and drainage density and slope datasets. These datasets are all stored in one database, and an AHP is employed to integrate and evaluate them. Following this, the data undergoes raster conversion, resampling, reclassification, and weighted overlay to produce single dataset. Ultimately, this process leads to the identification of suitable areas for SHP, aligning with suitability criteria. This walkthrough provides a more detailed understanding of the methodology's progression and the interplay of the various datasets within the flowchart.

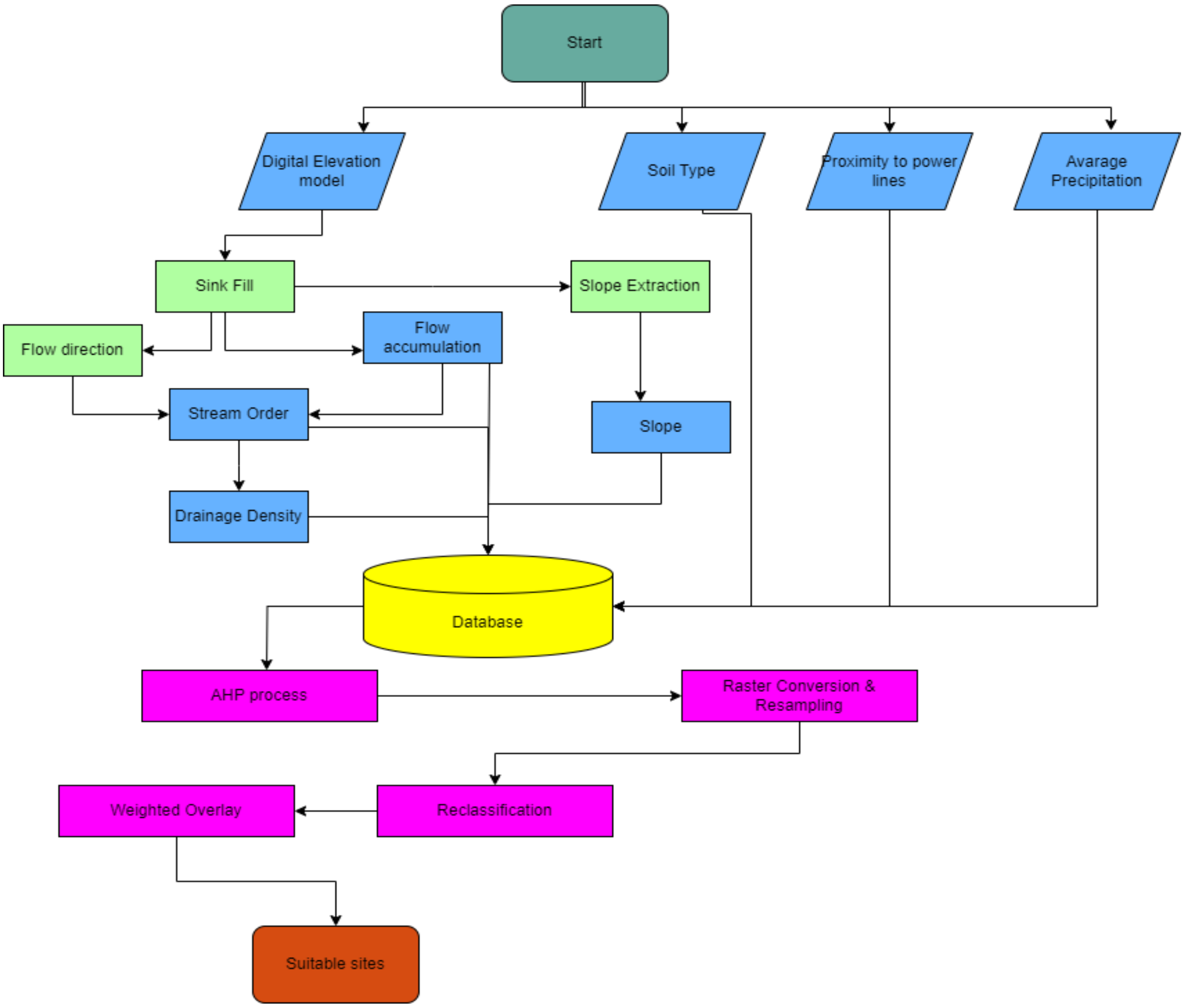

Figure 3-2 METHODOLOGY FLOWCHART

3.2 Criteria Selection For Identification Of SHP Potential Sites

Choosing a suitable SHP site involves the task of determining the most fitting location (Odiji et al., 2021). Having a consistent flow of power from a SHP requires a dam, so this study utilized criteria from previous studies to finding a suitable site for dam construction for storage SHP type. The criteria chosen for the study was based on a review of literature of previous studies as presented in chapter 2 from different authors including (Odiji et al., 2021),(Dai, 2016), (Othman et al., 2020),(Al-Ruzouq, Shanableh, Yilmaz, et al., 2019) and (Kamati, Smit & Hull, 2022). When evaluating potential sites for SHP within the Western Cape, seven (7) different criteria were considered including Rainfall, slope, soil texture, distance to powerlines, elevation, drainage density, and flow accumulation. The initial projection for most of the data in this study is GCS_WGS_1984, a geographical coordinate system that employs degrees as the angular unit. This was converted to a planar projection, WGS 1984 UTM 34S, which employs meters as the linear unit of measurement. All datasets are transformed from a national or global scale to a local scale that corresponds to the study area. To facilitate raster calculations in subsequent procedures, all criteria datasets are adjusted to have a consistent resolution matching that of the DEM data, which is 30 meters.

3.2.1 Slope (Head) data

The slope data of this study was derived from the SRTM30 DEM using the ArcGIS Pro 3.1 software. The slope degree parameter has a significant impact on the velocity of both surface and groundwater as it influences the direction and amount of surface run-off in a particular area (Odiji et al., 2021). When the slope is lower, there is a greater likelihood of water accumulating (Al-Ruzouq, Shanableh, Merabtene, et al., 2019). Slopes in the Western Cape range from 1.72% to 90%, with the flatter regions in the west and east (see Figure 3-3).

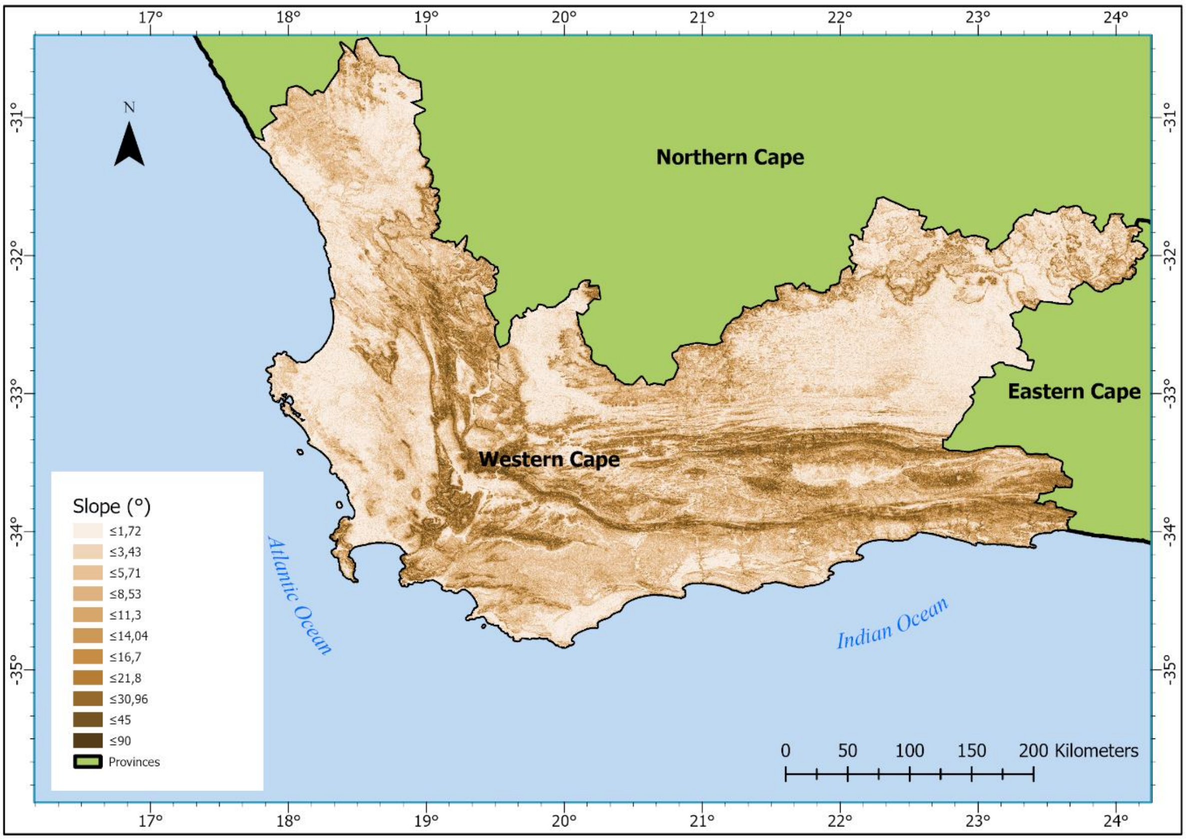

Figure 3-3 SLOPE CRITERIA MAP

3.2.2 Elevation data

The DEM in this study was extracted from openTopography data portal supplied by the shuttle radar topography mission (SRTM). The data was published in 2013 with a spatial resolution of 30m. Western Cape elevation ranges from 0 to 2309 m above sea level (refer to Figure 3-4). The Western Cape boundary was used to extract the DEM specific to the Western Cape region.

The DEM was used to derive other three datasets which are slope, stream order and flow accumulation. The location of a dam's optimal placement is influenced by the DEM as it has an impact on both water accumulation and flow patterns (Mura et al., 2018), so selecting a lower elevation is extremely suitable for dam site construction because it increases the potential for accumulating both Rainfall and groundwater (Al-Ruzouq, Shanableh, Merabtene, et al., 2019).

Before the DEM was utilized it was first filled to avoid any “sinks”. The DEM represents the topography by recording elevation data within specific-sized cells. Data inaccuracies or landforms can result in non-real depressions or sinks in the DEM. These data inaccuracies are typically a result of DEM resolution limitations in both vertical and horizontal dimensions or errors that occur during DEM generation (Dai, 2016). These sinks can lead to the generation of illogical flow directions during calculations. If these depressions aren't addressed through technical processes, the resulting drainage network may be discontinuous (Dai, 2016). The initial step in addressing sinks involved determining the flow direction of each cell, indicating the path water takes as it flows out of the cell. In ArcGIS, flow direction is determined by considering the cell's elevation and position of its eight neighbouring cells. Flow direction always points towards the steepest downslope neighbour. Sinks are identified based on the computed flow directions, with a sink defined as an area containing illogical flow directions. In other words, a sink consists of a cell or a group of connected cells for which a valid flow direction among the eight possible directions cannot be assigned within the flow direction raster.

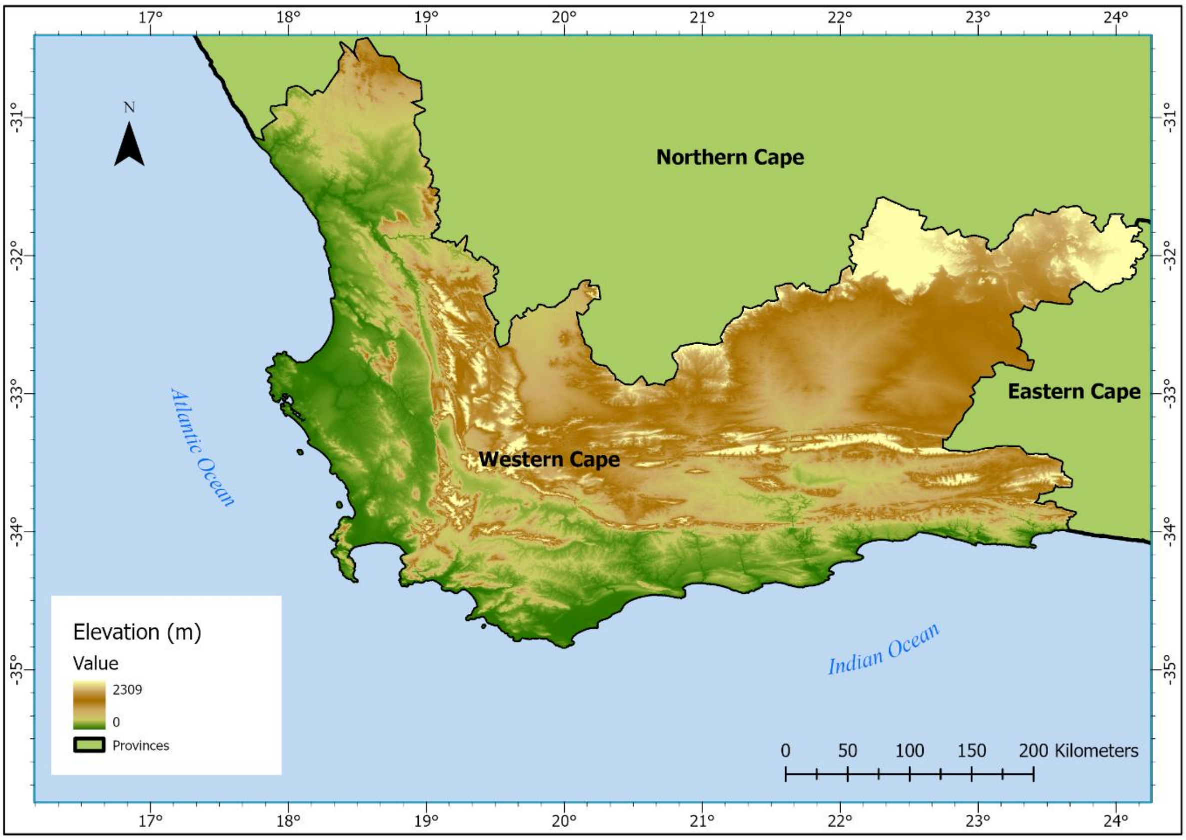

Figure 3-4 ELEVATION CRITERIA MAP

3.2.3 Soil Type data

Soil type data was obtained from the International Soil Reference and Information Centre (ISRIC). Soil texture plays a vital role in determining the suitability of a dam site (Odiji et al., 2021). Various types of soil exhibit varying rates of infiltration, which directly impact the runoff volume. Soil texture is particularly critical for establishing a solid foundation for the dam (Roy & Kumar Bhalla, 2017). In Figure 3-5, it is evident that the Western Cape region is characterized by seven primary classes of soil, with sandy loam and sandy clayloam soil dominant across the whole study area.

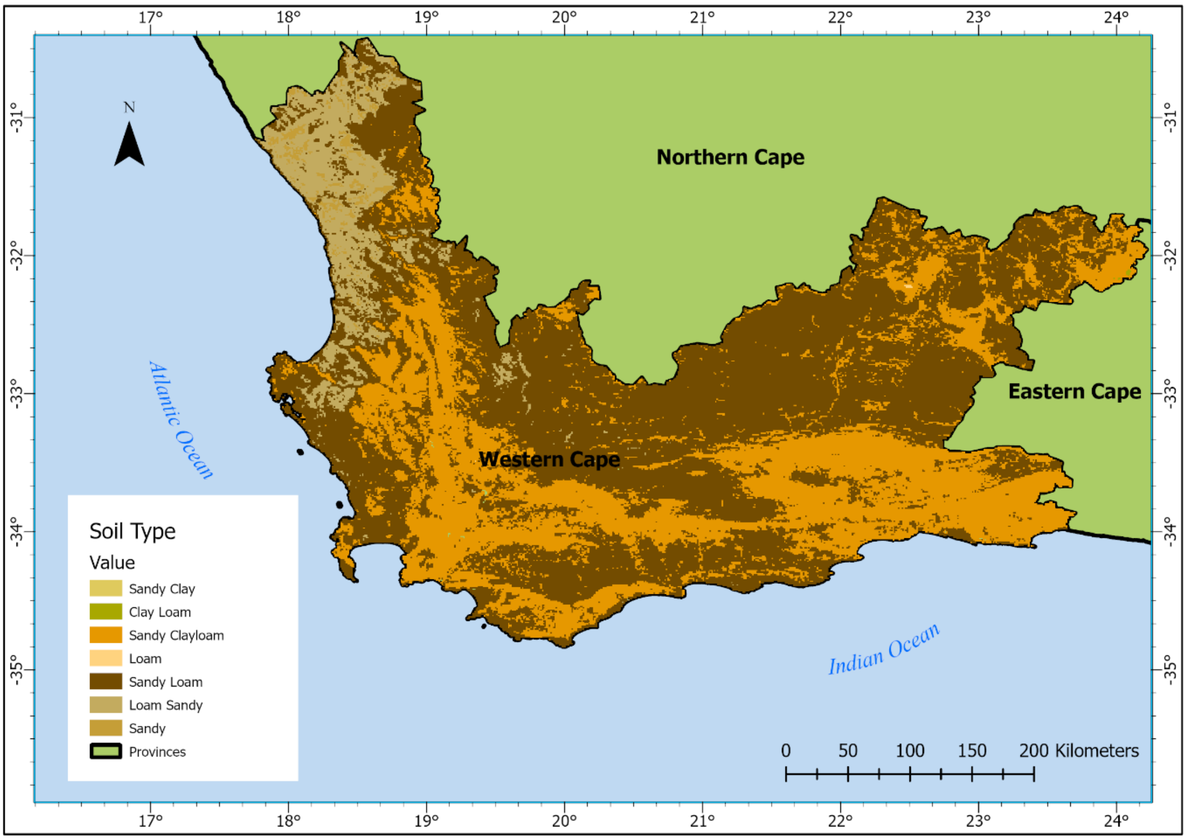

Figure 3-5 SOIL TYPE CRITERIA MAP

3.2.4 Powerlines data

The dataset was obtained from Open Street map (OSM) and clipped to the extent of the study area. The network comprises medium and high-voltage transmission lines, and it includes the following attribute data: the capacity of the transmission lines in kilovolts (Kv) and the status of the link, which is categorized as existing. The existing powerlines voltages range from 220 Kv to 533 Kv. Figure 3-6 shows the higher and medium power transmission lines of the Western Cape.

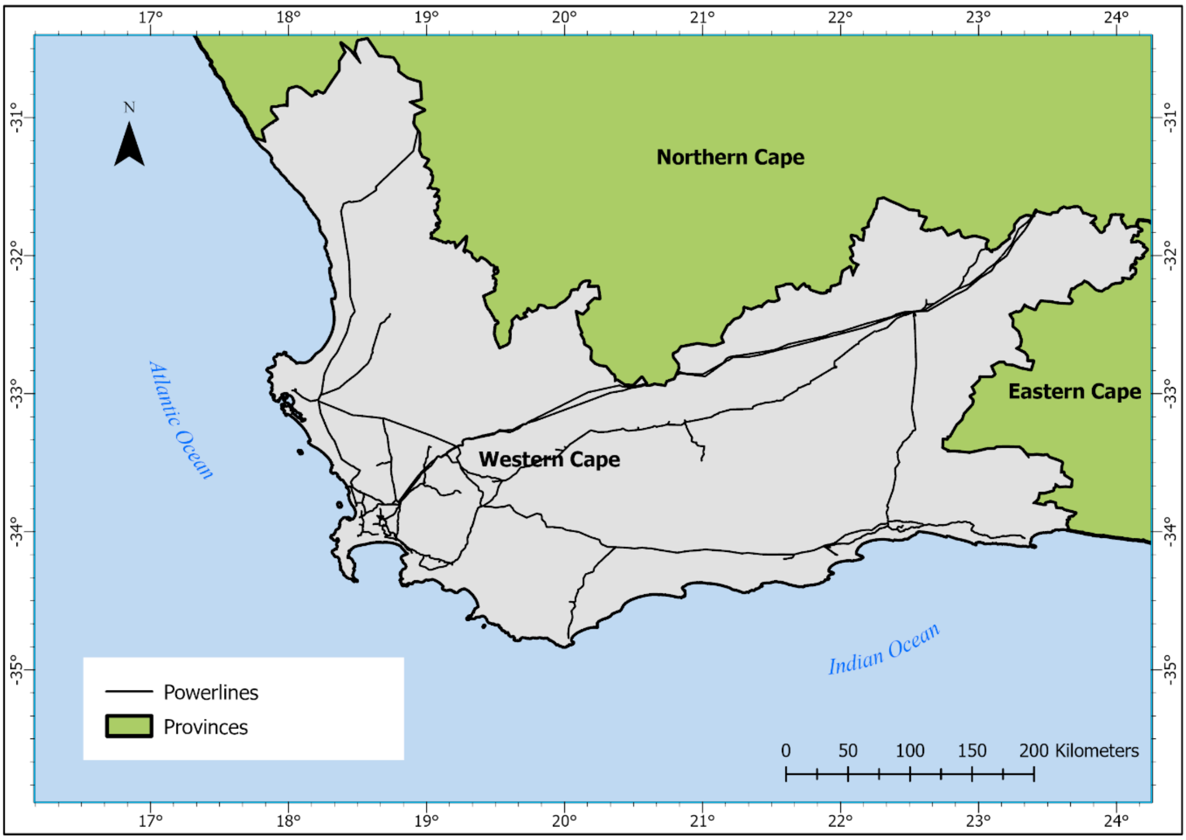

Figure 3-6 POWERLINES CRITERIA MAP

3.2.5 Drainage Density data

Drainage density measures the quantity of stream lengths within a given area. Areas with elevated drainage density suggest a heightened potential for both surface runoff and groundwater presence (Odiji et al., 2021). The drainage density data was derived from the stream networks of the watershed. It is calculated by dividing the total length of streams within the area by the total area of that region. This calculation helps assess how closely spaced and interconnected the drainage features are within the landscape, providing valuable insights into the hydrological characteristics of the area. Figure 3-7 shows Western Cape drainage density values ranging between 0.01 and 0.65 km/sq.km, with the eastern side areas having a relatively higher drainage density compared to the west side.

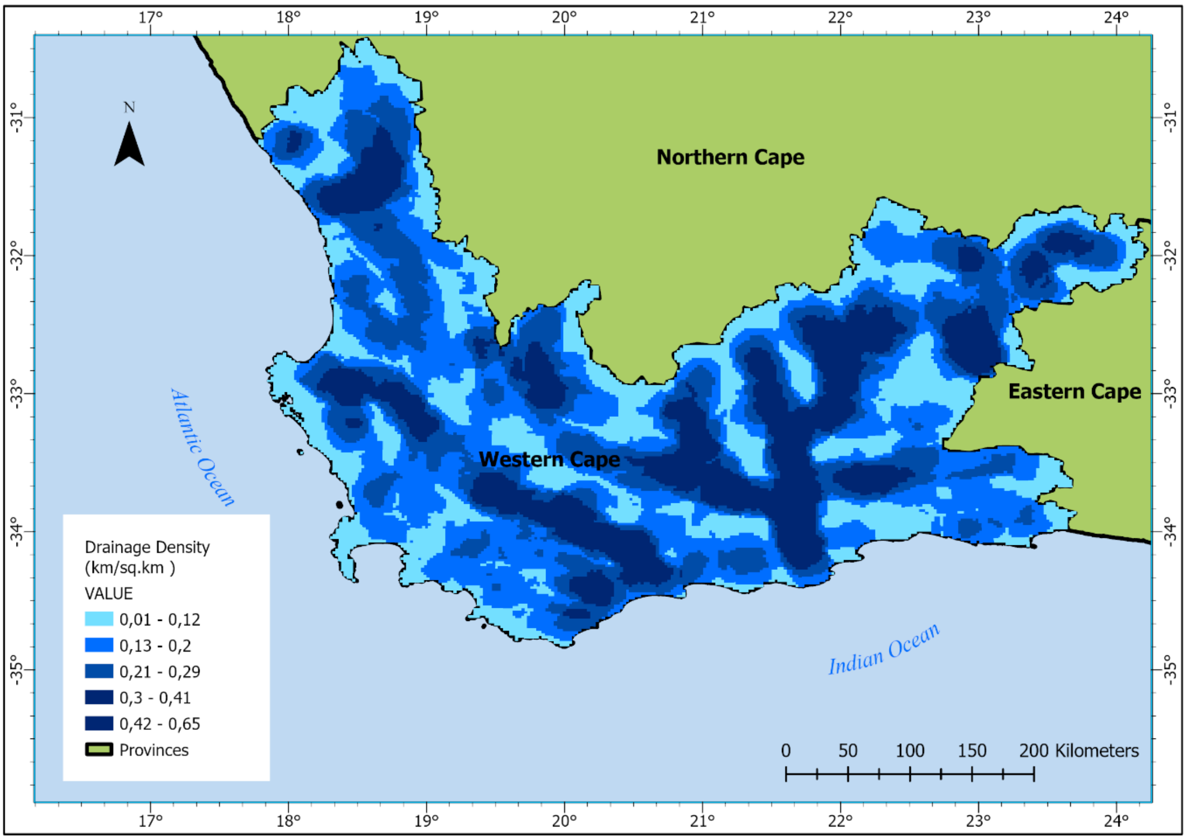

Figure 3-7 DRAINAGE DENSITY CRITERIA MAP

3.2.6 Rainfall data

Rainfall data was downloaded from WorldClim which is a rainfall database with a high spatial resolution that combines data from meteorological stations with satellite imagery. The dataset chosen was of 2.5 arc minutes resolution and averaged from year 2015 – 2019, in millimetres (mm). Due to regions of unobserved values, the dataset was interpolated using Inverse Distance Weighting (IDW). Regions with high levels of Rainfall are considered suitable for identifying appropriate locations for SHP dam construction (Al-Ruzouq, Shanableh, Merabtene, et al., 2019). Increased rainfall leads to greater water flow in the river, resulting in higher discharge. In Figure 3-8 it is evident that in the south of the Western Cape, along the coast, places experience a higher Rainfall compared to places far from the coast.

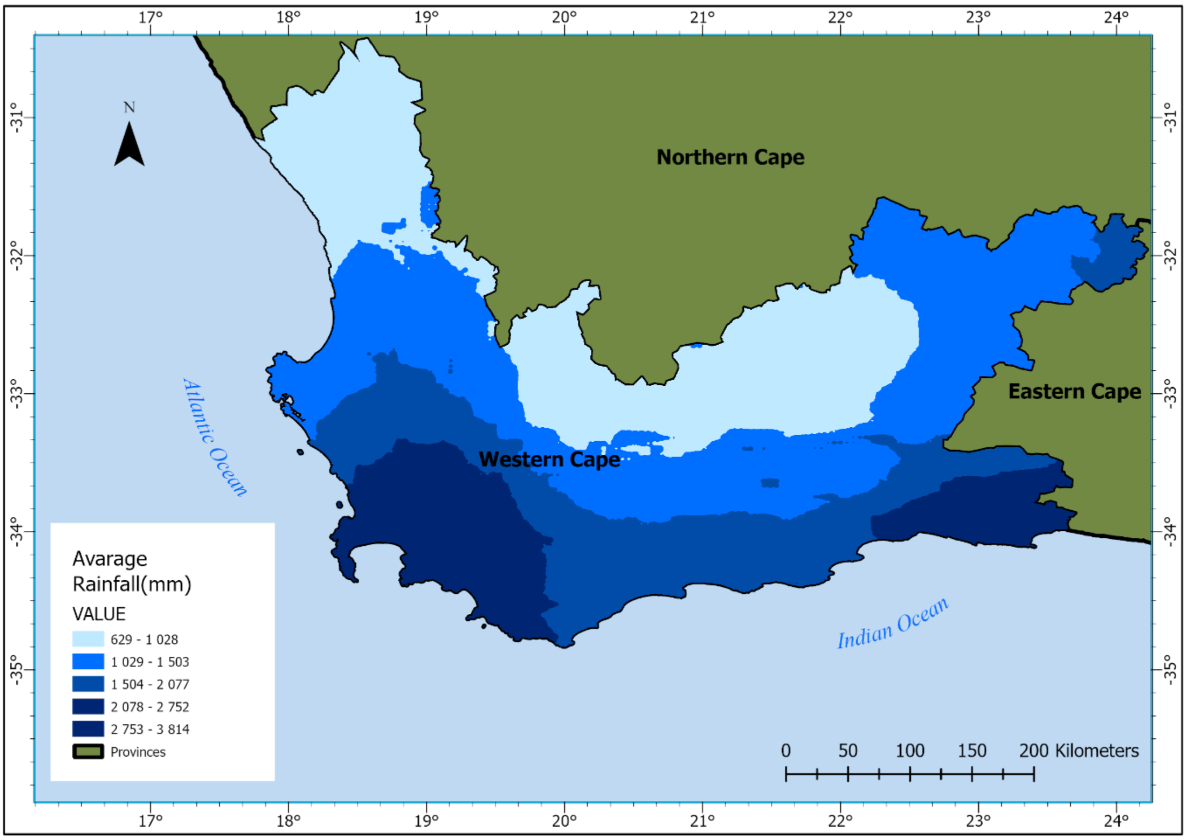

Figure 3-8 AVERAGE RAINFALL CRITERIA MAP

3.2.7 Flow Accumulation

The flow accumulation was extracted from the DEM. This data signifies the contributing area where rainfall water either drains into or collects. The process of determining flow direction in a DEM and subsequently calculating flow accumulation is essential for understanding how water moves across the terrain.

In this context, each cell contains a specific quantity of water, typically represented as one unit of water. The accumulated flow of a particular cell depends on how many cells direct their water into it. To distinguish between significant water flows, typically regarded as streams, and smaller flows that may be susceptible to natural processes such as infiltration and evapotranspiration, a user-defined threshold is applied. Cells with a flow accumulation value exceeding this threshold are designated as "1", while those below the threshold are assigned a value of "0". To determine an appropriate threshold value, various thresholds are tested by comparing the resulting stream network with water features depicted on a topographic map provided by ESRI on ArcGIS Online. After this comparative analysis, a better fit threshold value of 100 000 accumulated units was selected as the threshold for defining streams in this study. Consequently, all cells with an accumulated flow value equal to or exceeding 100 000 accumulated units are classified as streams.

One crucial factor in selecting a suitable location for a SHP dam is the consistent availability of water volume throughout the year. To ensure the effective operation of SHP systems, there must be a reliable and sufficient discharge of water. The Flow direction was determined by identifying the steepest descent from each cell using the DEM. Areas with higher flow accumulation values are indicative of streams, rivers, ponds, or other water bodies (Korkovelos et al., 2018).

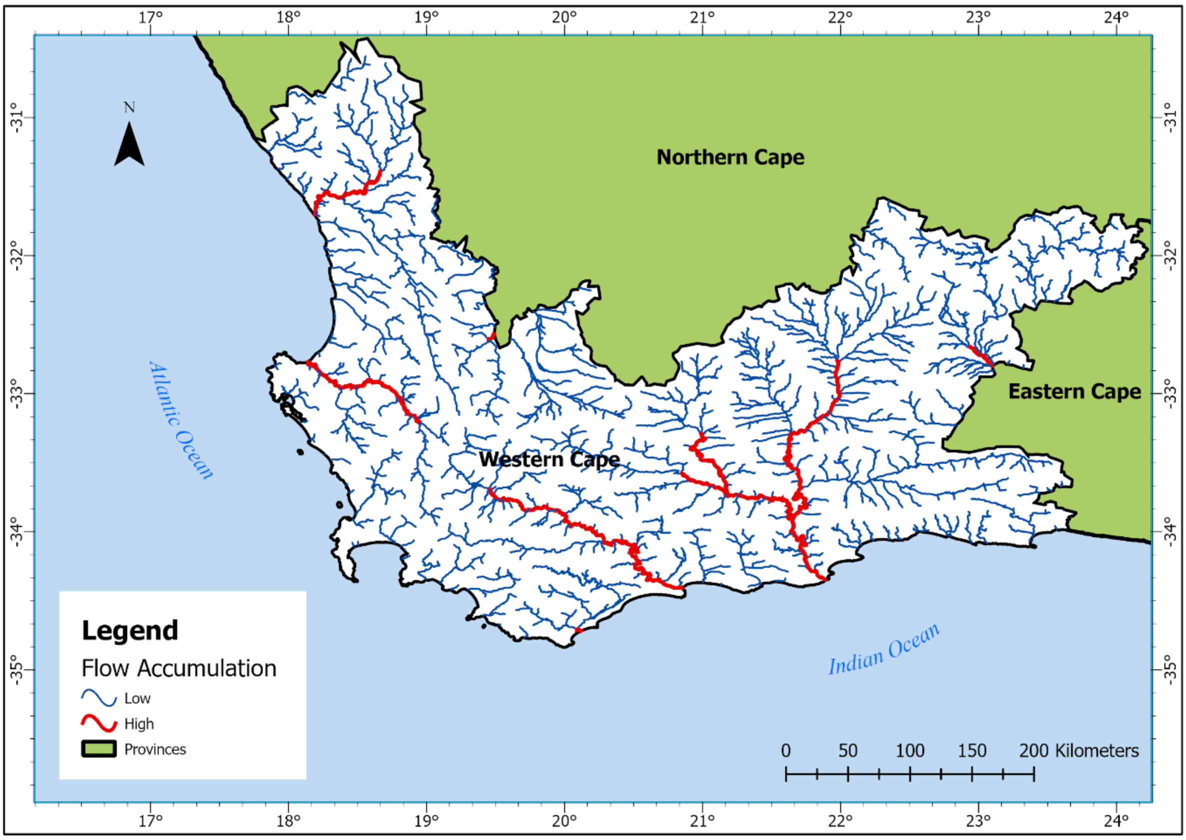

Figure 3-9 FLOW ACCUMULATION CRITERIA MAP

3.2.8 Stream Order data

The stream network was created from the DEM. The flow accumulation and flow direction were used. This flow accumulation ensured that each cell within the drainage network had a minimum of 100 000 contributing cells as mentioned in section 3.2.7. Therefore, the resulting stream network exhibited lower density compared to networks created with lower threshold values, with the actual density influenced by the size of the watershed (Chang 2014).

Next, each section of streams is assigned a drainage order, which is a numerical ranking given to segments of a linear stream network to represent varying levels of flow accumulation. Essentially, the higher the flow accumulation in a stream, the greater the drainage order assigned to it. In simpler terms, a higher drainage order suggests that more tributaries feed into the stream, increasing the potential for water collection. This drainage order becomes a crucial criterion in the later stages of selecting suitable dam sites. Since the entire Western Cape region is treated as a unified image, the Shreve method (Shreve, 1966) would result in a significant number of drainage order levels. Consequently, this study opts for the Strahler method (Strahler, 1957), which produces a more manageable set of drainage order levels, totalling five distinct orders. The arrangement of a drainage network aids in assessing the attributes of an area where water is retained (Jamali, Olofsson & Mörtberg, 2013).

The stream order was used later in this study. In Figure 3-10, streams originate from the northern part of Western Cape towards the ocean in the southern parts, thus streams with higher order are in the Southern part and streams with lower order in the northern part.

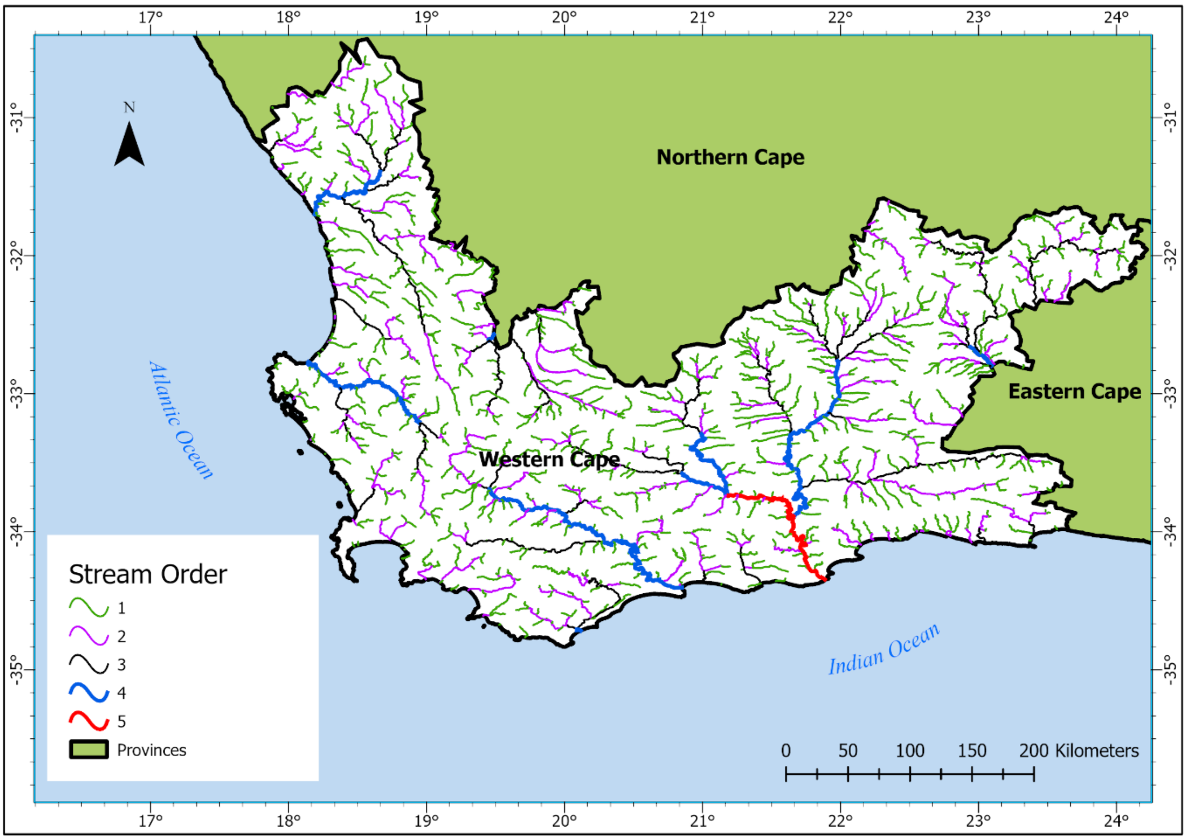

Figure 3-10 STREAM ORDER MAP

3.3 Minimum Suitability Criteria For SHP

Table 3-2 presents the ranging scores for various criteria used in the site suitability analysis. Each criterion is classified or buffered into specific categories ranging from barely suitable to extremely suitable, and the suitability levels were assigned to each category based on relevant previous literatures as also mentioned in section 3.2.

Table 3-2 RANGING SCORES FOR SHP CRITRERIA

Criteria	Classification/Buffering	Suitability	References
Flow Accumulation	Fifth order Fourth order Third order Second order First order	Extreme Suitable Highly Suitable Suitable Moderately Suitable Barely Suitable	(Odiji et al., 2021)
Slope (degrees)	<5 5 - 13.2 13.2 – 24.8 24.8 – 39.2 >39.2	Extreme Suitable Highly Suitable Suitable Moderately Suitable Barely Suitable	(Odiji et al., 2021)
Soil	Loam, Sandy, Loam sand Sandy Loam Sandy Clay Loam, Clay Loam Clay, Clay Loam Silt	Barely Suitable Moderately Suitable Suitable Highly Suitable Extreme Suitable	(Dai, 2016; Othman et al., 2020; Odiji et al., 2021)
Rainfall (mm)	<630 630 – 665 665 – 700	Barely Suitable Moderately Suitable Suitable	(Othman et al., 2020)

	700 – 730 >730	Highly Suitable Extreme Suitable	
Elevation (m)	0–55 55 – 109 109 –157 157 – 203 > 413	Extreme Suitable Highly Suitable Suitable Moderately Suitable Barely Suitable	(Al-Ruzouq, Shanableh, Yilmaz, et al., 2019)
Drainage Stream Density (km/sq.km)	0 – 0.14 0.14 – 0.23 0.23 – 0.32 0.32 – 0.42 >0.58	Barely Suitable Moderately Suitable Suitable Highly Suitable Extreme Suitable	(Al-Ruzouq, Shanableh, Yilmaz, et al., 2019)
Distance to Powerlines (m)	0–5000 5000–10,000 10,000–20,000 20,000-40000 >40000	Extreme Suitable Highly Suitable Suitable Moderately Suitable Barely Suitable	(Kamati, Smit & Hull, 2022)

3.4 Determining Weights Using AHP

In identifying a suitable location for constructing a dam, this study incorporated AHP method. The process of assigning weights to these parameters was carried out within a pairwise matrix, with a value of 1 assigned to its diagonal element, as mentioned in section 2.3.1.2. These weightings were determined based on relative scores gathered from previous literature reviews closely aligned with this study.

The initial step involves the creation of a pairwise comparison matrix with dimensions (n x n). This matrix enabled the evaluation of two criteria at a time in terms of their relative significance. To express individual preferences or judgments, a 9-point scale was employed, resulting in the generation of a reciprocal ratio matrix. If the importance of criterion A was deemed equivalent to that of criterion B, they were assigned an index of 1. If criterion A was significantly more crucial than criterion B, an index of 9 was attributed. Conversely, for less significant relationships, values ranging from 1/2 to 1/9 were assigned accordingly. In cases where criterion A was considerably less important than criterion B, a rating of 1/9 was used. These values were systematically inserted row by row into a cross-matrix, ensuring that the matrix's diagonal contained only values of 1. The upper right half of the matrix was then populated, ensuring that each criterion was compared to every other criterion. For instance, if the relative importance of A to B was rated as 'n,' the importance of B to A was rated as '1/n.' Subsequently, the lower half of the matrix was filled with corresponding fractions. Table 3-3 shows the pairwise comparison matrix for this study.

Table 3-3 PAIRWISE COMPARISON MATRIX

	Rainfall	**Slope**	**Drainage Density**	**Distance to powerlines**	**Flow Accumulation**	**Soil**	**Elevation**
Rainfall	1	2	4	9	6	3	3
Slope	1/2	1	1/2	7	5	3	2
Drainage Density	1/4	2	1	3	2	4	2
Distance to powerlines	1/9	1/7	1/3	1	1/7	5	8
Flow Accumulation	1/6	1/5	1/2	7	1	1/3	4
Soil	1/3	1/3	1/4	1/5	3	1	2
Elevation	1/3	1/2	1/2	1/8	1/4	1/2	1

Table 3-4 NORMALIZATION

	Rainfall	**Slope**	**Drainage Density**	**Distance to powerlines**	**Flow Accumulation**	**Soil Type**	**Elevation**	**Weights (%)**
Rainfall	0,37	0,32	0,56	0,33	0,34	0,18	0,14	**32**
Slope	0,19	0,16	0,07	0,26	0,29	0,18	0,09	**18**
Drainage Density	0,09	0,32	0,14	0,11	0,11	0,24	0,09	**16**
Distance to powerlines	0,04	0,02	0,05	0,04	0,01	0,30	0,36	**12**
Flow Accumulation	0,06	0,03	0,07	0,26	0,06	0,02	0,18	**10**
Soil Type	0,12	0,05	0,04	0,01	0,17	0,06	0,09	**8**
Elevation	0,12	0,08	0,07	0,00	0,01	0,03	0,05	**5**

Through a normalization process in Table 3-4, the weights are calculated to assign a percentage-based significance to each factor. The normalized weights represent the relative influence of each factor in the overall decision-making process. It's worth highlighting that these comparisons in Table 3-3, were not obtained through direct consultations with experts. Instead, the basis for these comparisons were drawn from existing studies within the same domain from authors mentioned in section3.2.This approach ensured that the weightings assigned to different criteria and factors are influenced by the collective knowledge and insights available in the related literature, contributing to a well-informed and organised analysis.

3.5 Weighted Sum Overlay

The criteria underwent resampling to achieve a uniform cell value and were subsequently reclassified and overlaid using the Weighted Overlay tool. The resulting output was categorized into five classes, namely: extremely high, high, moderate, low, and extremely low. The weighted overlay approach enables the computation and execution of a multi-criteria analysis involving sets of raster layers. It's essential that all these raster layers collectively account for a total influence of 100 percent. When the input rasters have been previously reclassified to a standardized measurement scale using the reclassify tool, it becomes crucial to select an evaluation scale that aligns with these reclassified raster layers. To consolidate these raster layers into a single analysis, each cell's criteria were transformed into a shared preference scale, ranging from 1 to 5, where 5 represents the extremely suitable condition. The input raster layers were assigned percentage weights derived from the AHP by directly comparing the relative importance of one criterion to another. Figure 4-9 illustrates the resulting spatial distribution, indicating potential sites suitable for siting of SHP dams.

4 RESULTS AND ANALYSIS

In regions characterized by elevated drainage density values, there exists a greater potential to harness and capture the abundant flowing water within the channel by constructing hydraulic structures across the watercourse (Zewdie & Tesfa, 2023). In this study drainage density is reclassified into five categories, from barely suitable to extremely suitable using the reclassification tool on ArcGIS Pro 3.1.0. According to Figure 4-1 , the eastern side of Western Cape watershed show a substantial location of sites with extremely suitable drainage density and the western side having fewer sites with extremely suitable site.

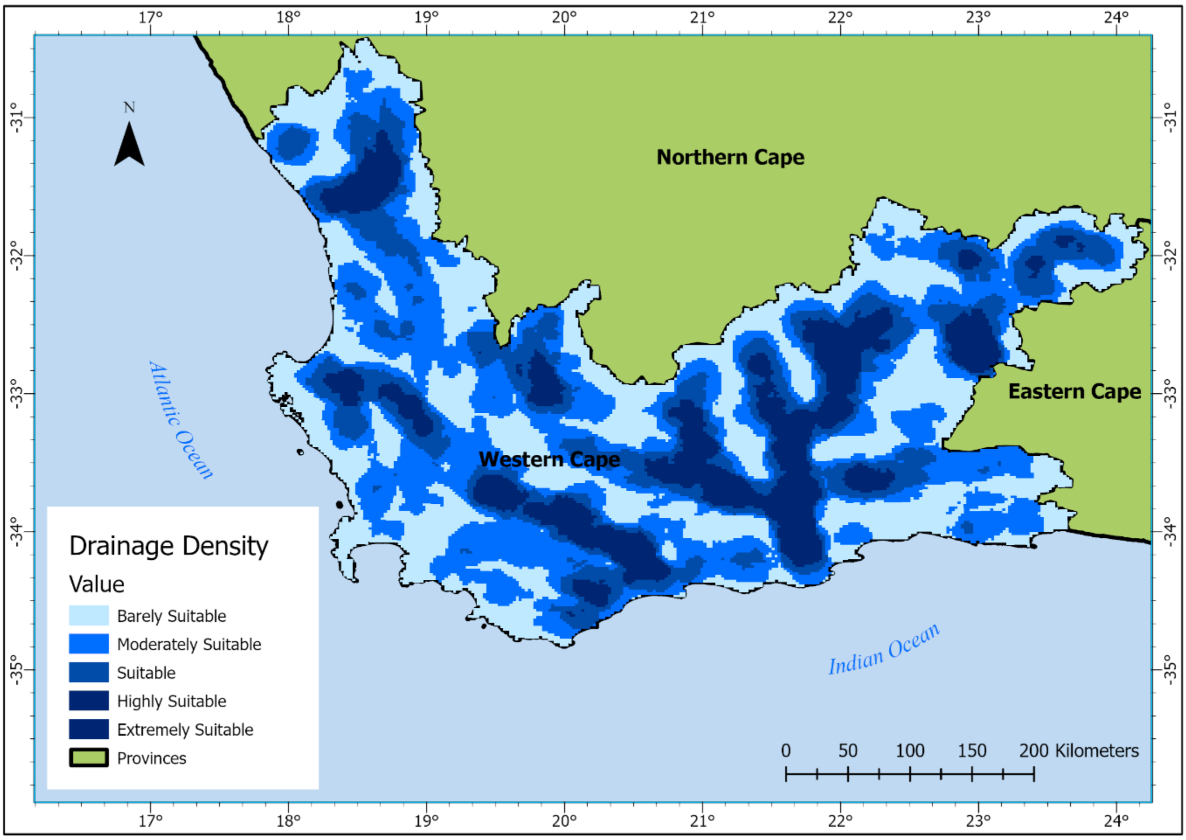

Figure 4-1 DRAINAGE DENSITY SUITABILITY INDEX

The slope in degrees was reclassified into five categories, with slope <5 degrees being the most favourable and slope > 39.2 the less favourable. According to Figure 4-2, most of Western Cape slope is steeper in the central part and gentler as you move away from the centre.

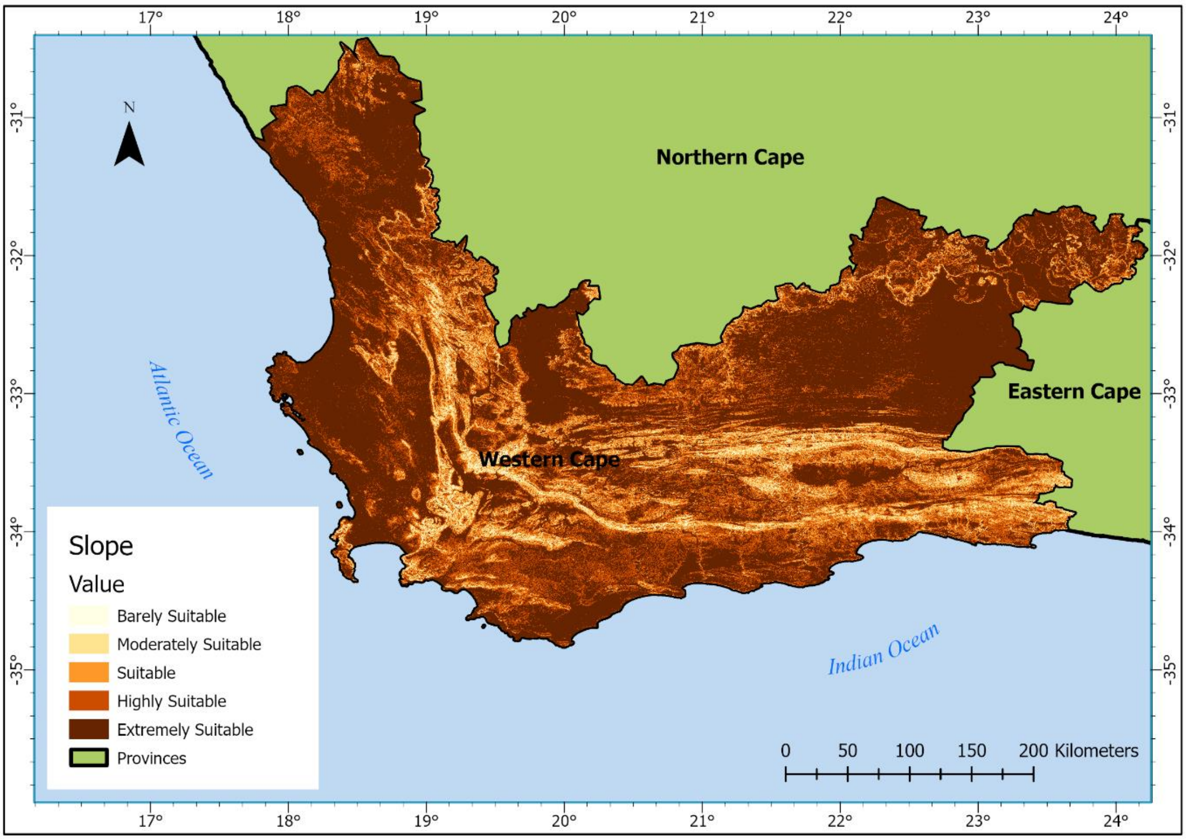

Figure 4-2 SLOPE SUITABILITY INDEX MAP

The elevation data was also reclassified into five distinct categories as referenced in Table 3-2 .According to Figure 4-3 the western and southern part of Western Cape region elevation is the mostly favourable site for SHP and the eastern part having more less favourable elevation for SHP development in the whole region.

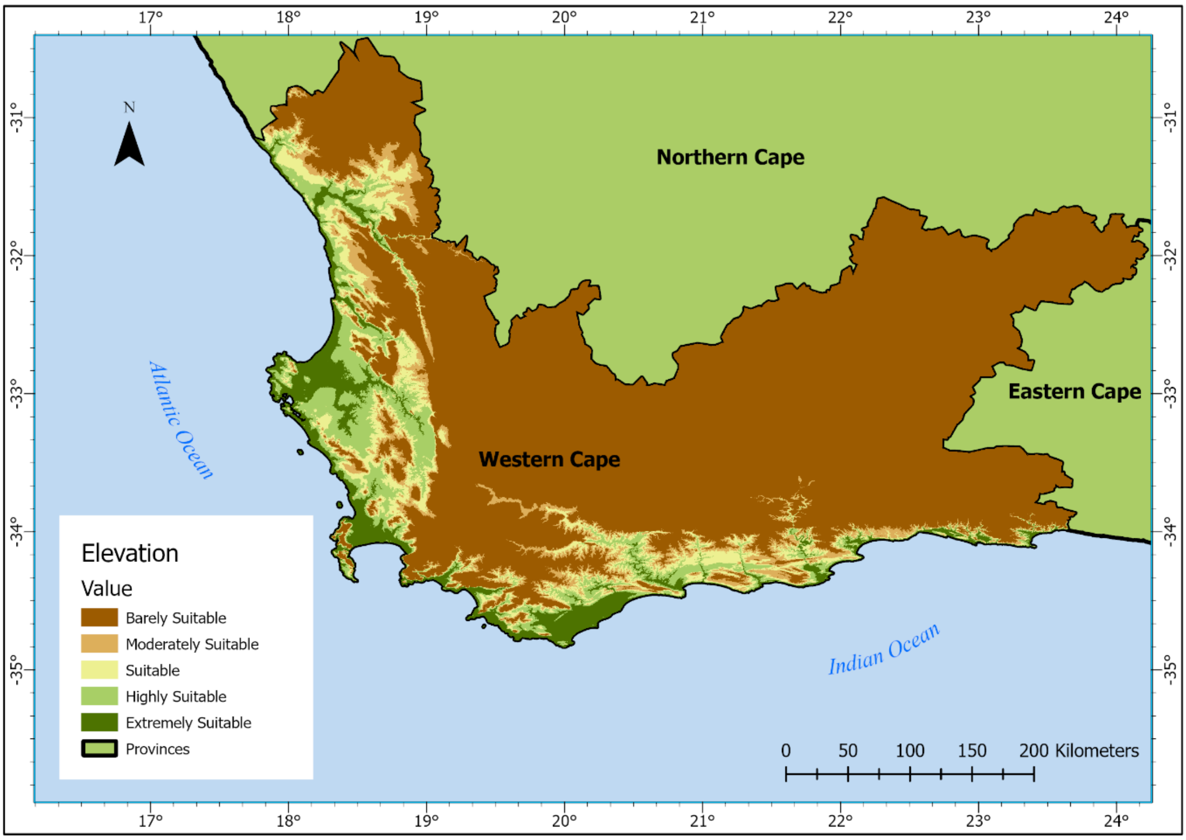

Figure 4-3 ELEVATION SUITABILITY INDEX MAP

In the Western Cape Region, the annual Rainfall from 2015 to 2019 ranged from 627 mm to 3814 mm. To facilitate decision-making regarding the suitability for dam construction, these values have been reclassified into five distinct levels, as referenced from Table 3-2. Most portion of the study are showed to have an extremely suitable average Rainfall for SHP.

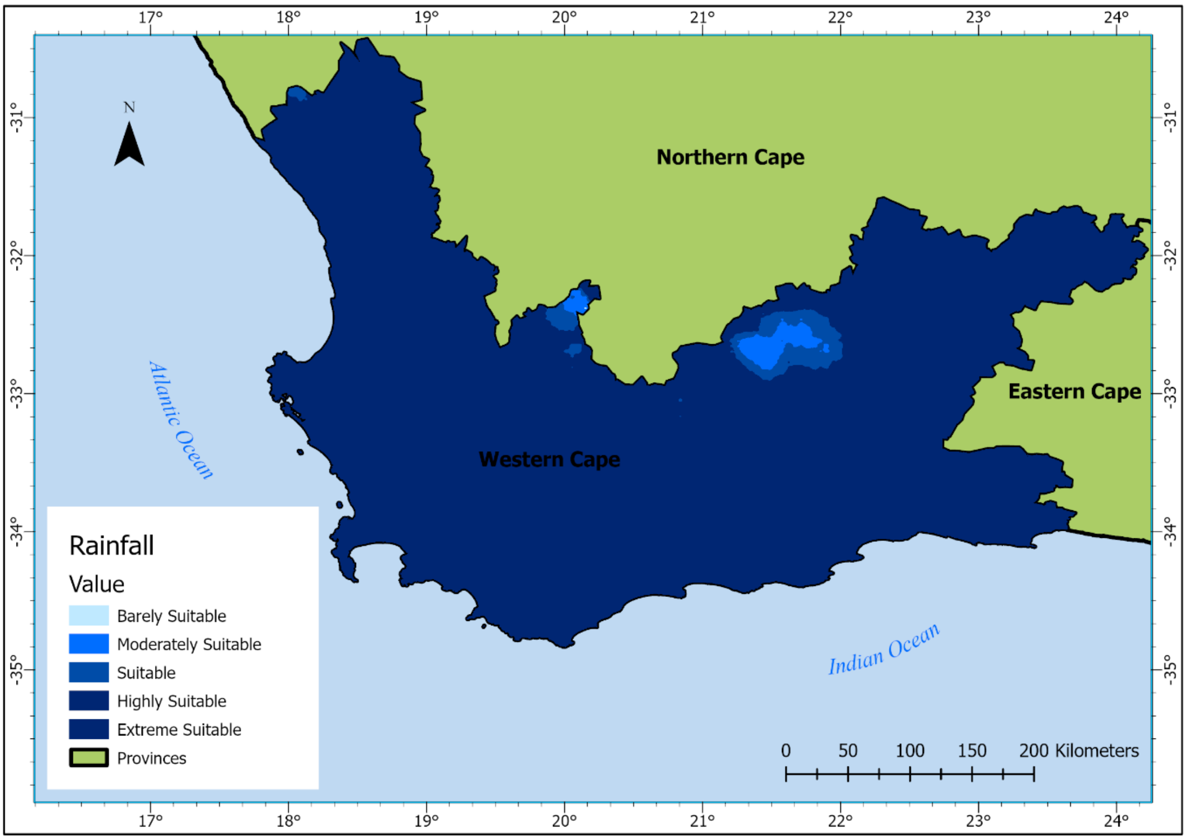

Figure 4-4 RAINFALL SUITABILITY INDEX MAP

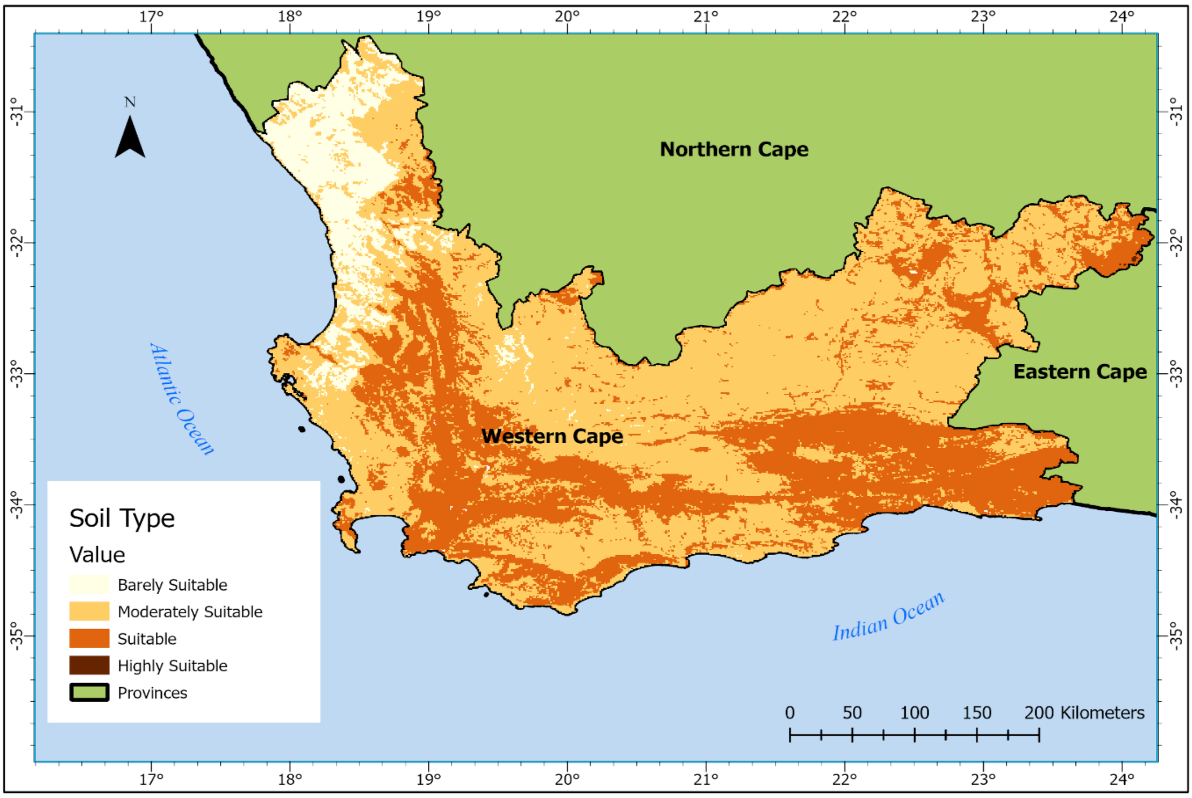

Figure 4-5 SOIL SUITABILITY INDEX MAP

The soils in the Western Cape were initially categorized into four distinct groups. These were subsequently reclassified into four categories, spanning from areas that were only marginally suitable to those that were highly suitable for SHP development. However, the absence of clay soil texture meant that there were no locations deemed extremely suitable for SHP installations. Referred from Table 3-2, Figure 4-5 reveals that Western Cape predominantly features highly suitable soil throughout most of its territory. However, in the central and southeastern regions, there is a prevalence of soils categorized as suitable for SHP.

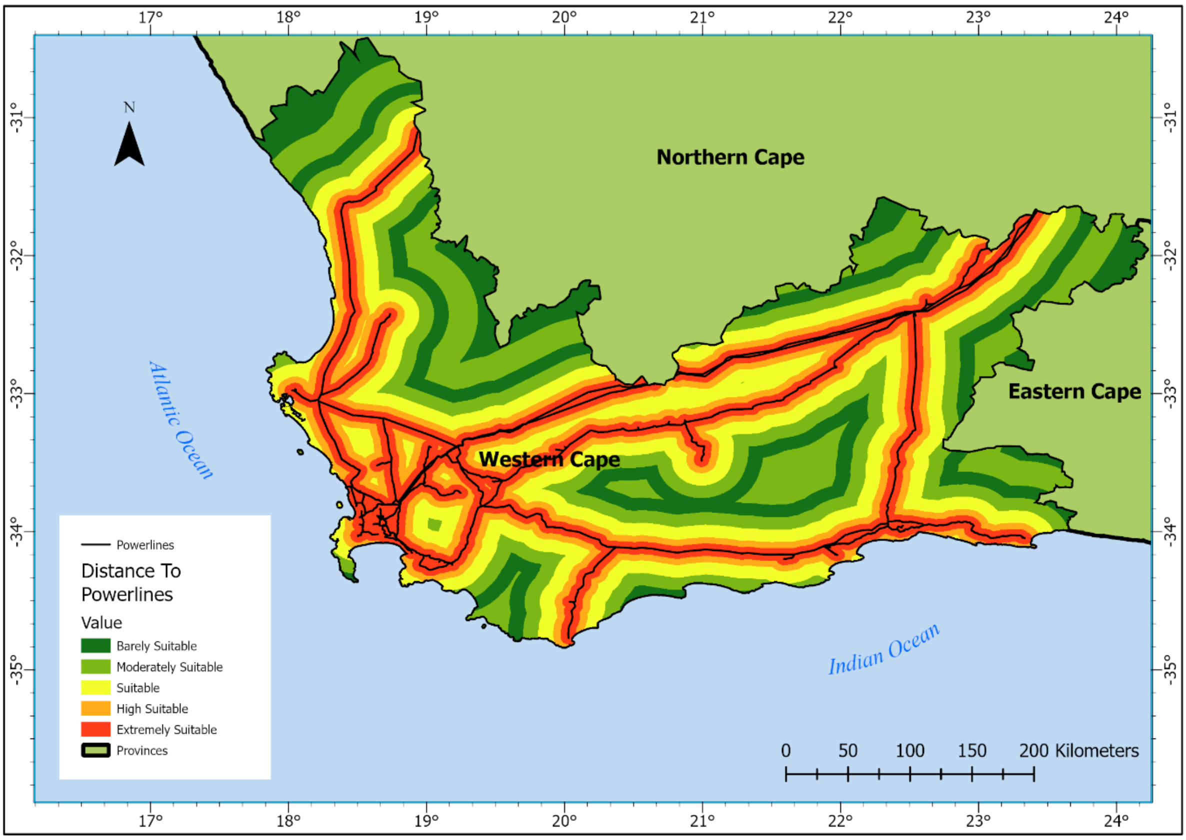

Figure 4-6 DISTANCE TO POWERLINES SUITABILITY INDEX MAP

For Proximity to Powerlines, the process began by creating multiple ring buffers around the existing powerlines. Subsequently, these buffers were clipped to match the study area's extent. Following this, the data was converted into a raster format and resampled to a 30-meter resolution. Finally, the information was reclassified into categories ranging from areas with minimal suitability to those considered extremely suitable for the intended purpose. According to Figure 4-6 in the southwestern part of Western Cape there is a concentration of powerlines, thus it has a highly favourable region when it comes to distance to powerlines, the powerlines.

4.1 Suitable Areas Identified

The map's generation involved the integration of multiple datasets, including elevation, average rainfall, distance to powerlines, flow accumulation, slope, soil type, and drainage density data. The weighting system derived from Table 3-3 played a pivotal role in combining these datasets, assigning relative importance to each criterion in the context of SHP site selection. Through a weighted overlay analysis, I harmonize these datasets to calculate an overall suitability score for each location. This score represents the site's suitability for SHP development, with higher scores to flow accumulation and Rainfall indicating a more favourable combination of criteria. The resulting suitability map serves as a decision support tool for stakeholders involved in SHP project planning and development within the Western Cape region. It not only identifies potentially suitable areas but also provides a clear spatial representation of the varying degrees of suitability. Figure 4-7 shows an illustration of the suitability index in a pie chart.

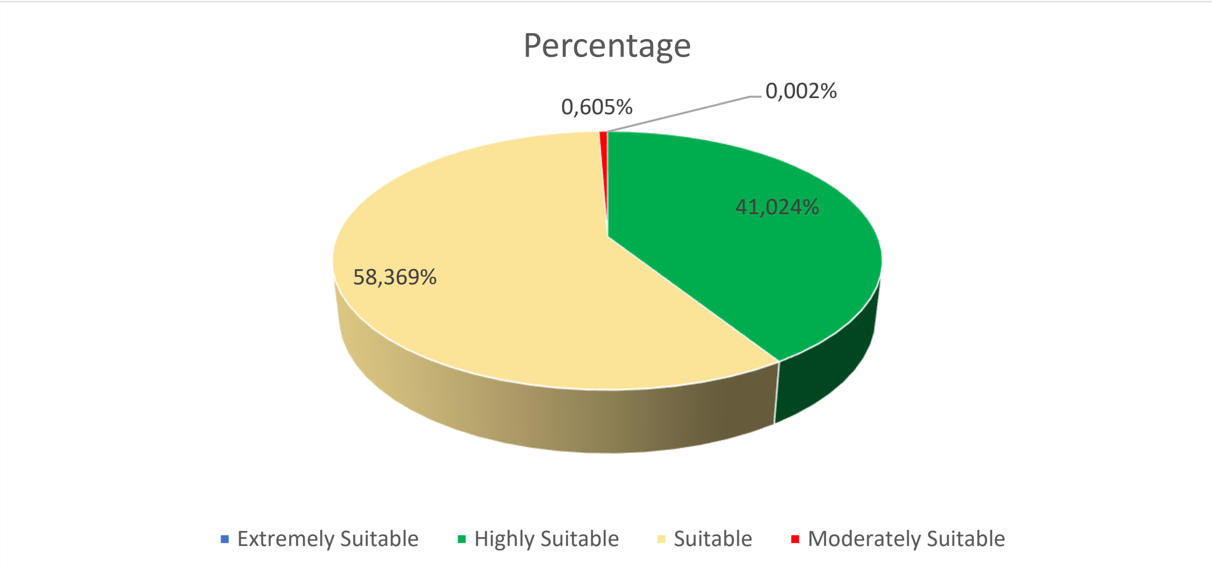

Figure 4-7 ILLUSTRATION OF THE SUITABILTY INDEX IN PIE CHART.

Figure 4-9 presents the suitability map, a critical component of this study, showcasing potential SHP sites within the Western Cape region. This map offers a visual representation of areas of application of the proposed criteria and weighting system, as stated in Table 3-3.It was found that extremely suitable class make up to 0.3285 ha (0,002%) of the watershed. The majority of the extremely suitable is located directly in the stream channel in the south along the Breë and Gourits River making it hard to visualize, while 5851.7357 ha (41,024%) of highly suitable class is spread across the watershed with mostly situated along the major rivers but only at the end of Olifants river. The suitable class accounts for 8325.8239 ha (58,369%) and it is the most dominant class spread proportionately across the watershed. The moderately suitable make up 86.2648 ha (0,605%) of the watershed occurring in most areas far for the major rivers in the northern part of Western Cape.

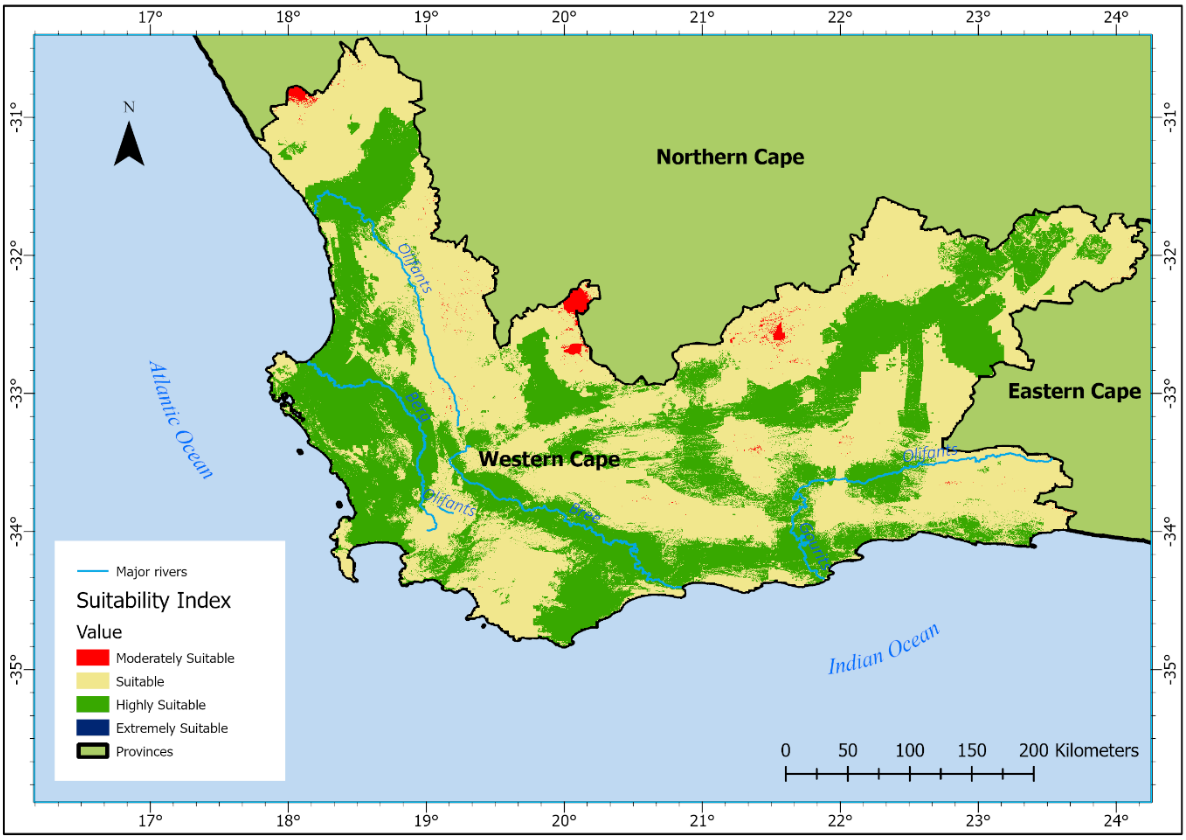

Figure 4-8 OVERALL SUITABILITY INDEX OF POTENTIAL SHP SITES

Additional layer of Stream order was placed on top of the map which is a crucial hydrological factor as it provides valuable insights into the flow network hierarchy within the region, helping in better understand the drainage patterns and the potential accumulation of water. Figure 4-9 shows the overlayed suitability index map with stream order.

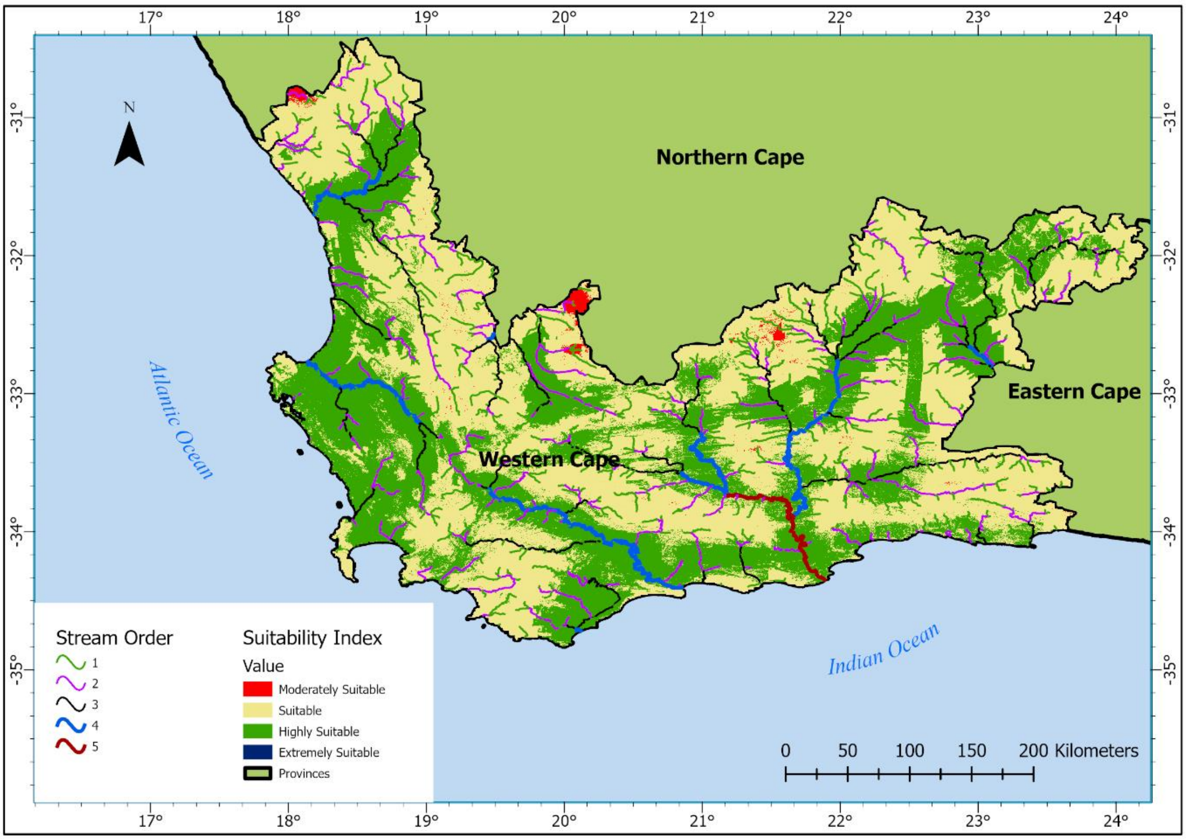

Figure 4-9 SUITABILITY INDEX MAP OVERLAYED WITH STREAM ORDER

4.2 Validation

This section adopted a robust validation process to affirm the reliability of SHP site suitability analyses, addressing objective 5 and research question 5a and 5b as mentioned in 1.4 . To accomplish this, the locations of existing SHP dams within the Western Cape region were examined. The purpose of this validation was to determine whether the actual placement of operational SHP dams aligned with desired suitability levels, which are specifically "highly suitable" and "extremely suitable" and exclude those that fall in suitable, moderately suitable and barely suitable. Figure 4-10, below shows the location of existing SHP relative to the suitability index map for this study.

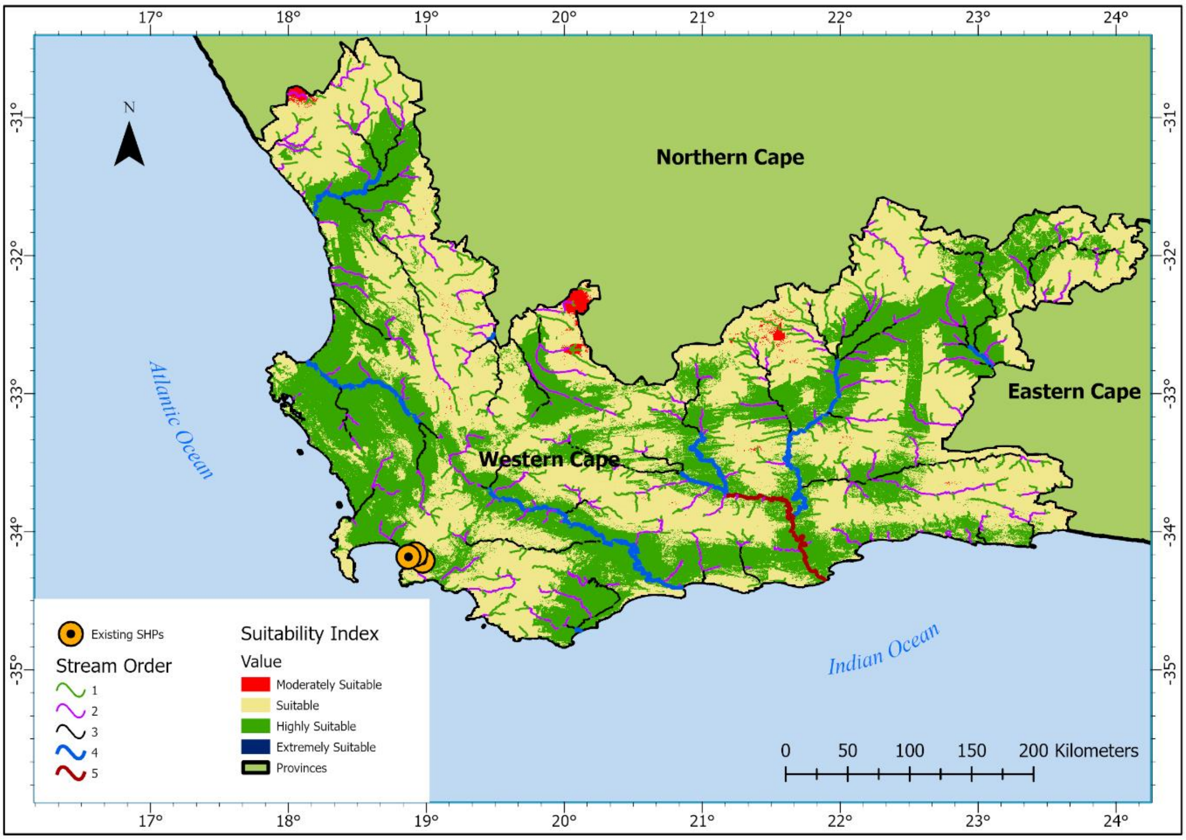

Figure 4-10 DISTRIBUTION OF EXISTING SHP DAMS

Western Cape has 40 dams (see Figure 4-11), with only three SHP dams which are pumped hydro-electric power. To validate my criteria, Figure 4-10 above was used to illustrate the suitability of the existing SHP and cross referencing them with the existing potential site on my analyses. Table 4-1 shows the attributes of the existing SHP.

These findings revealed a noteworthy consistency between the locations of the existing SHP dams and the suitability categories identified in my analyses. Specifically, the operational SHP dams are situated in areas designated as "Highly suitable" for SHP development, with an exceptional elevation of less than 55 m as mentioned in section 3.3. However, these existing SHP are located on a poor stream order because they rely on their reversible pump/turbine systems that are integral to transferring water between different catchment areas (Generation Communication, 2017).This validation not only underscores the accuracy and relevance of this suitability assessments but also carries substantial implications for the future of SHP development in the Western Cape region. It serves as a strong indicator that this suitability mapping, emphasizing these specific categories, effectively identifies regions with genuine potential for successful SHP projects.

Table 4-1, provides key characteristics of existing SHP dams within the Western Cape region. These established SHP dams serve as tangible examples of successful SHP projects in the area. This table includes information such as dam names, river supplying the SHP dams, geographical coordinates, elevation levels, primary purposes, suitability levels, and stream orders. By examining these existing SHP dams attributes, we aim to draw insights and lessons that can be applied to our research.

Table 4-1 CHARACTERISTICS OF EXISTING SHP DAMS

No	Names of Dams	River supplying	Location	Elevation(m)	Purpose	Suitability Level	Stream Order
1	Kogelberg	Palmiet River	34°12′57″S 18°58′31″E	54	Power generation	Suitable	1
2	Steenbras(upper)	Steenbras River	34°10′5″S 18°54′5″E	34	Power generation	Suitable	1
3	Steenbras(lower)	Steenbras River	34°11′12.61″S 18°51′9.11″E	28	Power generation	Suitable	1

4.3 Proposed Dam Sites For SHP Development

This section is dedicated to identifying dams that strictly meet the defined criteria for SHP development. Figure 4-11, depicting existing dams in the Western Cape, serves a crucial purpose in this study. It allows assessing how these established dams align with the SHP analysis. This alignment is significant as it provides valuable insights into the overarching goal, which is to identify suitable sites for SHP dam construction. By evaluating the compatibility of existing dams with the analysis, a clear understanding emerges of whether potentially repurposing these dams that meet the SHP requirements for this study or suggesting new ones.

This approach is cost-effective and environmentally sustainable because it enables making the most of the resources at hand rather than constructing entirely new dams. In essence, Figure 4-11 helps in making informed decisions about the optimal utilization of existing resources to meet the SHP needs outlined in the analysis.

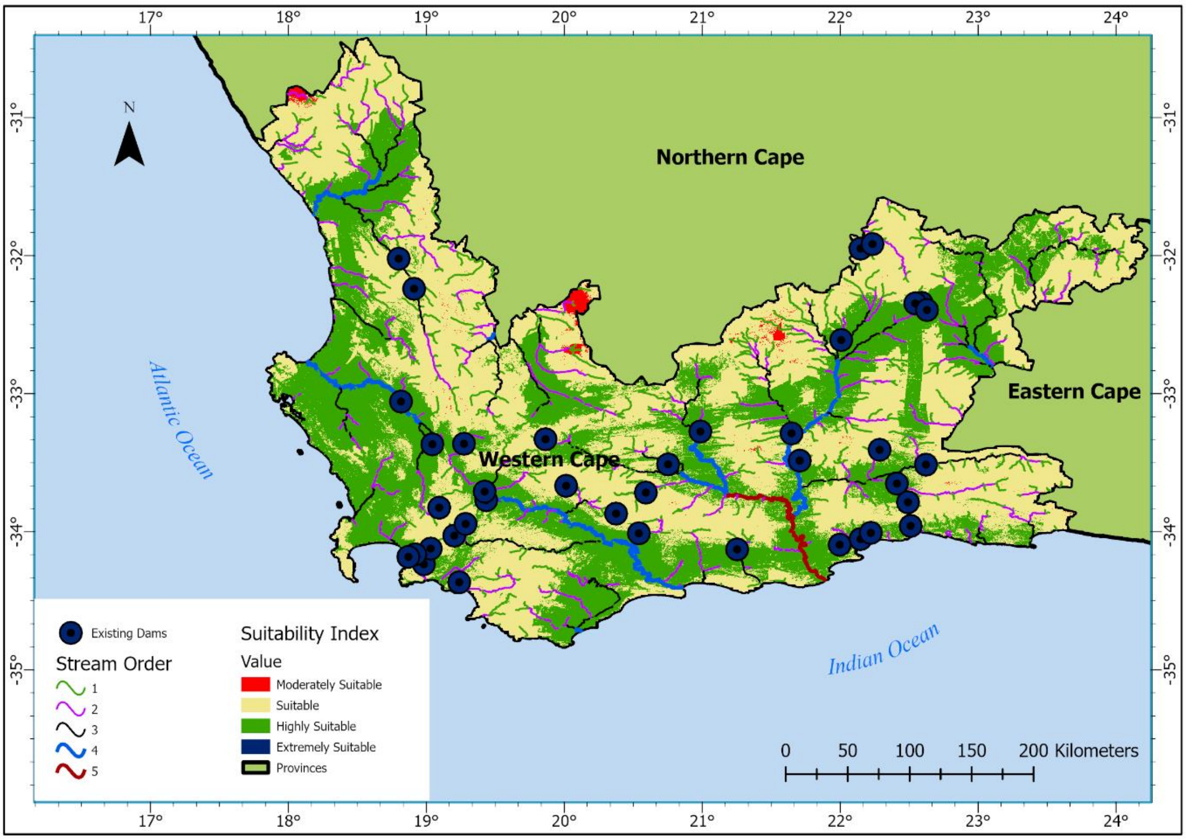

Figure 4-11 EXISTING DAMS ACROSS THE STUDY AREA

Figure 4-12 displays a selection of existing dams meeting the criteria of having a stream order greater than 3 and falling into the 'Highly Suitable' or 'Extremely Suitable' categories. A two-step selection process was applied: first, selection by Attributes SQL query was used to identify sites with stream order > 3 and the highly/extremely suitable classes. Subsequently, a selection by location query operation was performed to see where these two criteria intersect. This refined selection highlighted 13 strategically located dams (including existing ones) that meet the specified criteria, emphasizing their significance in the context of this research. Figure 4-12 shows the 13 strategically located dams in the watershed.

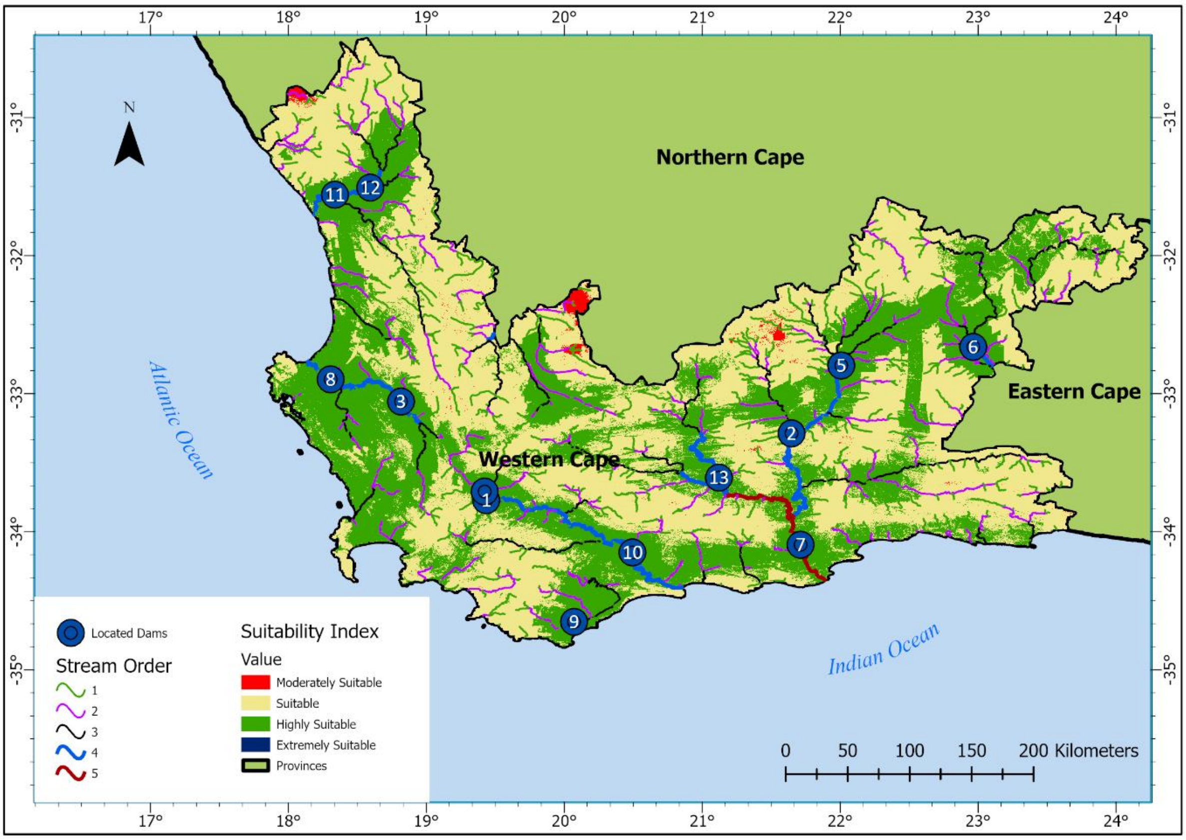

Figure 4-12 ALL LOCATED SHP DAMS

Most of the existing dams in the Western Cape region are situated in locations classified as 'suitable' and 'highly suitable' according to the geographical suitability assessment. However, upon closer examination, since this classes on the suitability map are not point location but irregular polygons, a key differentiation is identified in terms of elevation variations exceeding 109 meters. The study, specifically designed to find locations that meet the stringent criteria for SHP potential, places a strong emphasis on the combination of being either 'highly suitable' or 'extremely suitable' while also having a stream order of 4th or 5th and an elevation of less than 109 meters. This set of criteria is essential for harnessing the maximum hydrological potential for SHP projects.

Additionally, from the located dams map, Figure 4-13 showcases a carefully curated selection of dams that fulfilled the specific geographic and suitability criteria. Since my criteria specifically aimed at locating only highly suitable and extremely suitable sites with strictly an elevation <109 m as mentioned in section 3.3.From these located dams (see Figure 4-12) a SQL queries was done to extract dams with specifically an elevation < 109. Six dams were pinpointed to locations specifically meeting all the requirements, and their attributes are presented in Figure 4-13. These dams presented are final and meet all the desired specification of the analysis.

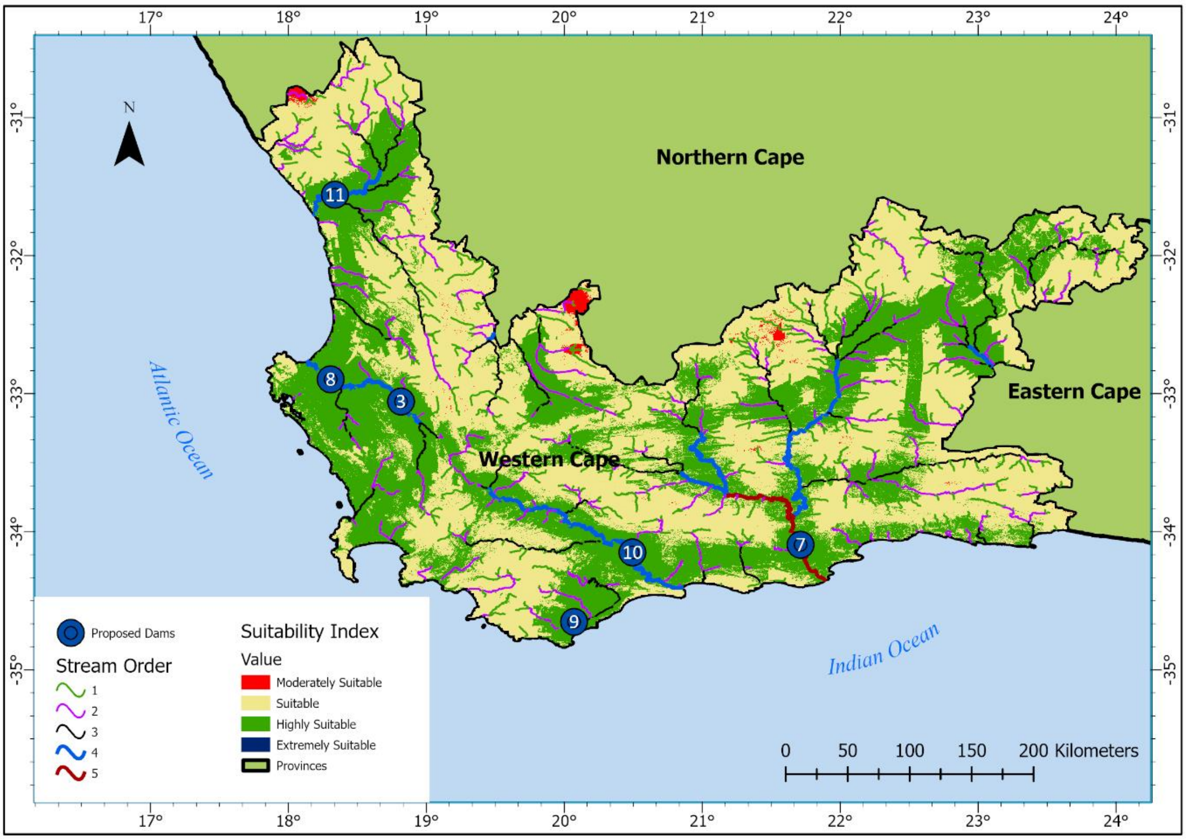

Figure 4-13 FINAL PROPOSED SHP DAMS

Regrettably, most of already existing dams in the Western Cape predominantly do not meet all these specific SHP criteria. However, it is worth noting that one exception stands out the "Misverstand dam". This dam is the sole existing structure that aligns perfectly with the conditions outlined in the study, making it an ideal candidate for potential SHP development. All the other are newly located dams and are given dam numbers (refer to Table 4-2). Table 4-2 accurately shows proposed dam sites that strictly meet the specific criteria, exclusively selecting locations deemed "highly suitable" and "extremely suitable". This filtered subset comprises dam number/name designations, precise X and Y coordinates, major river which the SHP dam is in, and elevation information, offering a comprehensive spatial perspective. Additionally, the table includes the crucial stream order attribute, shedding light on the hydrological significance of each prospective site. These attributes collectively represent a meticulous spatial analysis, enabling to pinpoint the most promising locations for potential dam construction for SHP, considering both geographical suitability and hydrological relevance.

Table 4-2 FINAL PROPOSED SHP DAMS ATTRIBUTE TABLE

Dam no/name	***Suitability level***	***Stream Order***	***Major river***	***X-Coordinates***	***Y-Coordinates***	***Elevations (m)***
Misverstand (3)	Highly Suitable	4^{TH}	Berg	18.81643	-33.0568	50.01788
7	Extremely Suitable	5^{TH}	Gourits	21.71279	-34.094	74.46106
8	Highly Suitable	4^{TH}	Berg	18.30619	-32.896	3.698746
9	Highly Suitable	4^{TH}	-	20.0708	-34.6526	9.075583
10	Highly Suitable	4^{TH}	Bree	20.4939	-34.1494	85.4553
11	Highly Suitable	4^{TH}	Olifants	18.33729	-31.5588	12.83275

5 DISCUSSION & CONCLUSIONS

Objective 1 was to identify suitable criteria for siting SHP with its associated research questions (1a, What criteria have been used by others in SHP site selection? and 1b, which criteria are suitable for this study's context?) have been addressed in Chapter 2. The literature review conducted in Chapter 2 provided insights into the criteria that have been utilized in prior SHP site selection studies. Several criteria were identified, such as flow accumulation, slope, soil type, elevation, drainage density, rainfall, and distance to powerlines, distance to roads, distance to settlements, curve number, geology and geomorphology. Of these criteria, the following were selected as being most relevant to this study: flow accumulation, slope, soil type, elevation, drainage density, rainfall, and distance to powerlines.

Objective 2 was to define a suitable method for siting SHP, with its associated research questions (2a, What methods have other researchers doing similar studies used? and 2b, What methods have other researchers doing similar studies used?) have been addressed in Chapter 3. Chapter 3 outlines the development of a robust methodology for the systematic selection of SHP project sites. The chosen approach integrates GIS with the AHP. This structured and comprehensive framework facilitates the identification of promising SHP sites based on the criteria defined in Chapter 2.

Objective 3 was to source suitable data for analysis according to the defined criteria with its reseach questions (3a, what data sources have other researchers doing similar studies used? and 3b, which of these data sources are relevant to the Western Cape context? and 3c, are these data sources freely available, or are there suitable substitutes?) have been addressed in Chapter 3 section 3.1.2. This section details the rigorous process of identifying and sourcing data that align with the criteria defined in Chapter 2. The original collected data was carefully selected to ensure accuracy and reliability, from open-access platforms, integral to the integrity of the subsequent analyses. Objective 4 was to analyse the data using the chosen method and according to the defined criteria, have been addressed in Chapter 4. Chapter 4 involved the careful analysis of the data collected in Chapter 3 section 3.1.2. Through the chosen GIS-AHP methodology, actionable insights through a composite map have been derived to inform the selection of SHP project sites.

Objective 5 was to validate the results against existing SHP locations, with its research questions (5a, how do the results compare to existing SHP locations? and 5b, where there are differences, how can these be explained?) have been addressed in Chapter 4. Chapter 4 also focuses on the validation of the suitability analyses. The comparison of the locations of existing SHP dams with the predefined suitability categories demonstrated the effectiveness of the approach and presented significant implications for the future of SHP development in the Western Cape region.

In summary the study considered seven key parameters for the suitability modelling of SHP dam sites. These parameters encompass flow accumulation, slope, soil type, elevation, drainage density, rainfall, and distance to powerlines. The integration of these factors using GIS and AHP yielded insightful results. Specifically, the analysis revealed that the areas classified as "extremely suitable" constituted a mere 0,002% of the entire watershed, while "highly suitable" areas accounted for 41,024%. This outcome serves as a preamble to understanding the spatial distribution of potential SHP dam sites within the watershed. Furthermore, it underscores the substantial untapped SHP potential in the region. If harnessed effectively, this potential could offer cost-effective electricity solutions to the local population residing within the watershed. Many of these residents currently lack access to the grid and face challenges related to regular power supply. The geographical distribution of SHP potential can significantly contribute to rural electrification planning and improve access to affordable, dependable, sustainable, and modern energy, as outlined in Goal 7 (Affordable and Clean Energy) and Goal 9 (Industry, Innovation, and Infrastructure) of the Sustainable Development Goals (SDGs). Additionally, the use of SHP supports Goal 13 (Climate Action) by reducing greenhouse gas emissions and promoting sustainable energy practices.

It is essential to highlight that this study should not serve as the sole basis for the definitive selection of SHP dam sites. Detailed on-site geotechnical investigations at the suggested locations are imperative. Nevertheless, by excluding sites with exceedingly high elevations, the study has pinpointed potential sites that warrant further exploration. These areas hold promise for conducting in-depth assessments required for the design and construction of the dam.

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