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Multicriteria decision method for renewable energy production: siting solar, wind and small hydropower plants in Zimbabwe

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Abstract

Energy development in Zimbabwe has not been coincident with the rising demand for energy, thus placing a large strain on existing resources. The National Renewable Energy Policy states that by 2030, Zimbabwe should to some extent be driven by clean and sustainable energy sources. In support of this initiative, this study sought to identify suitable locations for renewable energy production plants (solar, wind and small hydropower) in Zimbabwe. The Analytic Hierarchy Process (AHP) was used to evaluate the decision criteria. A raster-based suitability model was constructed using the decision criteria, and areas showing suitable sites to install wind, solar and small hydropower (SHP) plants were identified. The results showed that suitable sites for small-scale wind turbines are in the Beitbridge rural district covering a land area of approximately 12 719 km^2. Hwange rural was found to be the district with a large potential for siting solar power plants with a land area of approximately 26 974 km^2. Several river channels distributed throughout the country were identified as potential sites for establishing SHP plants. The main contributions of this paper are the identification of the evaluation criteria and suitable sites for wind, solar and SHP plants in Zimbabwe.

***Keywords**: Geographic Information System (GIS); multicriteria decision method (MDCM); renewable energy; site suitability analysis; analytical hierarchy process (AHP)*

1. Introduction

Increasing urbanisation and insufficiency of investment in modern energy sources are placing Zimbabwe's energy sector under stress. The energy supply for Zimbabwe is a mixture of coal, hydroelectricity, and a small percentage of other renewable energy sources such as wind and solar (Makonese, 2016). Coal-fired power stations in Zimbabwe require major upgrades as they are subjected to frequent production stops or are not producing at all. Energy imports from neighbouring countries (which are facing their own energy crises) are insufficient to overcome the low-capacity problem, resulting in power cuts that affect the economic performance of industries and services (Chirisa & Ncube, 2020).

Crippling power shortages have led to the formulation of Zimbabwe's National Renewable Energy Policy (NREP) under the overall framework laid out by the National Energy Policy (NEP) of 2012, which recognises that by 2030 the economy needs to be driven to a certain extent by clean and sustainable energy sources (Republic of Zimbabwe, 2019). The Zimbabwe Voluntary National Review (VNR) of Sustainable Development Goals (SDGs) reveals that the government has fully devoted itself to achieving the sustainable development goals ─ a universal call-to-action to end poverty, preserve the planet and ensure that people enjoy peace and prosperity (Voluntary National Review, 2017).

Energy is one of the most important components of any long-term development strategy; increasing energy output from renewable sources can directly contribute to poverty alleviation (Li, Yang & Lam, 2013). Adequate access to energy makes it possible to grow and prepare food in sufficient quantities to avoid hunger and malnutrition (Struble & Aomari, 2003). Food, water and energy are inextricably linked: food production needs water, and energy is needed for water extraction, its treatment and distribution (Hussey & Pittock, 2012). The pollution of the air and water caused by the use of fossil fuels has been linked to breathing problems, neurological damage, cancer and a slew of other health concerns (Bagher et al., 2016). Making energy access inexpensive means that most rural and urban homes can easily and affordably join the national electrical network. Reliable energy is required for equitable development (Park, 2012).

The study's aim is to find optimal locations for renewable energy production plants (solar, wind and SHP) in Zimbabwe, in accordance with the NREP. The existing situation is that the country relies heavily on the carbon intensive model and the desire is to shift to renewable energy production (Makonese, 2016). Developing raster-based suitability maps that show the optimal locations for these plants has the potential to contribute to the development of renewable energy in Zimbabwe. This research can also assist in determining the country's alternative renewable energy potential. The study seeks to determine the minimum criteria for effective wind, solar and small hydropower energy production in Zimbabwe. The second objective is to identify areas in Zimbabwe that meet the criteria for efficient wind, solar and small hydropower.

Zimbabwe is a landlocked country in southern Arica with a population of about 14 million people and a total land area of approximately 390 757 km^2. Most of the country is elevated, with a central plateau extending from the southwest northwards and reaching heights of 1 000 to 1 600 metres above sea level. The country has a tropical climate and high humidity, with the southern areas being recognized for their warmth and aridity, while the eastern highlands have cool temperatures and the country's highest precipitation (Baruya & Kessels, 2013).

Zimbabwe is currently divided into 10 administrative provinces, two of which are cities with provincial status. In this study, the analysis focuses on the district level, which is the third level of administration. Using districts helps to precisely locate the areas that are identified as suitable for the siting of wind, solar and SHP power plants. The largest district in Zimbabwe is Hwange with an estimated land area of 29 688 km^2 and the smallest is Chitungwiza with an estimated land area of 63 km^2.

2. Materials and Methods

The methodology followed in this study is illustrated in Figure 1 and further described below. Drawing on relevant literature, we determined the criteria for siting renewable energy plants and their appropriate scores. These were then weighted using the AHP method. Exclusion zones were identified, and all datasets were processed using Model Builder. Suitable sites for each of the renewable energy production methods were thus identified. Each of these steps is explained further below.

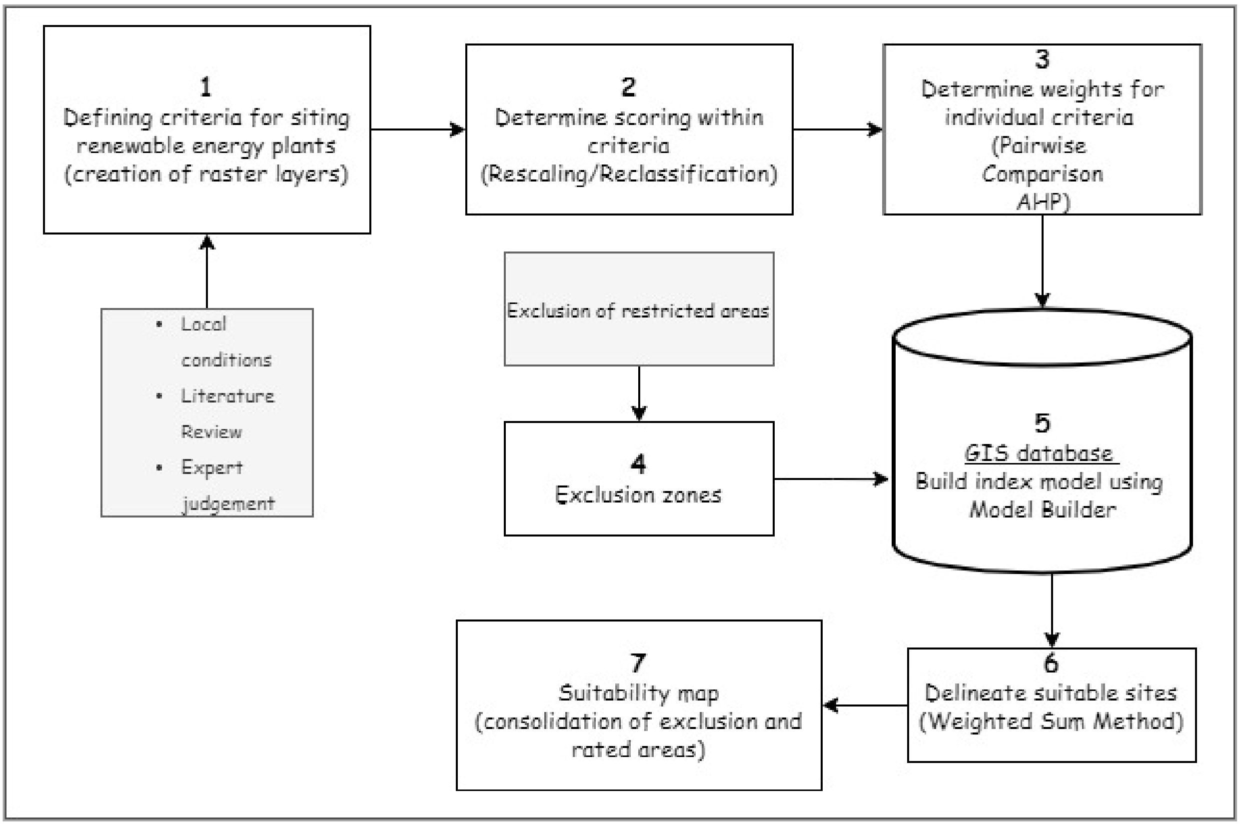

Figure 1: Methodological framework for siting wind, solar and small hydro power plants

2.1. Site selection criteria

Social, environmental, economic, and technical considerations all influence the suitability of a site for power production. These variables are influenced by the physical topography, the existing infrastructure, factors such as proximity and location, and land-use restrictions and laws (Brewer et al., 2015). The site selection criteria can be constructed using literature that complies with national and international standards and guidelines (Ramachandra & Shruthi, 2007; Van Haaren & Fthenakis, 2011; Sunak et al., 2015).

2.1.1. General criteria

The following are considerations that apply to the location of wind, solar and SHP plants.

- Proximity to the existing power grid – To cut down on construction costs and minimise power loss over transmission, power production plants should be sited as close to the existing grid as possible (Baseer et al., 2017; Palmer, Gottschalg & Betts, 2019).
- Proximity to roads – The costs of construction and maintenance are reduced by ensuring that the proposed power production plant is located close to the existing road networks (Sliz-Szkliniarz & Vogt, 2011; Latinopoulos & Kechagia, 2015).

- Proximity to settlements – Wind turbines can be perceived as unsightly by some, and the rotating blades contribute to noise pollution (Van Haaren & Fthenakis, 2011). Similarly, solar power plants alter the landscape in practical ways and compromise the aesthetics of the environment (Uyan, 2013). Although SHP plants do not contribute to the same extent to visual and noise concerns, it is considered practical to locate power production plants away from existing settlements to allow for settlement expansion.

2.1.2. Wind power plants

The most important criterion to consider when siting a wind power plant is the promise of wind. The parameter that captures wind power potential at a site is the average wind speed (Ackermann, 2005). Acquiring sufficient data on wind speed and the wind power density of the area makes it possible to identify optimum locations for power plants (Solangi et al., 2018). Climate conditions also play a critical role where the performance of a wind turbine relies on the weather conditions at the site. The additional factor to consider is that wind speed must be consistent throughout the year (Pryor & Barthelmie, 2010). The average interpolated wind speed criterion has been given the highest weighting in several reviewed studies (Janke, 2010; Sliz-Szkliniarz & Vogt, 2011; Van Haaren & Fthenakis, 2011; Baseer et al., 2017).

Wind turbines may have a negative impact on wildlife; hence, wind farms should not be located near sensitive wildlife / ecological areas (Van Haaren & Fthenakis, 2011). The tactical location of wind turbines outside imperative breeding grounds and high wildlife population areas can ease their environmental impact.

Wind turbines are tall and can interfere with the flight path of aircraft as they take off or land. They can also interfere with signals of aviation radars; hence, it is important that they are placed away from airports (Baseer et al., 2017).

Slope has a high impact in establishing the optimum location for wind power plants. The allowable slope threshold ranges from 10% (Baban & Parry, 2001) to 30% (Tegou, Polatidis & Haralambopoulos, 2009). A threshold slope value of 10% is generally considered acceptable; hence, regions having higher slope values should be excluded from the surface analysis (Noorollahi, Yousefi & Mohammadi, 2016).

Elevation is another factor that affects the siting of wind power plants. This is because wind tends to blow faster and more consistently at higher altitudes (Sunderland et al., 2013).

2.1.3. Solar power plants

The most important factor for the establishment of a solar power plant is the level of solar irradiation. It may be generally represented as global horizontal irradiance (GHI) which is the sum of direct normal irradiance (DNI), diffuse horizontal irradiation (DHI) and ground reflected irradiation (Yang et al., 2013). Regions with a high insolation capacity influence the placement of solar power plants. The concentration of radiation determines the magnitude of the electrical output from the system

(Janke, 2010). The solar systems addressed in this study include both concentrated solar power (CSP) and photovoltaic (PV) technologies. The CSP technology makes use of lenses and tracking systems to focus a large portion of the sun's radiation into a small beam. Conversely, the PV technology uses solar cells to transform the solar radiation directly into electricity through the photovoltaic effect (Bagher et al,2016).

Land use assessments are required before establishing solar energy projects (Uyan, 2013). Most projects include slope and elevation as the basic topographical factors affecting the siting of solar power plants (Bennui et al., 2007; Janke, 2010; Latinopoulos & Kechagia, 2015). It is suggested that large scale solar power plants be established on flat terrain (Anwarzai & Nagasaka, 2017). Shorter vegetation is also preferred over taller vegetation to avoid the obstruction of incoming solar irradiation (Janke, 2010).

The direction of the solar panels plays a key role in determining the exposure of a plant to the received solar radiation (Kacira et al., 2004). In the southern hemisphere, solar panels must be oriented towards the geographic north to maximise the energy coming from the sun (Doorga, Rughooputh & Boojhawon, 2019).

The height of the region above sea level is inversely proportional to the viscosity of the atmosphere, which influences the solar potential (Doorga, Rughooputh & Boojhawon, 2019). The entry of long and shortwave energy is influenced by the density of the atmosphere and the compounds in the atmosphere (Noorollahi, Yousefi & Mohammadi, 2016). Atmospheric density is greatest at low elevations; hence, elevated areas experience a greater solar radiation potential than lower regions (Noorollahi et al., 2016).

2.1.4. Small hydropower plants (SHP)

The location of a river course is an important criterion in siting SHP plants. The modelling of a suitable site for a SHP plant critically depends on the availability of adequate information on the river channel, catchment area, river runoff and other relevant attributes (Kuriqi et al., 2019). The amount of energy produced by SHP depends on the flow of water and the elevation of the inlet (Nasir, 2014). Elevation data play a role in deriving other relevant topographical factors, such as the natural head, which are required to site SHP plants (Yi, Lee & Shim, 2010). Having a constant stream flow is also a crucial factor (Kuriqi et al., 2019). Hence, it is important to consider the precipitation levels associated with the different areas suitable for siting the plant. Runoff data is another important factor. It is derived from the precipitation data and also takes into account the losses of surface water through evaporation or infiltration.

2.1.5. Data types and sources

Table 1 displays the respective websites from which the relevant data types were sourced.

Table 1: Data types and sources

Wind	https://paepaha.pacioos.hawaii.edu/erddap/griddap/ncep_global.graph
Solar	https://globalsolaratlas.info/download/zimbabwe
Precipitation	https://www.worldclim.org/data/worldclim21.html
Road network	https://geonode.wfp.org/layers/geonode:zwe_trs_roads_osm
Airports	https://ourairports.com/data/
Electricity grid	https://datacatalog.worldbank.org/search/dataset/0039590
Settlements	https://data.humdata.org/dataset/zimbabwe-settlements
Elevation data	https://opendata.rcmrd.org/datasets/zimbabwe-srtm-dem-30-metres/
Waterbodies	http://geoportal.rcmrd.org/layers/servir%3Azimbabwe_rivers
Land cover	http://geoportal.rcmrd.org/layers/servir%3Azimbabwe_sentinel2_lulc2016

The identification of the criteria for analysis necessitated the collection of the associated data. This project was carried out from 2020-2021, during the global Covid-19 pandemic. Data acquisition at this time was difficult; hence, we relied solely on secondary data, as listed in Table 1 and as described below.

Wind data for Zimbabwe were extracted from weather forecast data generated by GOES-R satellite imagery. **Solar data** for Zimbabwe were sourced from the Global Solar Atlas, which is published by the World Bank Group. The solar resource map provides estimates of the solar energy available for power generation and other applications. The parameter used for energy yield calculation for concentrated solar power (CSP) and photovoltaic (PV) technologies in the study was the direct normal irradiance (DNI). The DNI denotes the long-term average of yearly/daily sum of direct normal irradiation at a nominal spatial resolution of 250 m. **Precipitation data** for Zimbabwe were downloaded from WorldClim, which is a database for high spatial resolution global weather and climate data. The variable of interest is the average minimum precipitation (mm) for 2010 - 2018 at a spatial resolution of 2.5 arc minutes. The **primary road network** of Zimbabwe was obtained from Open Street Map. The dataset consists of highway, primary, secondary, and tertiary road networks. **Airport data** were obtained from OurAirports community website, which includes three international airports, namely, Joshua Mqabuko Nkomo Airport, located in Bulawayo, Robert Gabriel Mugabe Airport, located in Harare, and the Victoria Falls Airport, located at Victoria Falls. The data also show that the country has 11 unscheduled and two military airports that are currently operational.

The **Zimbabwe Electricity Transmission Network data** were obtained from Africa Infrastructure Country Diagnostics, led by the World Bank. The network represents medium and high voltage transmission lines and includes transmission line capacity in kilovolts, the name of the locality where the transmission line starts and where it ends, and the status of the link (existing, planned, proposed, under study). Existing and future transmission lines range from 66 kV to 400 kV. The cross-border interconnectors, representing the lines to/from Botswana, Mozambique, South Africa, and Zambia, are also included. **Settlement data** were derived from the population census and show that urban population densities are high and are positively correlated with the density of the electricity network. **Elevation data** were derived from the Shuttle Radar Topography Mission (SRTM), which is a satellite radar system used for the acquisition of topographic data. The data characterise images with a 30 m spatial resolution of Zimbabwe created through the mosaicking of tiles and clipping in accordance with the extent of the country. The data were used to derive two other raster criteria maps, namely, slope and aspect. The **waterbodies data** were obtained from the Regional Centre of Mapping Resources for Development (RCMRD). The main waterbodies, including Lake Kariba and Victoria Falls, are located along the western border of the country with Zambia. The **key river systems** of Zimbabwe include the Zambezi, Limpopo, Runde and Save, along with their several tributaries. **Land cover** data were obtained from the RCMRD geo-portal and represented as a raster with a 30 m spatial resolution. The raster surface was categorised according to suitability for development. The most suitable sites were characterised by short vegetational cover (e.g., shrubs, grassland) and bare areas which would not obstruct wind or affect solar insolation. The less suitable areas contained sparse vegetation and aquatic vegetation, which, owing to their environmental vulnerability, would make it difficult to develop renewable energy plants there. Other unsuitable sites contained trees, cropland, open water bodies, or built-up areas, that owing to their inaccessibility or present development, would make it impossible to develop.

2.2. Suitability scores

The tables below show the criteria chosen for the suitability analysis of wind, solar and SHP power plants. References are given to the sources from which the relevant criteria were derived, including the identification of exclusion zones / unsuitable sites. The overall method of scoring was adopted from Bennui et al. (2007), where the score for each criterion depends on its importance and suitability. The suitability scores are classified in a six-point scale, where 0 = unsuitable/exclusion, 1 = barely suitable, 2 = moderately suitable, 3 = suitable, 4 = highly suitable, and 5 = extremely suitable.

Table 2: Ranging Scores for wind power plant criteria

	Exclusion zone / unsuitable (0)	Barely suitable (1)	Moderately suitable (2)	Suitable (3)	Highly suitable (4)	Extremely suitable (5)	References
Mean wind speed (m/s)	>25.0	<4.0	4.0 – 6.00	6.0 – 8.0	8.0 – 10.0	10.0 – 25.0	(Ottinger, 2019)
Proximity to a power grid (km)	<0.2	>1.0	0.8- 1.0	0.7 – 0.8	0.5 – 0.6	0.2 – 0.4	(Sliz-Szkliniarz & Vogt, 2011)
Proximity to major roads (km)	<0.5	>2.5	2.0 – 2.5	1.5 – 2.0	1.0 – 1.5	0.5 – 1.0	(Bennui et al., 2007)
Proximity to settlements (km)	<1.0	1 .0 – 2.0	2.0 – 3.0	3.0 – 4.0	4.0 – 5.0	>5.0	(Bennui et al., 2007)
Proximity to water bodies (km)	<0.4	0.4 – 0.6	0.6 – 0.8	0.8 – 1.0	1.0 – 1.2	>1.2	(Baban & Parry, 2001)
Proximity to airports (km)	<3.0	3.0 – 6.0	6.0 – 9.0	9.0 – 12.0	12.0 -15.0	>15.0	(Bennui et al., 2007)
Slope of terrain (%)	>30.0	>25.0	20.0 – 25.0	15.0 – 20.0	10.0 – 15.0	<10.0	(Latinopoulos & Kechagia, 2015)
Land cover	Open water	Aquatic vegetation	Sparse vegetation	Grassland	Shrubs	Bare areas	(Janke, 2010)

Table 3: Ranging Scores for solar power criteria

	Exclusion zone/ unsuitable (0)	Barely suitable (1)	Moderately suitable (2)	Suitable (3)	Highly suitable (4)	Extremely suitable (5)	References
Solar irradiation (KW/m^2)	NA	<2050	2050 - 2100	2100 - 2150	2150 - 2200	>2200	(Aly, Jensen & Pedersen, 2017)
Proximity to a power grid (km)	<0.2	>1.0	0.8- 1.0	0.6 – 0.8	0.4 – 0.6	0.2 – 0.4	(Sliz-Szkliniarz & Vogt, 2011)
Proximity to major roads (km)	<0.5	>2.5	2.0 – 2.5	1.5 – 2.0	1.0 – 1.5	0.5 – 1.0	(Bennui et al., 2007)
Proximity to settlements (km)	<1.0	1 .0 – 2.0	2.0 – 3.0	3.0 – 4.0	4.0 – 5.0	>5.0	(Bennui et al., 2007)
Proximity to water bodies (km)	<0.4	0.4 – 0.6	0.6 – 0.8	0.8 – 1.0	1.0 – 1.2	>1.2	(Baban & Parry, 2001)
Aspect (degrees)	NA	67.5 – 292.5 (not facing north)	10.0 – 22.5	22.5 – 67.5	292.5 – 337.5	337.5 - 360, 0- 10.0	(Noorollahi, Yousefi & Mohammadi, 2016)
Elevation (m)	<40	40.0 – 80.0	80.0 – 120.0	120.0 – 150.0	150.0 – 200.0	> 200	(Bennui et al., 2007)
Land cover	Open water	Aquatic vegetation	Sparse vegetation	Grassland	Shrubs	Bare areas	(Janke, 2010)

Table 4: Ranging Scores for small hydropower criteria

	Exclusion zone/ unsuitable (0)	Barely suitable (1)	Moderately suitable (2)	Suitable (3)	Highly suitable (4)	Extremely suitable (5)	References
Precipitation (mm/yr)	NA	<300	300 – 450	450 – 600	600 - 750	>750	(Unganai, 1996)
Proximity to a power grid (km)	<0.2	>1.0	0.8- 1.0	0.6 – 0.8	0.4 – 0.6	0.2 – 0.4	(Sliz-Szkliniarz & Vogt, 2011)
Proximity to major roads (km)	<0.5	>2.5	2.0 – 2.5	1.5 – 2.0	1.0 – 1.5	0.5 – 1.0	(Bennui et al., 2007)
Proximity to settlements (km)	<0.2	>1.0	0.8 – 1.0	0.8 – 0.6	0.6 – 0.4	0.4 – 0.2	(Rojanamon, Chaisomphob & Bureekul, 2009)
Proximity to rivers (km)	NA	>1.0	1.0 – 0.8	0.8 – 0.6	0.6 – 0.4	<0.4	(Rojanamon, Chaisomphob & Bureekul, 2009)
Elevation (m)	<40	40.0 – 80.0	80.0 – 120.0	120.0 – 150.0	150.0 – 200.0	> 200	(Bennui et al., 2007)

2.3. Determining weights

The AHP was used to assign weights to the criteria through the application of pairwise comparisons. This method comprises four stages (Saaty, 1980), as described below.

1. The first stage is the structuring of the decision problem in a hierarchy (Figure 2). Composing this hierarchical structure provides an overall view of the dynamic relationships and helps assess whether the elements at each level are comparable. At the top level of the hierarchy is the overall goal of the problem; the next level presents the criteria, showing the various possibilities from which the alternatives could be considered; the lower level comprises decision alternatives, which are the various choices that one could make.

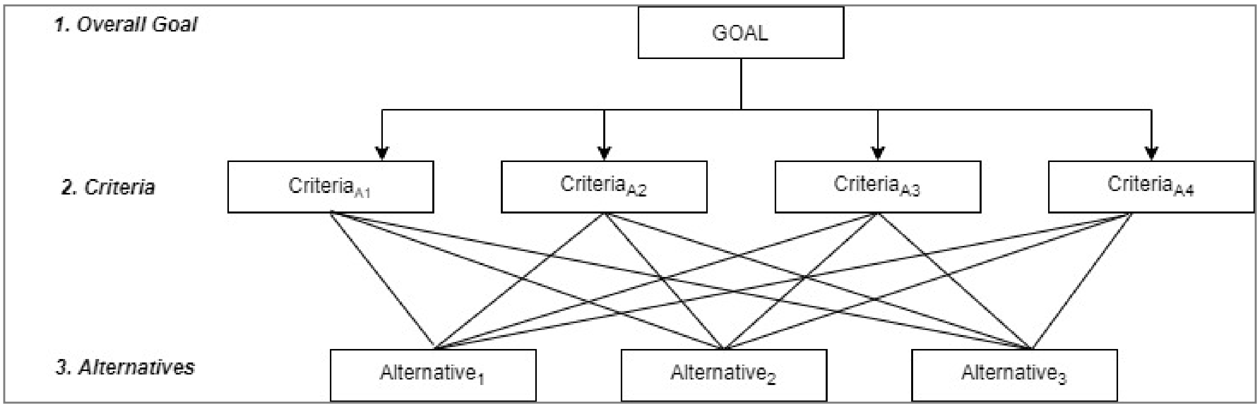

Figure 2: First stage of the AHP: identifying criteria and alternatives

2. The second stage involves the calculation of the priority level for each criterion with respect to the goal, and the priority level of each alternative with respect to one ideal criterion. The rating of the priority is carried out by assigning a weight between 1 (equal importance) and 9 (extreme importance) in respect of the criterion, whereas the reciprocal of these values is given to the other criterion in the pair (see Table 5). The pairwise comparison matrix, M, is the (n x n) matrix, where n is the number of criteria. Each cell a_{jk} of matrix M represents the comparison values between the j^{th} (row) criterion relative to the k^{th} (column) criterion. If the cell $a_{jk} > 1$, the j^{th} criterion is more important than the k^{th} criterion and *vice versa* (see Table 6 to Table 8).

Table 5: Pairwise comparisons on a relative scale

Degree of importance	Definition	Explanation
1	Equal importance	Two candidates contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favour one candidate over another
5	Strong importance	Experience and judgement strongly favour one candidate over another
7	Very strong importance	One candidate is favoured very strongly over another
9	Extreme importance	The evidence favouring one candidate over another is the highest possible order of affirmation
Degrees of 2,4,6,8 can be used to express intermediate values.		
Degrees of 1.1, 1.2 ,1.3, etc. can be used for alternatives that are very close in importance.		

3. The third stage is to carry out a consistency check of the pairwise comparison matrix, which is generated using the pairwise comparison method with a 1-9 fundamental scale. For pairing within each criterion, the most suitable option is given a score, again on a scale between 1 (equally good) and 9 (absolutely better), whilst the alternate option in the pairing is given a rating equal to the reciprocal value.

4. The last stage involves a set of priorities summarised to make the final decision. The alternative that is at the highest priority level with respect to the goal is the final decision choice. The option scores are combined with the criterion weights to produce a final score for each option.

The weights are calculated as follows: Suppose w_j denotes the relative weight of the importance of the criterion C_j and a_{ij} is the performance value of alternative A_i when evaluated in terms of criterion C_j, … the overall importance of alternative A_i is defined as (Kamano, 2018):

$$A_i = \sum_{j=1}^{n} w_j \, a_{ij}, \; for \; i = 1,2,3, \ldots, m. \qquad [1]$$

This approach provides the ability to evaluate (weigh) and combine the inputs at once, creating an integrated multi-criteria analysis. The criteria were easily combined incorporating the weights generated by the AHP pairwise matrix. The cell values of each standardised (reclassified) raster were multiplied by the raster's weight.

The pairwise comparison process was guided by the surveyed literature. Expert opinions derived from literature were used to assess the significance of one criterion relative to another to determine the criteria weights within the matrix shown in the tables below. For example, Table 6 shows how wind speed was weighted: extremely important compared to distance to airports; very important compared to distance to major roads; of strong importance compared to distance to power grid, distance to settlements, land cover; and of moderate importance to slope and elevation. Distance to water bodies was weighted as of more importance compared to mean wind speed. This was deduced from how the scholars favoured one criterion over another.

Table 6: Pairwise comparison for the wind power plant criteria

	Mean Wind Speed	Dist: power grid	Dist: major roads	Dist: settle-ments	Dist: water bodies	Dist: air-ports	Slope	Elevation	Land Cover	Weight
Mean Wind Speed	1	5	7	5	1/7	9	4	3	5	0.2463
Dist: power grid	1/5	1	3	1/3	2	2	5	6	6	0.1396
Dist: major roads	1/7	1/3	1	1	1/5	4	3	7	5	0.0909
Dist: settle-ments	1/5	3	1	1	1	4	5	5	4	0.1341
Dist: water bodies	7	½	5	1	1	5	5	3	7	0.2187
Dist: airports	1/9	½	1/4	1/4	1/5	1	7	8	8	0.0914
Slope	1/4	1/5	1/3	1/5	1/5	1/7	1	2	1	0.0297
Eleva-tion	1/3	1/6	1/7	1/5	1/3	1/8	1/2	1	1/3	0.0221
Land Cover	1/5	1/6	1/5	1/4	1/7	1/8	1	3	1	0.0272

Since the figures in the table were based on extracts from literature and not from face-to-face expert judgements, the results of the analysis may be biased. There is a need to work on the comprehension of the elements and components contributing to the uncertainties in decision-making and how these uncertainties affect the quality of the final decisions.

Table 7: Pairwise comparison for the solar power plant criteria

	Solar irradiation	Dist: power grid	Dist: major roads	Dist: settlements	Dist: water bodies	Aspect	Elevation	Land Cover	Weight
Solar irradiation	1	7	6	9	9	5	2	2	0.2847
Dist: power grid	1/7	1	3	8	2	1/7	4	5	0.1429
Dist: major roads	1/6	1/3	1	7	6	8	2	2	0.1364
Dist: settlements	1/9	1/8	1/7	1	3	5	1/5	1/3	0.0513
Dist: water bodies	1/9	1/2	1/6	1/3	1	6	1/4	1/6	0.0482
Aspect	1/5	7	1/8	1/5	1/6	1	8	6	0.1618
Elevation	1/2	1/4	1/2	5	4	1/8	1	5	0.1017
Land Cover	1/2	1/5	1/2	3	6	1/6	1/5	1	0.0732

Table 8: Pairwise comparison for the SHP criteria

	Precipitation	Dist: power grid	Dist: major roads	Dist: settlements	Dist: rivers	Elevation	Weight
Precipitation	1	9	7	2	1/6	1/5	0.228
Dist: power grid	1/9	1	5	8	9	8	0.284
Dist: major roads	1/7	1/5	1	3	7	1/7	0.1
Dist: settlements	1/2	1/8	1/3	1	1/8	1/6	0.021
Dist: rivers	6	1/9	1/7	8	1	5	0.195
Elevation	5	1/8	7	6	1/5	1	0.174

2.4. Building the model and generating the map

The building of the GIS model was performed using Model Builder, which is a visual language in ArcGIS Pro that allows one to build new tools that model the geo-processing workflow. Geo-processing tools were chained together in a sequence, feeding the output of one tool as the input to another. The processing tools and data elements were visually represented, as shown in Figure 3, where the existing input data variables are in blue, the derived / output data variables are in green and the built-in tools for performing specific operations on the data are in yellow. The data variables are the model elements that contain the descriptive information about the data, including the field information, spatial references, and pathways. The arrows represent the connection between the data variables and the tools. Three models, representing wind power, solar power and SHP plants, were constructed.

Figure 3: Illustration of GIS index model for solar suitability constructed using Model Builder

3. Results

3.1. Suitable areas identified for wind power plants

Figure 4 shows the generated wind power suitability map of Zimbabwe. The extremely suitable sites were in the Matabeleland South, Midlands, and Mashonaland East provinces. Barely suitable sites were in Mashonaland West and Manicaland province. Extremely suitable and highly suitable sites were considered as potential sites for wind power production. The largest area suitable for wind power plants is in Beitbridge Rural District with a land area of 12 719 km^2.

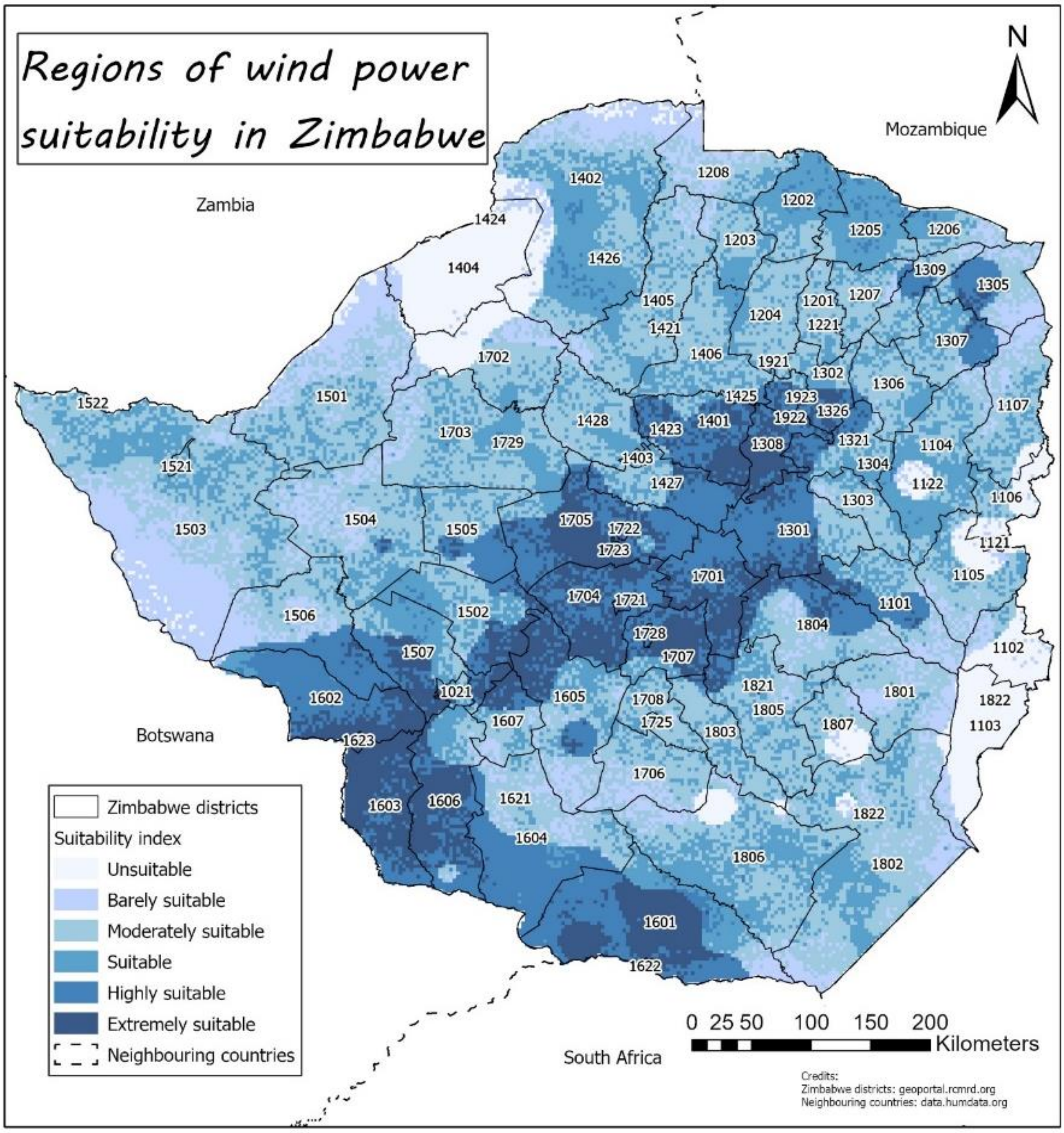

Figure 4: Regions of wind power site suitability in Zimbabwe

3.2. Suitable areas identified for solar power plants

Figure 5 shows the generated solar power suitability map of Zimbabwe. The extremely suitable areas are in Matabeleland North, Bulawayo, and part of Matabeleland South, as well as in the Midlands province. The unsuitable areas are in Masvingo, Mashonaland West, and parts of Mashonaland Central. The largest area suitable for siting solar power plants is in the Hwange rural area, with a land area of 26 974 km2.

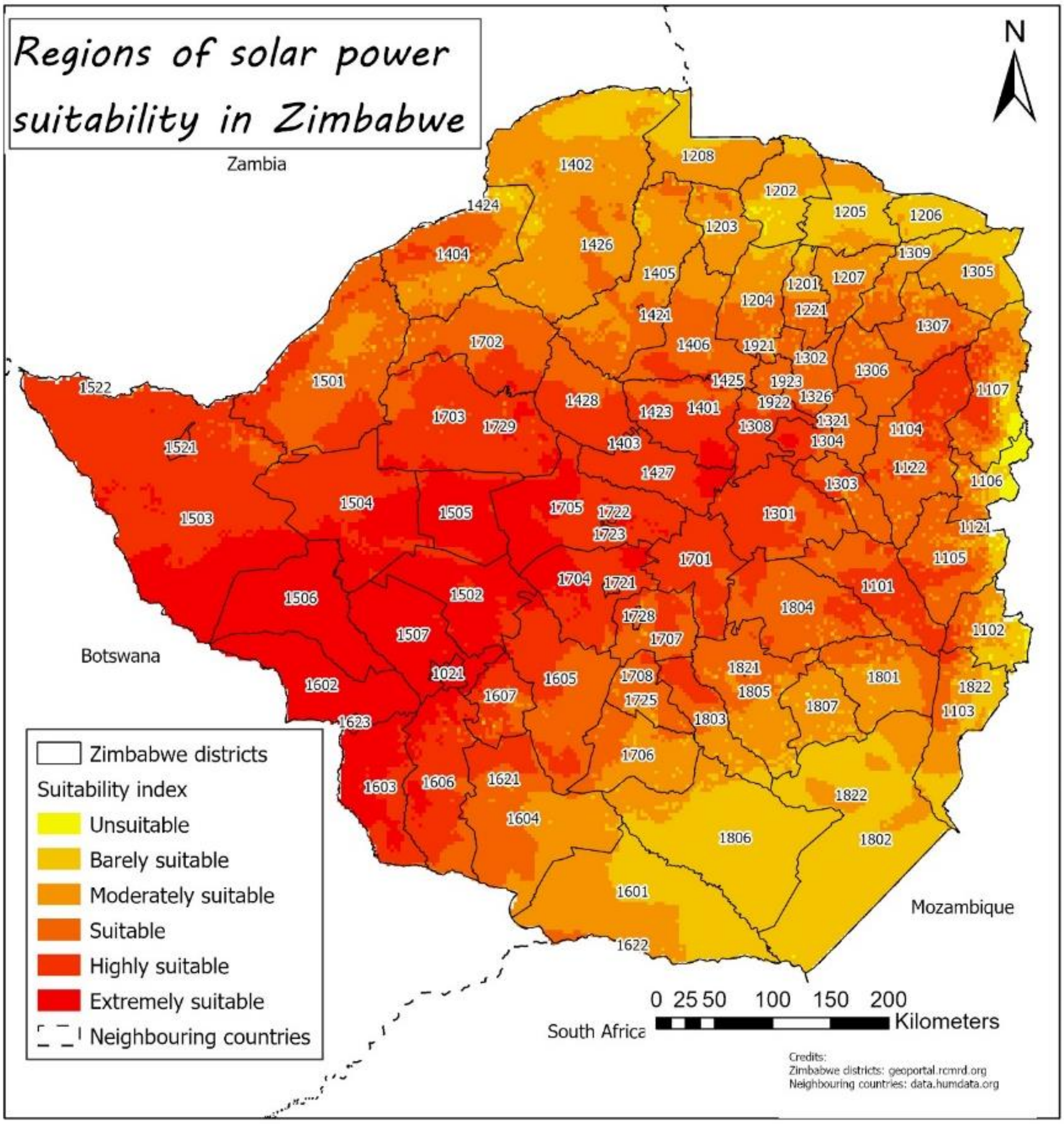

Figure 5: Regions of solar power site suitability in Zimbabwe

3.3. Suitable areas identified for SHP plants

Figure 6 shows the generated small hydropower suitability map of Zimbabwe. The selected type of SHP is run-of-river. The river network was identified to determine which river catchment area would be suitable for the run-of-river SHP plants. Extremely suitable sites were found along the Gwayi, Shangani, Lukhosi, Hunyani, Nyagui, and Odzi river channels. Barely suitable sites were identified along the Thuli, Mzingwane, and Save river channels.

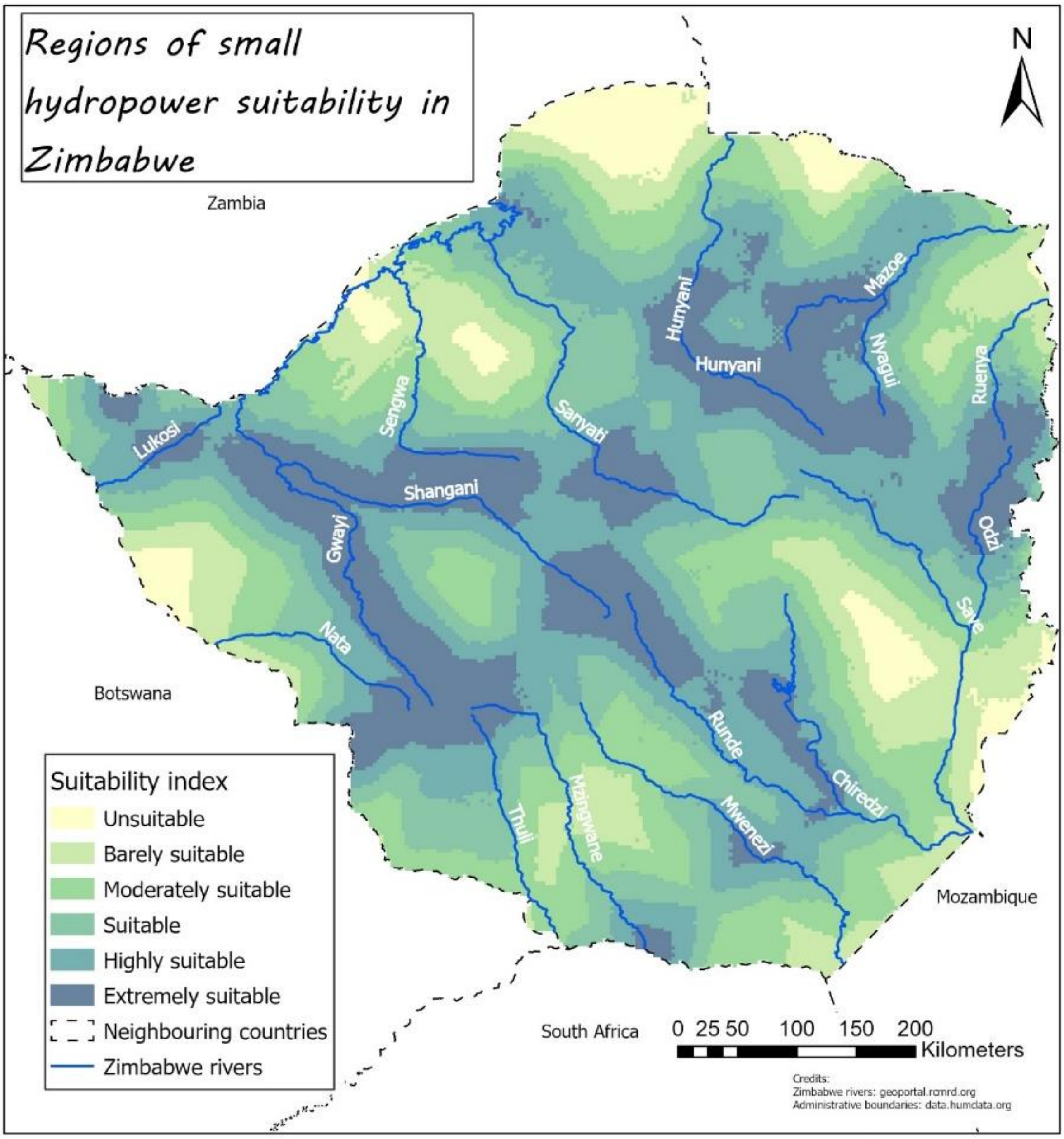

Figure 6: Regions of small hydropower plant site suitability in Zimbabwe

3.4. Validation

Data used for spatial analysis are affected by uncertainty. Since errors might emanate from variations in the database or analytical model, validation of a model is recommended (Graham et al., 2008). The renewable energy suitability model can be validated by choosing a different region where wind, solar or small hydro power plants already exist and by establishing whether the suitable areas identified by the model match the locations of the existing power plants. The region selected for model validation was South Africa because it is a neighbouring country to Zimbabwe and shares certain geographic and climatic features that are similar to those of Zimbabwe. Figures 7, 8, and 9 show the results of the same suitability analysis for wind, solar and SHP energy production plants in South Africa. The renewable energy resources (points) overlayed on the maps were extracted from the utility scale renewable energy generation sites map of South Africa (http://www.energy.org.za/map-south-african-generation-projects). The map shows the distributions of solar, wind, gas, hydropower, and bioenergy plants across the nine provinces of South Africa.

The results show that some of the already existing renewable energy power plants are located within the suitable regions as generated by the validation model. Variations in the results may be due to imprecisions in the secondary data used in this project. Another reason that could have resulted in the variations in results is that the criteria used in the utility scale of South Africa were dissimilar to the criteria used to generate the suitability maps in this study. Most of the existing solar power plants in South Africa are in the Northern Cape, which is identified as an extremely suitable region for solar power potential.

A feasibility study of hydrokinetic power in South Africa was carried out by Kusakana and Vermaak (2012). Their results were compared with those derived from our model of SHP suitability for South Africa. The results showed that the potential sites were in suitable regions identified by the validation model, and these are spread out in the Eastern Cape, Mpumalanga, and KZN provinces. It is noted that although there is a cluster of SHP plants in the Western Cape, our model did not identify this region as being suitable for SHP production. We are unsure as to the reasons for this anomaly; however, it could be related to the coarseness of the data we used, namely, publicly available secondary data sets, as listed in Table 1. Further investigation is required in this instance.

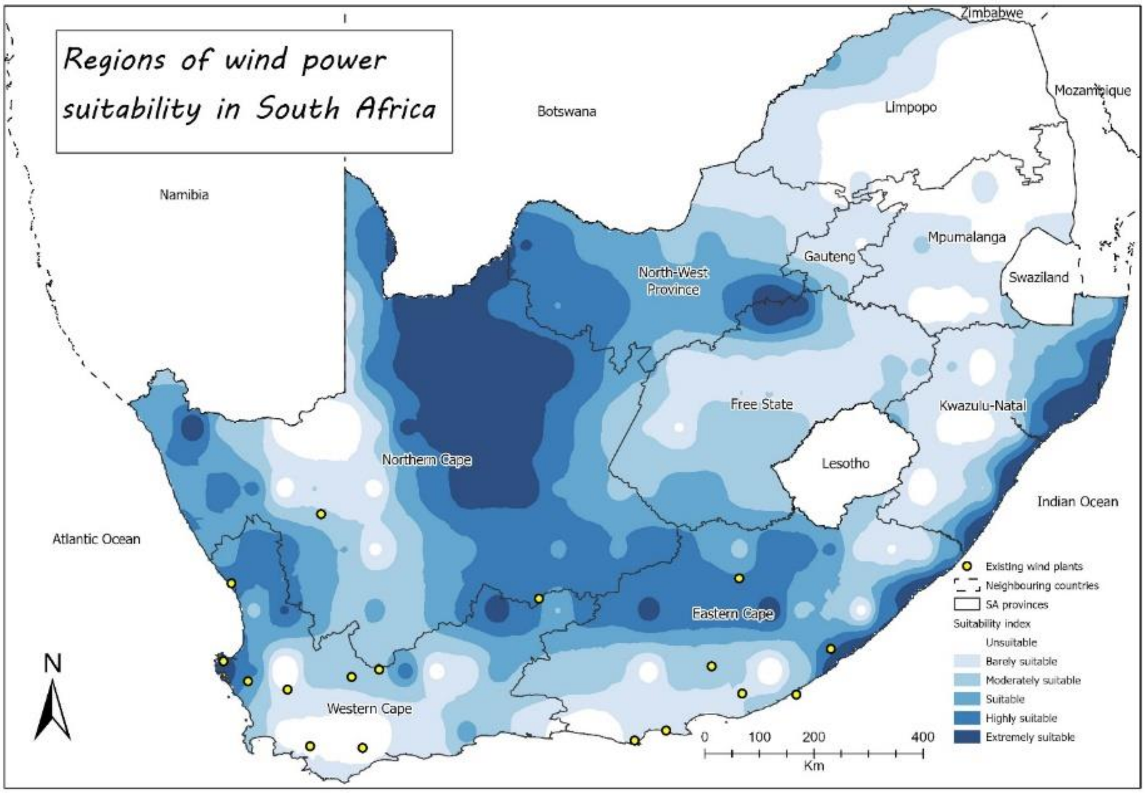

Figure 7: Validation of wind power output against existing renewable energy sources in South Africa

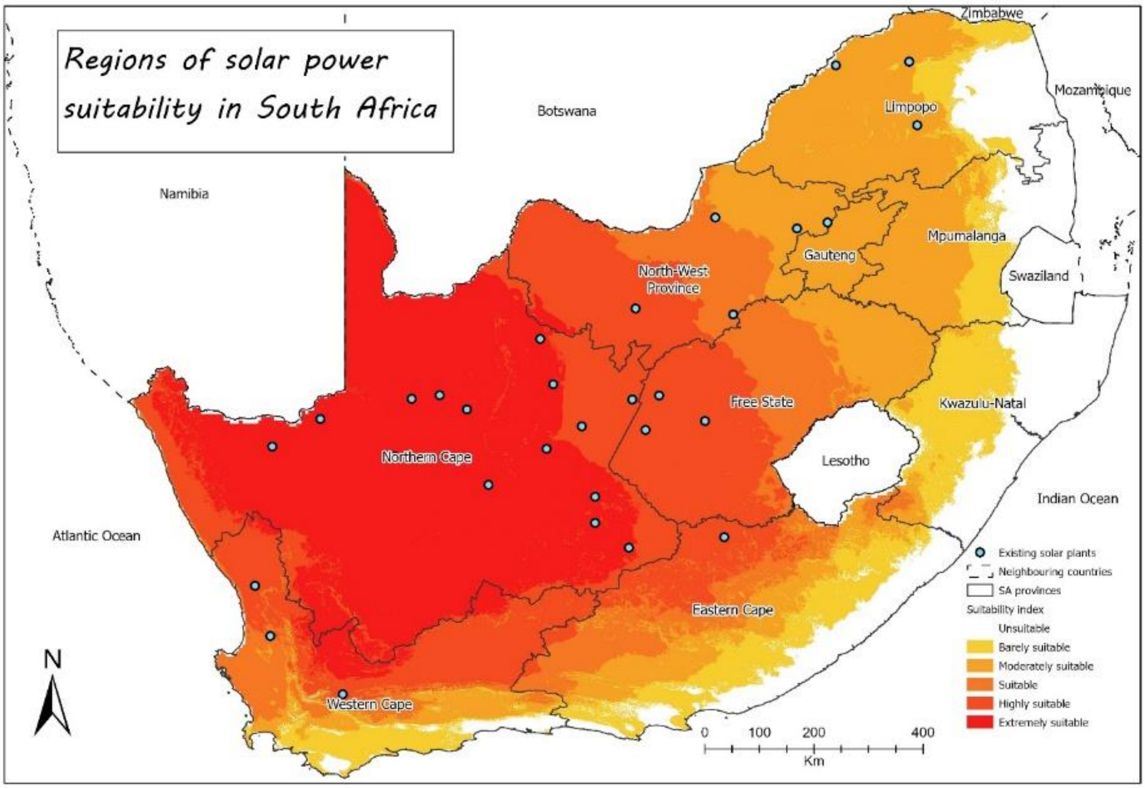

Figure 8: Validation of solar power output against existing renewable energy sources in South Africa

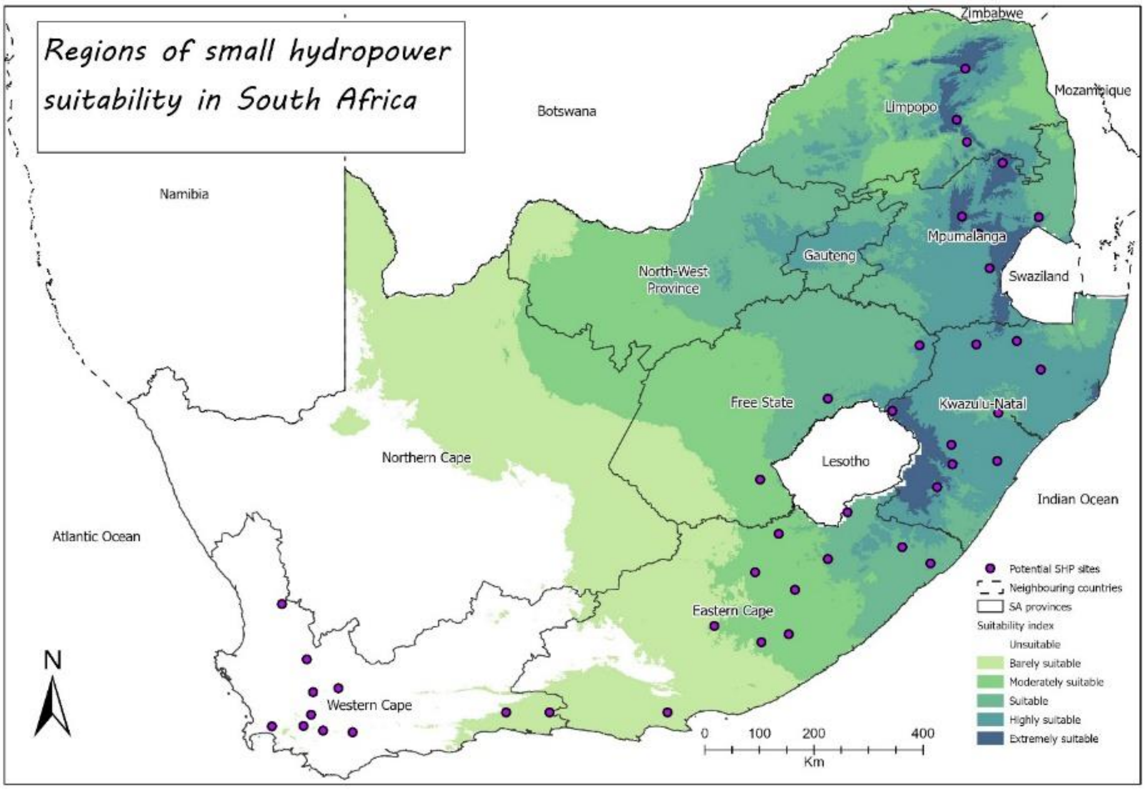

Figure 9: Validation of small hydropower output against existing renewable energy sources in South Africa

4. Discussion and Conclusions

The aim of the study was to identify suitable renewable energy regions within Zimbabwe. Various datasets were integrated with the AHP method to build a raster-based suitability model. Using data collected from online secondary resources, criteria maps representing wind, solar and SHP resources in Zimbabwe were created. Relying on secondary data only meant that the accuracy of the derived criteria was to some extent compromised.

The workflow of the suitability model was created using Model Builder in ArcGIS Pro and produced weighted site suitability maps. These maps depict potentially suitable regions for wind, solar and SHP plants in Zimbabwe. By using the same method to test the validity of the GIS model, wind, solar, and SHP suitability maps were produced for South Africa. The results from these maps suggest that the model produced fairly accurate maps. Although there were some discrepancies, this validation is further supported by the existence of renewable energy plants within the identified suitable areas.

The generated suitability maps could be used for determining the potential contribution of the identified sites to the energy needs of the country. The process involves creating exclusion criteria where all land areas that are not feasible for implementation are removed from the reference list of suitable locations. Examples of such land areas include, amongst others, privately owned land, protected places, and agricultural sites.

In conclusion, the study shows that Zimbabwe has a vast potential in terms of wind, solar and SHP resources that could contribute to the alleviation of the country’s high energy deficits. Government officials could approach landowners in the highly suitable regions with these results and encourage them to develop renewable energy plants on their land.

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