SITE SUITABILITY ANALYSIS FOR SOLAR PV POWER PLANT IN NORTHEASTERN DISTRICTS OF KARNATAKA STATE USING GIS

A B.Tech project Report submitted

in partial fulfillment for the award of the Degree of

BACHELOR OF TECHNOLOGY

in

PHYSICAL SCIENCES

by

NIKHIL S HUBBALLI

(SC13B158)

pursued in

DEPARTMENT OF EARTH AND SPACE SCIENCES

INDIAN INSTITUTE OF SPACE SCIENCE AND TECHNOLOGY

Submitted to

DEPARTMENT OF EARTH AND SPACE SCIENCES

INDIAN INSTITUTE OF SPACE SCIENCE AND TECHNOLOGY

THIRUVANANTHAPURAM – 695547, INDIA

JAN - MAY 2017

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CERTIFICATE

This is to certify that the project titled "**Site Suitability Analysis of Solar PV Power Plant in the Northeastern districts of Karnataka State using GIS**" submitted by **Nikhil S Hubballi,** to the Indian Institute of Space Science and Technology, Thiruvananthapuram, in partial fulfilment for the award of the degree **B.Tech** in **Physical Sciences**, is bonafide record of the project work carried out by him under my supervision. The contents of this report, in full or in parts, have not been submitted to any other institute or university for the award of any degree or diploma.

Dr. Gnanappazham L.
Associate Professor,
Department of Earth and Space Sciences,
IIST, Trivandrum

Place: Thiruvananthapuram
Date: May 2017

Dr. Anandmayee Tej
Head of Department,
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Declaration

I declare that this report titled "Site Suitability Analysis for Solar PV Power Plant in north-eastern districts of Karnataka state using GIS" submitted in partial fulfillment of the Degree of "Bachelor of Technology in Physical Sciences" is a record of original project work carried out by me under the supervision of Dr. Gnanappazham, and has not formed the basis for the award of any degree, diploma, fellowship or other titles in this or any other Institution or University of higher learning. In keeping with the ethical practice in reporting scientific information, due acknowledgments have been made wherever the findings of others have been cited.

Nikhil S Hubballi
May 2017

Acknowledgements

First and foremost I would like to thank Dr. Gnanappazham for providing me this opportunity to work on Geographic Information System Analysis for the site suitability study. She has been a motivation throughtout the entire duration of this project. Her support and guidance has been invaluable for my work. I also thank KPTCL, Bengaluru for their help in getting the powergrid data necessary for the study. I thank my family and friends for providing the encouragement to excel in my goals. Lastly, I would like to thank all my teachers and professors for shaping my career and enabling me to undertake this project.

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Abstract

North-eastern region of Karnataka has very high potential for solar power generation. Solar energy can satisfy the growing demand of energy in the region. This study, working towards identifying the suitable locations for establishing solar PV plants, is based on two step framework. In the first step, a map for unsuitable regions is generated based on the defined constraints such as urban lands, forest and protected areas, industrial areas, water bodies, roads etc. And in the next step, to identify the suitable locations in the remaining regions, maps of 6 defined criteria are prepared. Then using the Analytical Hierarchy Process (AHP) technique, relative weights for the criteria and sub-criteria are determined. By overlaying these criteria layers with Simple Additive Weights (SAW) method, the final map of suitability of different regions of study area for exploiting solar PV plants is developed. Analysis of the results is presented for each of the seven district. And suitability for the solar power plant is provided in 5 different classes of Excellent, Good, Fair, Low, Poor level. The obtained results shows that 4.32%(2353.97 km^2), 23.11% (12601.88 km^2), 15%(8180.10 km^2), 15.63%(8527.26 km^2), 6.28(3427.81 km^2)% and 35.66% (19451.4 km^2) of area the entire study region are classified as excellent, good, fair, low, poor and dismissed areas respectively. And four districts Bellary, Raichur, Yadgir and Koppal are concluded as well suited for establishment of solar PV plant in decreasing order of suitability.

Table of contents

List of figures

List of tables

Chapter 1

Introduction

1.1 The need for Renewable energy

Around the globe, there has been discussions on the problems of global warming due to increased use of carbon based fuels to generate energy. Increased concentrations of carbon dioxide in atmosphere from greenhouse gas emissions, volatile energy prices and depleting fossil fuel reserves have resulted in countries looking for renewable sources as the means for energy production. There's an ever increasing challenge of making this renewable generation sustainable and cheaper. Governments around the world are taking steps to support this by providing tax credits and programs.
Solar energy is one the major source of renewable energy. And in the recent years, a lot of solar power plants have been setup to address the energy crisis in many of the countries. In India, the government considers utilizing these renewable sources as the critical step towards making the country more sustainable, reducing greenhouse gas emissions. It has setup a saparate ministry to look after non-conventional energy resources called Ministry of New and Renewable energy. Under this, the government started a National Solar Mission in 2010, with the target of 20,000 MW which was later revised to 100 GW. It aims to be able to generate 100 GW of grid-connected power by the year 2022 [2] and to reduce the cost of solar power generation through long term policy, large scale development goals, aggressive R&D and domestic production of critical raw materials, components and products.
With solar energy of about 5000 trillion kWh per year incident over India, it has a vast potential for solar power generation. Most of the parts receive $4-7kWh/m^2/day$ [2]. Generally, Concentrating Solar thermal Power (CSP) and photovoltaics (PV) are the two major technologies for exploiting solar energy. Both the methods of solar thermal and solar photovoltaic can be harnessed in the country. The Solar resource available over the country can be seen in

the figure 1.1.

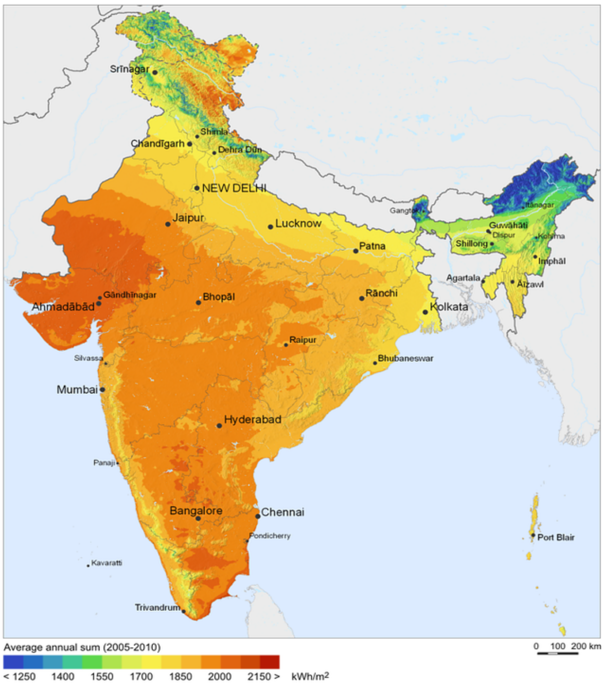


Fig. 1.1 Solar resource map of India

Solar radiation can be harnessed and converted to electricity by photovoltaic (PV) technologies. Photovoltaic cells produce electricity by absorbing photons and releasing electrons that can be captured in the form of an electric current. Cells can be used individually to power small electronics or grouped together into modules and arrays to generate larger amounts of power. PV array systems are becoming an increasingly popular means for powering residential and commercial locations in the form of distributed generation. Utilization of solar energy systems is increasing due to its simplicity, easy transport, high reliability, compatibility and no need for fuel to run the plant.

1.2 The Study Area

Solar energy is one of the best and economical way to generate electricity. India has vast potential for development of this energy system. It can be seen that states like Gujarath, Rajasthan and Tamil Nadu have already a established network of solar power plants at large scale, generating solar power at scales of 1000s of MW. But the state of Karnataka is still to progress on that frontier. Even though there is high potential for solar power, the region lacks large scale solar power projects. Thus, for this project of solar power plant suitability analysis, seven north-eastern districts of Karnataka State were chosen. These districts include Bidar, Gulbarga, Yadgir, Bijapur, Raichur, Koppal and Bellary. Since the northern region of Karnataka is mostly semi-arid and the solar radiation incident over the region is over $2000 kWh/m^2/year$, the potential for solar power generation is high.

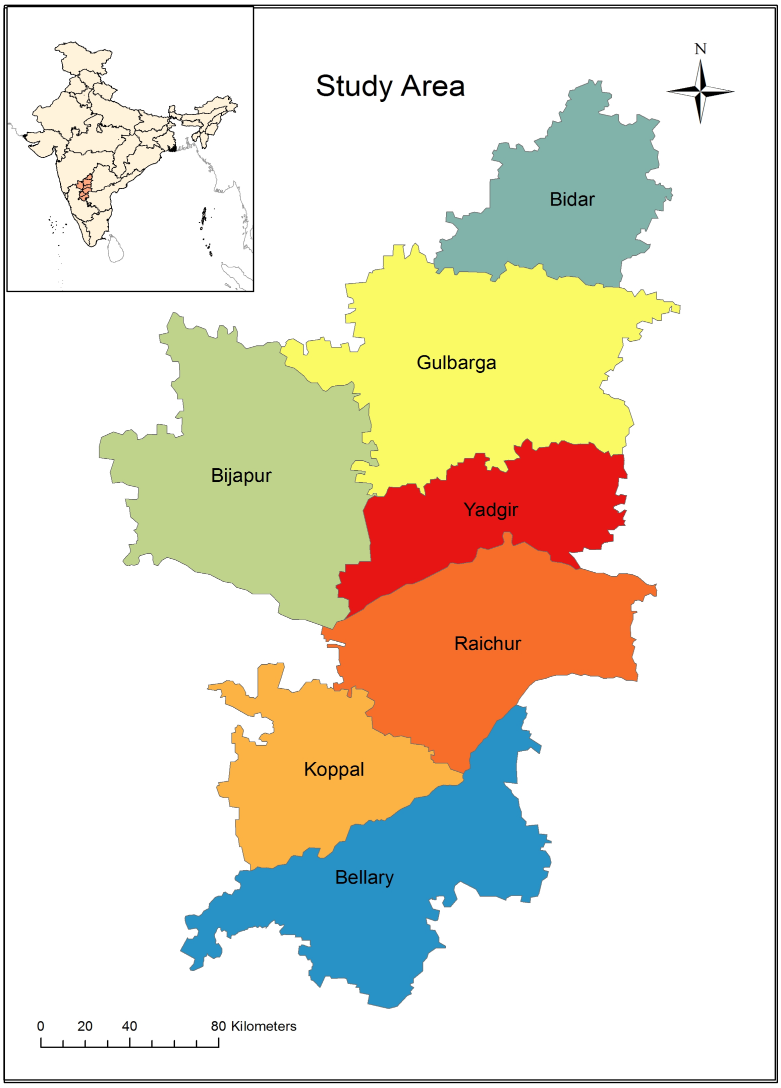


Fig. 1.2 Study Area chosen for analysis

The chosen study area suffers insufficient supply of electricity throughout the year and there are many power outages during summer. This is mainly due to dependence on hydro-electric power stations which are active mostly during monsoon season. The region has the potential to generate solar power throughout the year. Also because the region lies entirely in the deccan plateau with flatlands, it's suitable to establish solar power plants in larger areas. The study area considered also lies in the focus of three major urban agglomerations such as Hyderabad, Bengaluru and Pune. This would be helpful in providing necessary infrastructure for the establishment of solar power plants. In the recent years, there have been financial incentives to establish industries and solar power plants in the region provided by both state and central governments.

Geographic Information System (GIS) tool is very powerful tool which that can integrate, store, edit, share, visualise and analyse the spatial (geographic) information. GIS is a includes number of different technologies, processes, and methods. It is attached to many operations and has many applications related to engineering, planning, management, transport/logistics, insurance, telecommunications, and business. Several methods can be used to perform the study of any chosen area like raster analysis, vector analysis, weighted methods. It includes several spatial analyst and statistics tools to help generate the required results. Geographic Information System (GIS) is a very useful and practical tool capable of developing a database which can act as the departure point for guiding any decision support system (DSS). Hence, GIS is used to perform the analysis and identify suitable locations for exploiting solar energy. This project focuses on identifying suitable location for the construction of solar power plant which requires detailed information and planning through GIS. Different places are to be investigated considering various technical, socioeconomic, and environmental criteria, in the process of exploiting solar energy, alongside the necessity of existence of solar power potential in the region. The objective of the study is to generate a land suitability map for the entire study area based on 5 classes (excellent, good, fair, low, poor) of suitability. And find the distribution of these classes in each of the district to determine the Land Suitability Index for these districts.

Chapter 2

Literature Review

In the process to identify suitable location for establishing solar PV plants, it's required to follow a detailed planning and investigate all the factors that affect solar power generation. To study these factors by visualizing and analyzing the spatial data, we need to have a guiding system which here is GIS. And a system which would act as a decision support system, for investigating all the criteria, is required for this study. The defined criteria, to be classified based on their weights, should be assigned weights based on their influence over the study. A suitable algorithm, which is efficient in assessing all the parameters, is to be used.
Because of various issues and characteristics of utilized energy resources in electricity generation industry, a multi-lateral survey is needed for comprehensive evaluation. Hence, multi-criteria decision analysis (MCDA) techniques have become increasingly prominent in sustainable energy planning to handle the conflicts of decision makers' opinions and the complication of criteria [3].
A model to rank various renewable and non-renewable electricity production technologies was proposed by Stein by utilizing the analytic hierarchy process (AHP) based on four comprehensive criteria: financial, technical, environmental and socio-economic-political [4].
In order to identify the best location for the exploitation of wind farms, Sánchez-Lozano et al [5]. proposed an integrated model based on GIS and fuzzy Multi-Criteria Decision Making (MCDM) technique. They utilized Fuzzy Analytic Hierarchy Process (FAHP) to determine the relative importance of the criteria, and GIS was also applied to generate the database of the alternatives.
Because of site selection of large ground-mounted PV plants, a GIS based model to identify the suitable areas for the installation of photovoltaic systems in Piedmont region, Italy was proposed by Borgogno Mondino et al. [6]. Several criteria including qualitative and quantitative criteria were considered and Artificial Neural Network (ANN) was applied for the aggregation of the quantitative criteria.

In order to determine the best location for placement of solar thermoelectric installments, GIS and AHP were utilized for determining the weights of criteria. Thereafter, evaluation and prioritization of 10 candidate regions was carried out by fuzzy TOPSIS [7].
In order to investigate the various energy generation scenarios in the province of Frosinone, Massimo et al. developed and experimented a model based on Geographical Information Database System (GIS DB) due to new distributed generation technologies. Their detailed examination is done for solar energy based on the availability of land use to estimate the appropriate potential, the amount of residential electricity consumptions and the integration of renewable energy sources [8].
Appropriate use of solar energy involves the identification of regions with high potential for utilizing this energy. Although most regions may have good potential for solar energy, identifying the areas with suitable condition can increase the efficiency of electricity generation.

Chapter 3

Methods

Since the analysis is GIS based, a software which can be used to create, edit, store, manage, analyze, and visualize the geographic data is required. A desktop GIS is well suited for this purpose. Of the several available desktop GIS softwares, ESRI ArcGIS 10 is chosen because it's most suitable because of it's highly scalable server architecture. It provides data in both raster and vector formats and integrates data from multiple sources. ArcGIS 10 is a complete system for designing and managing solutions through the application of geographic knowledge. It has the ability to automate many aspects of cartography, it take less time for producing any map intelligently. Therefore, ArcGIS 10 is chosen as the software tool for the study.

3.1 Proposed Framework

Multi-criteria Decision approach is used in the study to identify the suitable locations for solar power plant in the region. The analysis is performed in seven districts of the Karnataka state. Land Suitability Index (LSI) for each of the district is determined. In summary, the proposed methodology for the study consists of following steps:

1. Identify the areas to be eliminated/dismissed in different regions for establishing solar power plants by identifying criteria based on technical, economic, social and environent constraints.

2. Generating map layers associated with defined constraints in GIS

3. Preparing a map of all eliminated/dismissed regions in GIS

4. Identifying and evaluating the criteria influencing the solar energy potential for land suitability analysis modeling

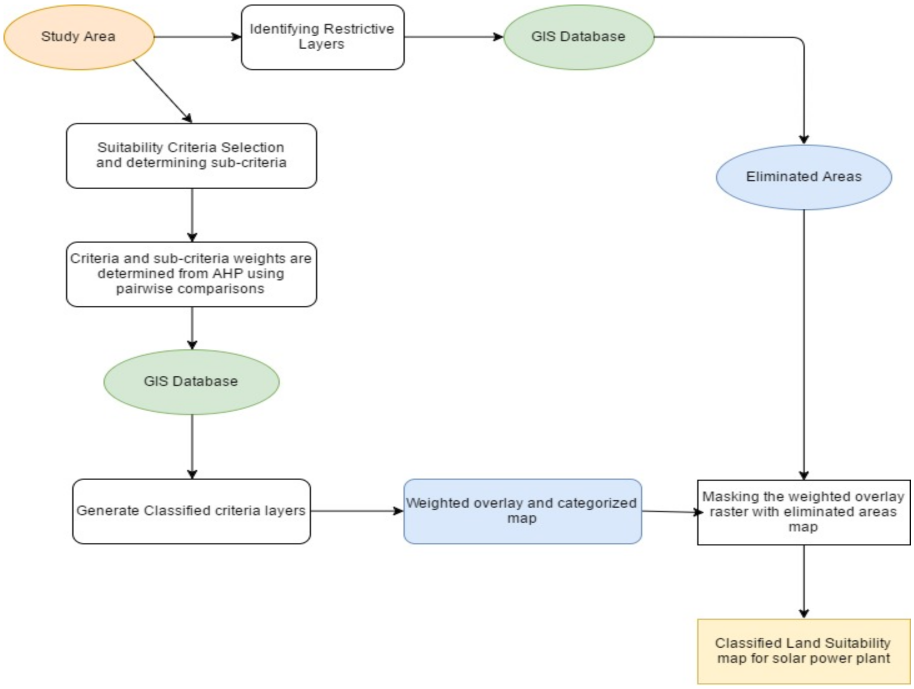


Fig. 3.1 Proposed Framework for the study

5. Determining the weights of evaluation criteria using AHP

6. Generate all the criteria map layers in GIS

7. Overlaying of map layers in GIS via Simple Additive Weight (SAW) method and preparation of the land suitability map of regions for establishing solar power plant.

All the processes related to GIS such as digitization, conversion and analysis of maps were carried out in ArcGIS desktop. And the the calculations related to AHP were carried out in a software called PriEsT following the references for the determination of crisp values for pairwise comparisons of criteria.

3.2 Eliminated/Dismissed Areas

After a framework has been established for the study, in the next step, the aim is to undertake a detailed investigation of different regions and check for feasibility to establish power plant in the region. GIS is very useful and powerful tool to perform this task. It can be used to visualize and analyze spatial information of the study area and help in decision support systems to identify suitable locations by generating a database.
It is necessary to remove some of the inappropriate areas from the study considering all

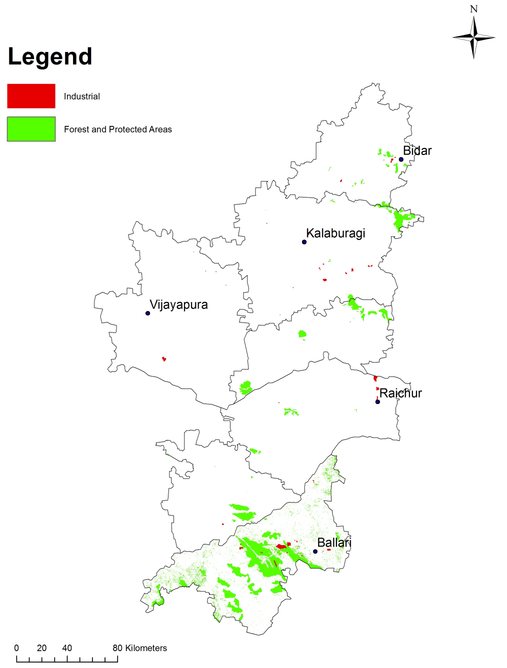
the constraints of social, economical, technical and environmental importance[9] [10]. For solar power plant to be established, land is one of the major requirement. On average, total land-use requirement for PV plant is 7.9 acres/MW [11]. But the lands which are restricted areas such as forest, protected areas, builtup areas can't be utilized for the plants.
In order to establish a solar plant, the following buffer constraints should be taken care of. The areas under these constraints are either considered unacceptable or uneconomical practically[11]:

- Regions with a solar radiation lower than 1300 $kWh/m^2/year$
- Regions with land-use category of protected regions such as national natural monuments, wildlife conservation areas, and national parks etc
- Regions located closer to the minimum distance determined for the criteria of cities and populated centers (the minimum distance should be 3000 m from cities, 1500 m from towns and 500 m from villages)
- Land-use such as forest, industrial areas, cannot be suitable options for the construction of solar plant
- Regions with a distance less than 0.1 km from roads
- Regions with a distance less than 1 km from rivers, wetlands, dams, 500m from lakes, 300m from streams
- Regions with a slope greater than 8% is considered as unsuitable area

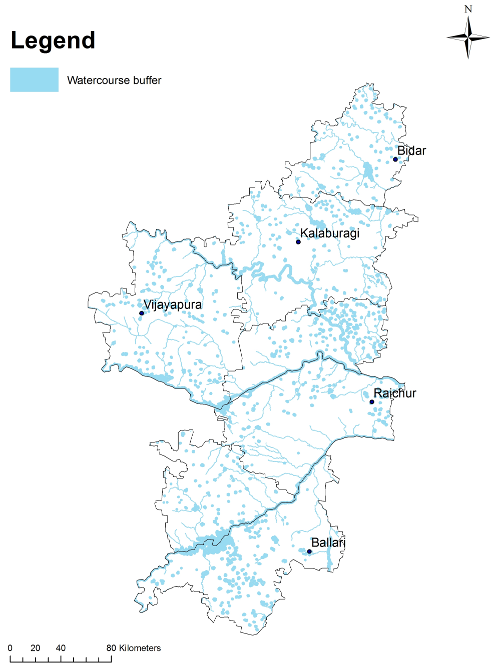
After analyzing these constraints in GIS, a final map layer of unacceptable areas in the study is generated using the boolean logic. These maps of defined restricted layers are shown in figure 3.2 and the final combination of these layers in figure 3.3.

3.3 Evaluation Criteria

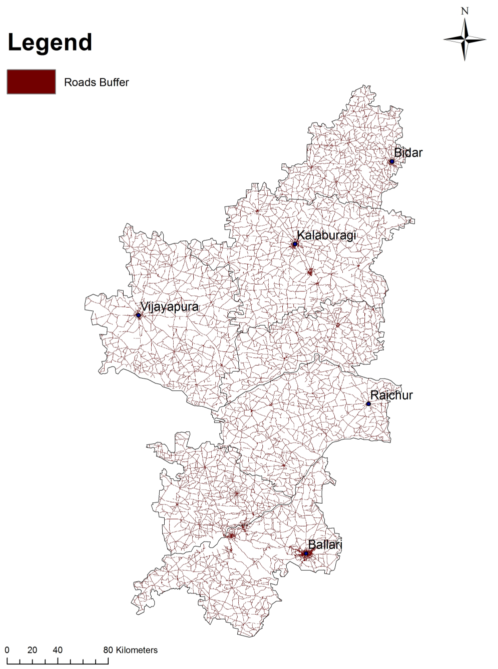
To establsih a solar power plant, there are a lot of criteria to select suitable locations in different groups such as technical, economical, social, environmental, geographical, land-use etc. In this study, as many as 10 criteria were identified [12], to reduce the complications of the study and by prioritising the GIS related criteria, 6 main criteria were considered for the study. The hierarchy of the evaluation criteria for the study is shown in the figure 3.4.



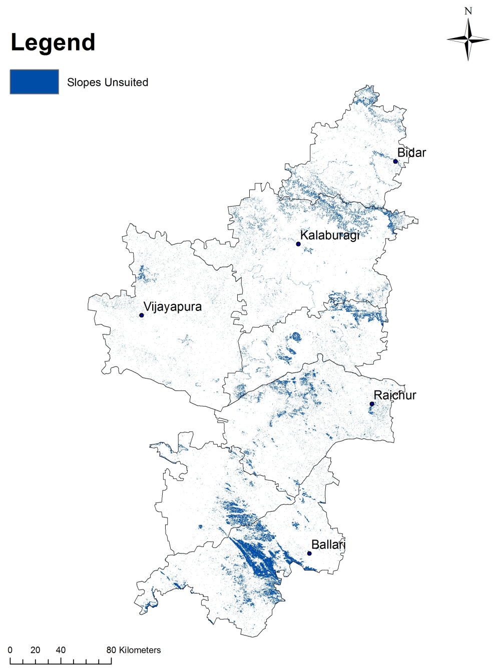
(a) Industrial, Forest and Protected Areas



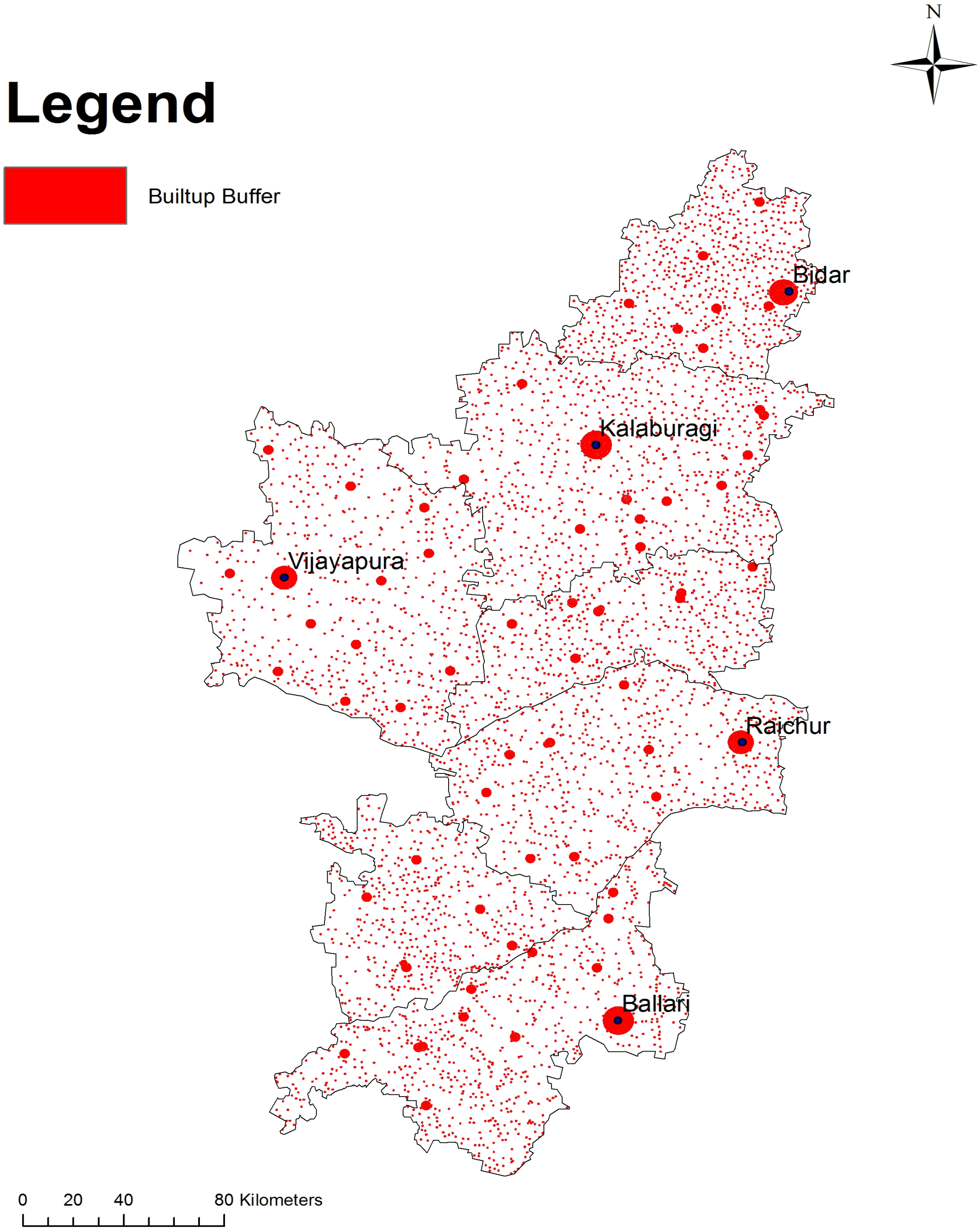
(b) Watercourse buffer



(c) Road Buffers to be eliminated



(d) Unsuited Slopes



(e) Builtup Areas and buffer

Fig. 3.2 Restrictive criteria layers

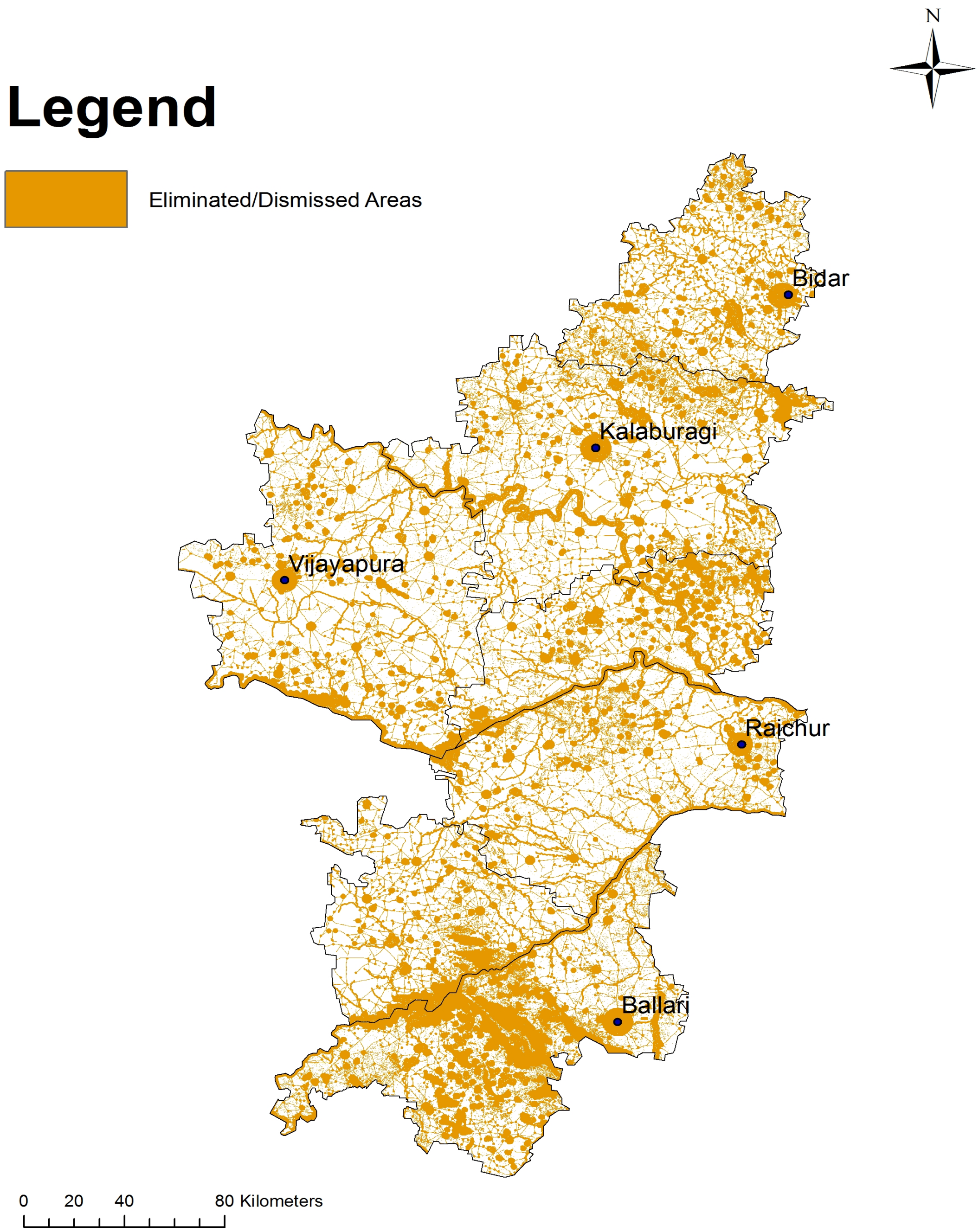


Fig. 3.3 Combined map of Eliminated/Dismissed Areas

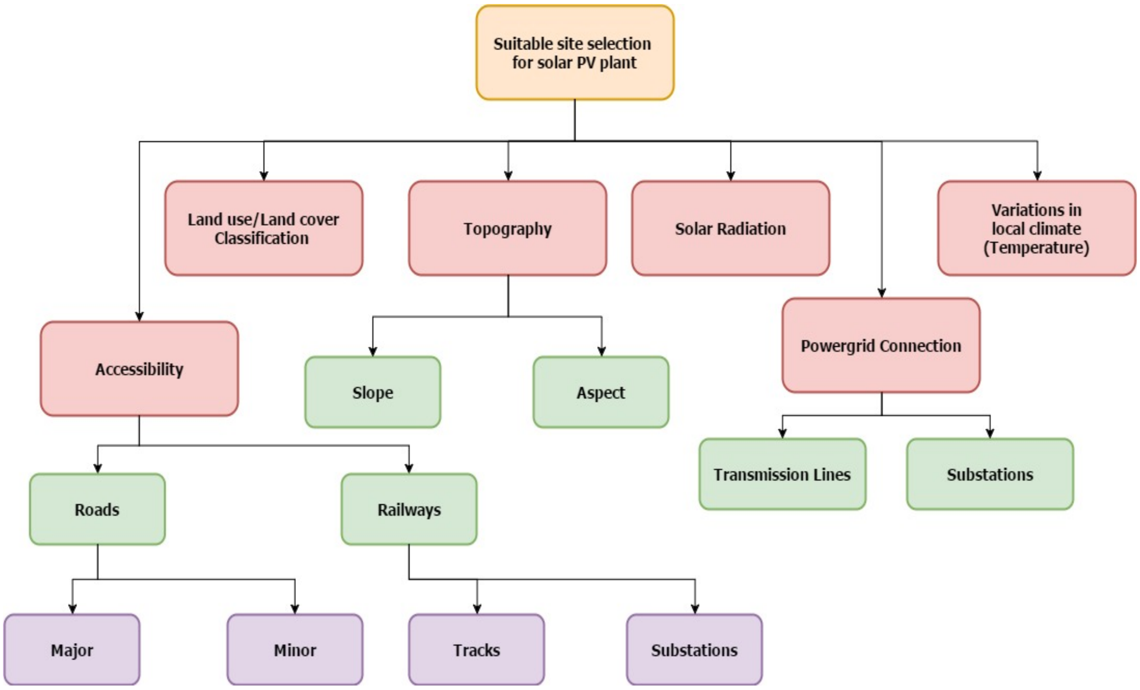


Fig. 3.4 Hierarchy of the evaluation criteria for the study

3.3.1 Solar Radiation Data

Solar radiation is one of the most important factor for the study to find an optimal location for establishing the solar power plant. The locations chosen for the plant should receive sufficient solar radiation to generate power throughout the year. In the regions where it's usually sunny, PV systems are considered to be more efficient. The location selected must be able to receive a minimum of 3.5 $kWh/m^2/day$. It should be noted that the regions with shady areas due to mountains, buildings, trees etc. can affect the generation potential of the plant. Solar irradiance data for the present study is obtained from The Satellite Application Facility on Climate Monitoring (CM SAF) [13]. The data is monthly observation of Surface Incoming Shortwave radiation (SIS) over 6 years (2010-2015) at 5 km resolution observed form European METSAT. It is then converted to Global Horizontal Irradiance (GHI) with units $kWh/m^2/day$ from SIS in units of w/m^2. The map of solar irradiance data for the study area is shown in the figure 3.5.

3.3.2 Land Use/Land cover classification

Land use is another important criteria for the site selection study. Solar PV plants are ideally built on low value land. The best locations for solar plants are usually previously developed lands or brownfield sites because they often have existing energy use nearby. It's required to

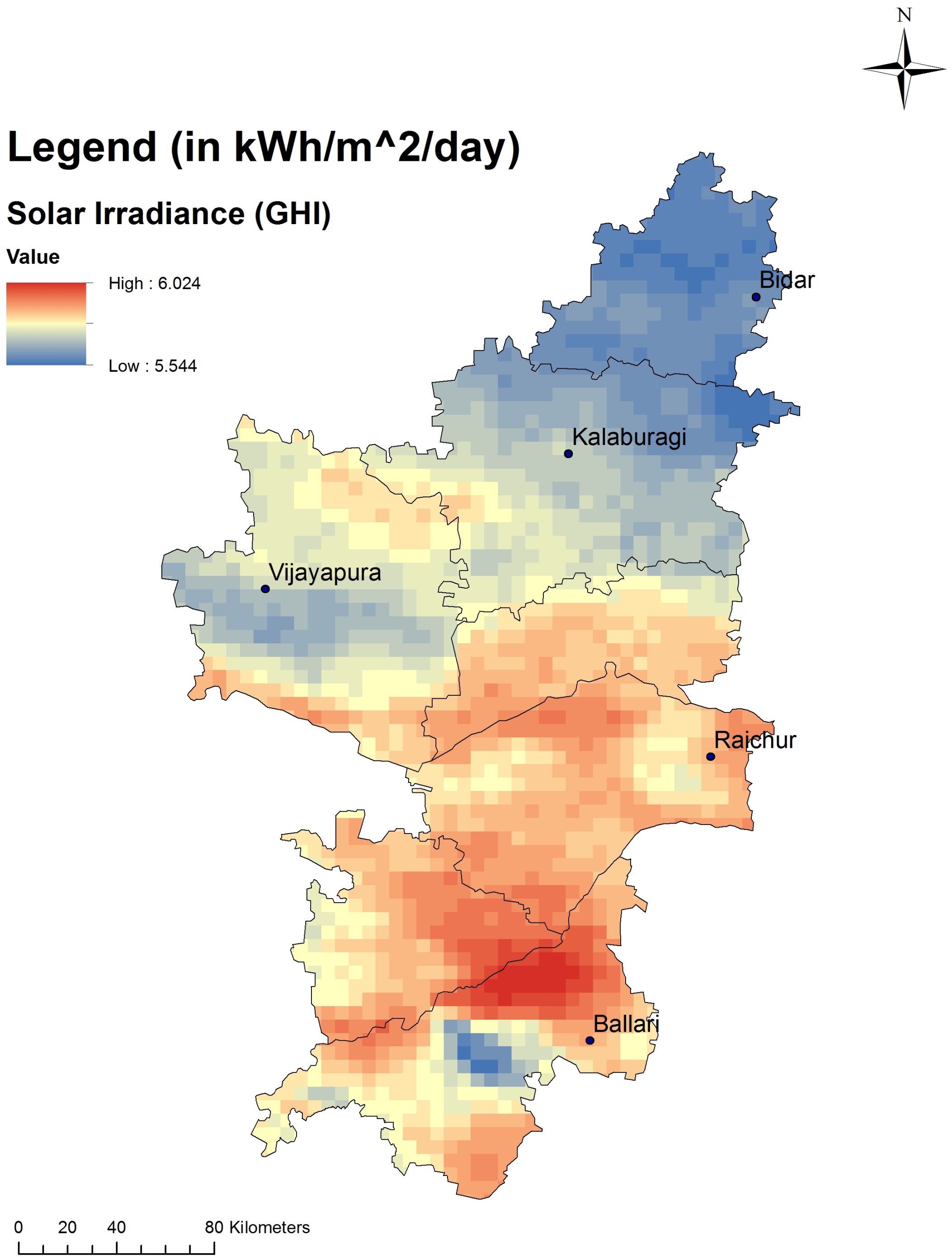


Fig. 3.5 Solar Irradiance Map - Global Horizontal Irradiance (GHI)

have the land use/land cover classification data in different levels such as agriculture, fallow land, wasteland, scrubs and non-agricultural land. Wastelands are the most suitable locations for solar power plant establishment. Use of high-quality agricultural land should be avoided if possible. The available maps on land use/land cover classification have very large scale 0f 1:250,000 where as for the current study, it's needed to have smaller scale of around 1:60,000. And hence, classification for land use/land cover is also undertaken. The land use/land cover classification process was done to identify the land use/land cover in the study area by using the Landsat 8 OLI data [14]. For classification Band 3, 4, 5, 6, 7 of the satellite sensors were used which correspond to green, red, Near InfraRed (NIR) and ShortWave InfraRed (SWIR) spectrum. Unsupervised classification of the study area is performed along with supervised re-classification into smaller required classes. The Land-use classification of the study area is shown in the figure 3.6. Also accuray assessment of the classification is undertaken and classification is found to have an overall accuracy of 95.3%.

3.3.3 Powergrid Connection (Transmission lines and Substations)

Connecting the solar plant with the powergrid is another major aspect of the study. Since the costs of the installation of power transmission lines are higher for longer distances, it is essential to consider the proximity of transmission lines and substations for the plant establishment. These transmission lines provide safety, grid stability and quick accessibility for installing equipment and repairs at the solar plant. The best distance considered for the distance of transmission lines from the plant is 0-5 km [15], [16]. This helps in efficiency in both reducing electricity losses and economical advantages. The data used for transmission lines and substations was provided by the Karnataka Power Transmission Corporation Limited (KPTCL), Bengaluru. The raster data was digitised, georeferenced using GIS software to get the features of transmission lines and substations. Both the features are shown in the figure 3.7.

3.3.4 Topography

Two major features in topography are slope and aspect. Since the solar plants are established in larger areas and the shading of solar panels in any manner should be avoided, the site is expected to be flat ideall. The change in slope for the entire site should be minimal. And hence a slope change of 8% is considered to be the maximum for the study above which the area is considered to be unsuitable. Generally slopes above 4% have lower priority [9] since panels shadow the adjacent rows of panels affecting the efficiency solar power generation. Another factor is aspect. Based on the location of the site whether in northern hemisphere or

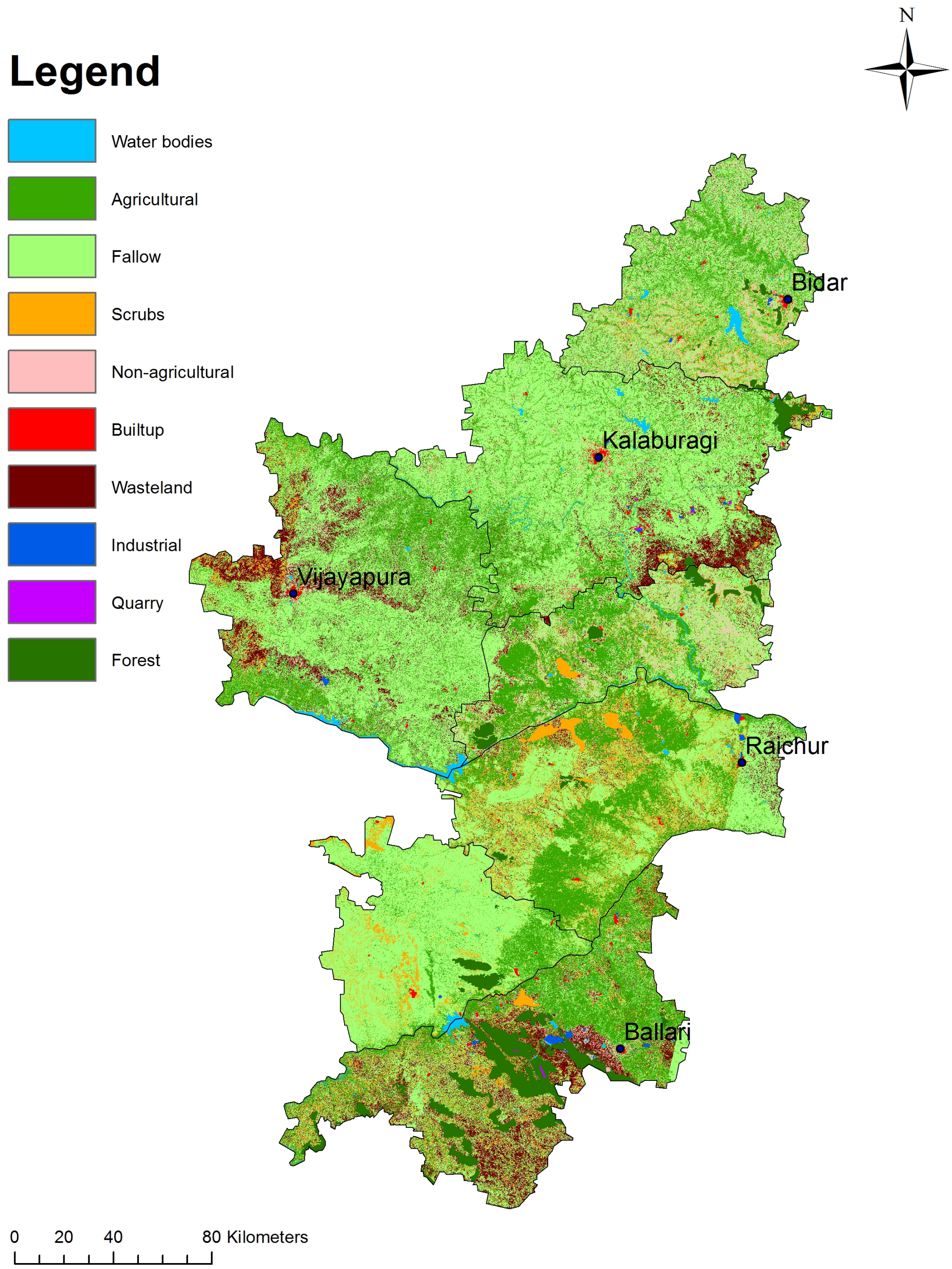


Fig. 3.6 Land Use/Land cover Classification

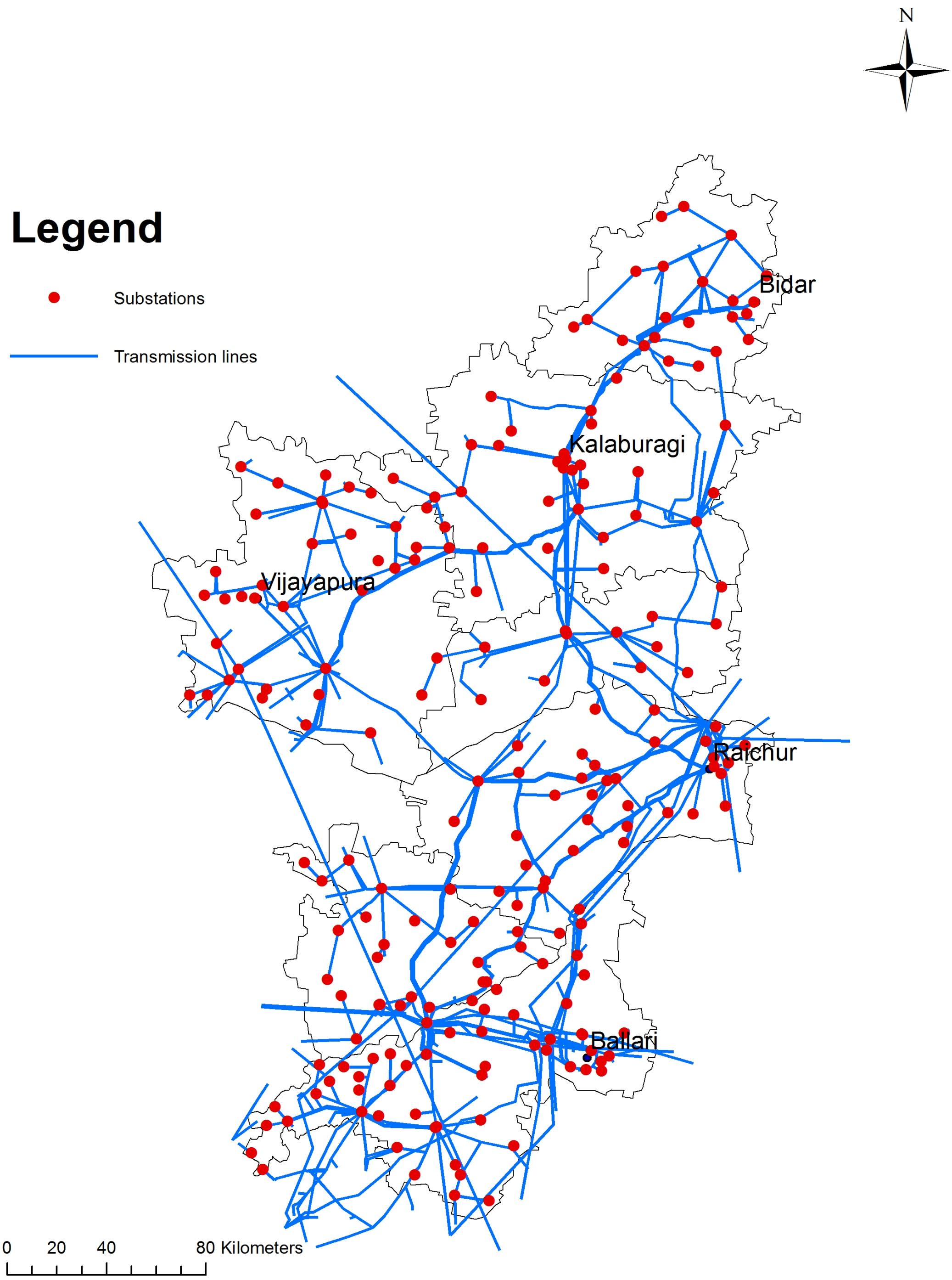


Fig. 3.7 Substations and Transmission line network

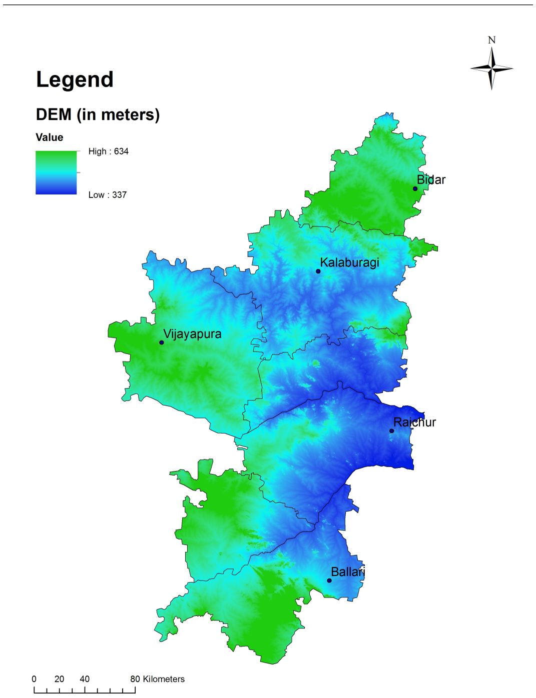
souther hemisphere on earth, the location can be slightly south-facing or north-facing. Such topography helps in making installation of modules simpler and reduces costs of technical modifications required to adjust for undulations on ground. Thus aspect angles from 135° to 225° is most suitable since the location is in northern hemisphere. The SRTM data from USGS explorer [17] is used to generate change in slope map and aspect map at a resolution of 1 arcsec(30m). The Digital Elevation Model(DEM) map, slope and aspect maps are shown in the figure 3.8.

3.3.5 Accessibility (Roads & Railways network)

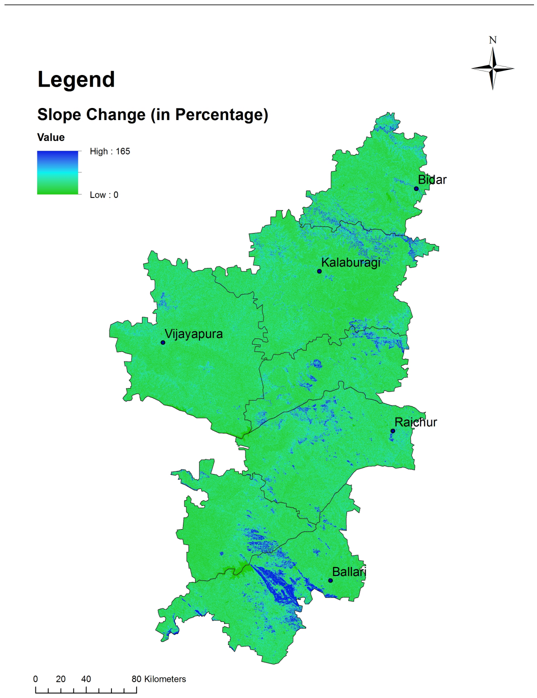
Access roads to the plant are necessary for providing infrastructure to the site. It's expensive to construct new access roads for transportation of goods and equipment. Cost of construction would be lesser if there's an easy access to the site. Also the infrastructure can be transported through railway. Thus two major networks are defined in the accessibility criteria - Roads and Railways. In roads, there are two more sub-categories - Major roads : consisting of state and national highways, Minor roads : connecting villages. In case of railway network, there are further two more categories of railway track and stations. The data for roads and railways network was taken from OpenStreetMap database [18] and was verified and updated with latest Google Earth data. The netowrk data for roads and railways are shown in figure 3.9.

3.3.6 Variations in local climate

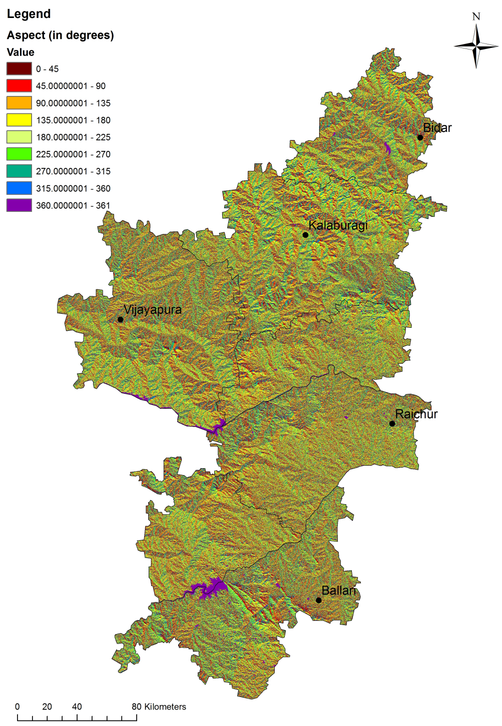
Apart from good solar resources and other criteria, the site chosen for plant should not suffer from extremes of weather. This will increase the risk of downtime for solar plant and reduce the efficiency of power generated. Weather events such as flooding, high wind speeds, snow, temperature etc are few factors that affect solar power generation. In the study area, effect of snow can be neglected since it's in the tropical region. Considering buffer from the river, stream, lakes etc. in dismissed areas, effect of flooding is taken care of. Temperautre variations of $25-45°C$ are considered to be favorable for the solar plants. The efficiency of solar panels depends on its temperature and the panel's temperature itself results from the ambient temperature and the intensity of the solar radiation. The performance of the modules of PV systems declines with increase in ambient temperature. For every $1°C$ rise in the cell temperature at temperatures above $25°C$, the amount of generated energy declines by about 0.4% - 0.5% [19] [20]. For the study, data for annual average temperature was used, provided by WorldClim - Global Climate Data [21] at a resolution of 30 arcseconds(1km). The temperature map for the study area is shown in the figure 3.10



(a) Digital Elevation Model (DEM) map

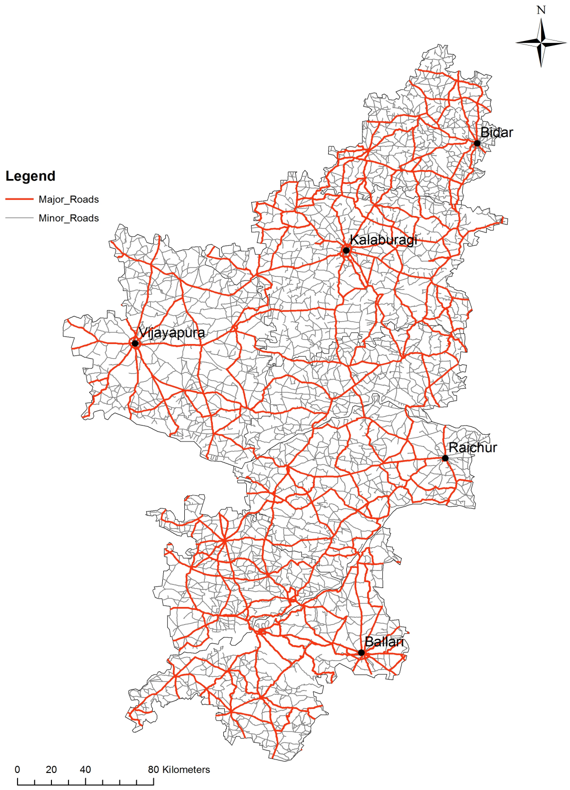


(b) Slope map

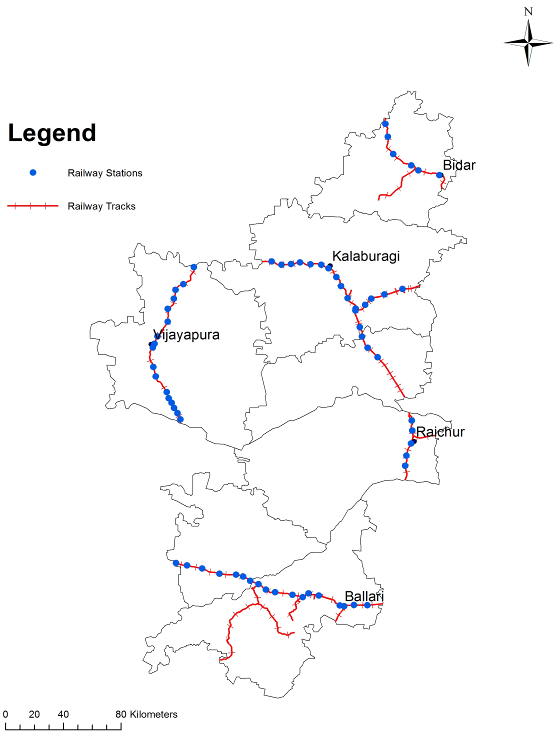


(c) Aspect map

Fig. 3.8 Topography map



(a) Road Network Map



(b) Railway Network Map

Fig. 3.9 Accessibility map

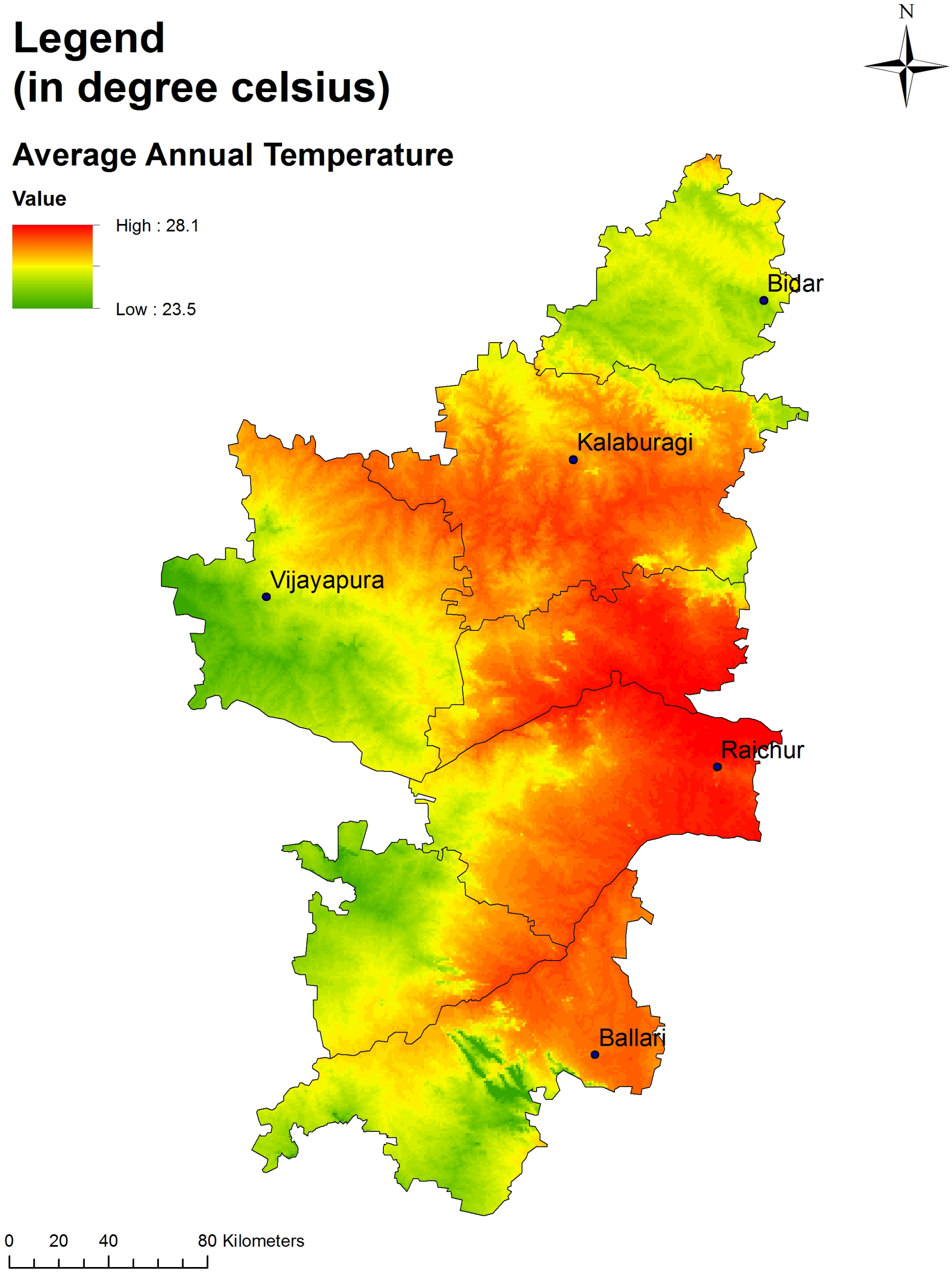


Fig. 3.10 Average Annual Temperature map

3.4 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP), introduced by Thomas Saaty (1980) [22], is an effective tool for dealing with complex decision making, It aids the decision maker to set priorities and make the best decision. The process works by reducing complex decisions to a series of pairwise comparisons, and then synthesizing the results, the AHP helps to capture both subjective and objective aspects of a decision. In addition, the AHP incorporates a useful technique for checking the consistency of the decision maker's evaluations, thus reducing the bias in the decision making process.

The AHP considers a set of evaluation criteria, and a set of alternative options among which the best decision is to be made. Since some of the criteria could be contrasting, it is not true in general that the best option is the one which optimizes each single criterion, rather the one which achieves the most suitable trade-off among the different criteria.

The AHP generates a weight for each evaluation criterion according to the decision maker's pairwise comparisons of the criteria. The importance of a criterion is measured by the weight assigned to it. For a fixed criterion, the AHP assigns a score to each option according to the decision maker's pairwise comparisons of the options based on that criterion. The higher the score, the better the performance of the option with respect to the considered criterion. Finally, the AHP combines the criteria weights and the options scores, thus determining a global score for each option, and a consequent ranking. The global score for a given option is a weighted sum of the scores it obtained with respect to all the criteria. The implementaion of AHP in the study is explained in Appendix.

For the study, the solar irradiance data was classified into 5 categories ranging from 5.544 to 6.024 $kWh/m^2/day$. For land-use only wasteland, scrub, non-agricultural, fallow adnd agricultural classification are used. In case of powergrid connection, buffers of 5, 10, 15, 20 and 50 km are used. Slope change was classified into 4 categories 0-2, 2-4, 4-6, 6-8 percentage and aspect into 3 categories 0-90 & 270-360, 135-225, 90-135 & 225-270 degrees. Major roads were classified into buffers of 5, 10, 15, 20 and 50 km and minor roads into buffers of 2, 4, 6 and 8 km [7] [16]. Railway tracks and substations were classified into buffers of 10, 20, 40, 60 and 80 km. And finally average annual temperature was classified into 5 categories of 23.5-25, 25-26, 26-27, 27-28, >28 $^{\circ}C$. Using AHP, weights for all the criteria and sub-criteria are generated based on pairwise comparisons in the software PriEsT [23]. The results of the calculated weights for these defined criteria are shown in the table 3.1.

Table 3.1 The calculated weights for all the criteria and sub-criteria using AHP

Criteria	Weights	Sub-criteria	Weights	Sub-criteria	Weights	Classification	Weights
Solar Radiation (in kWh/m^2/day)	0.378					5.8299 - 6.024	0.373
						5.7622 - 5.8299	0.288
						5.6764 - 5.7622	0.171
						5.6076 - 5.6764	0.103
						5.544 - 5.6076	0.065
Land cover	0.302					Wasteland	0.378
						Scrub	0.218
						Non-agri	0.218
						Fallow land	0.123
						Cultivated land	0.062
Power grid Connection (buffers in km)	0.136	Transmission lines	0.615			0-5	0.418
						5-10	0.266
						10-15	0.164
						15-20	0.108
						20-50	0.044
		Substations	0.385			0-5	0.417
						5-10	0.263
						10-15	0.16
						15-20	0.097
						20-50	0.063
Topography	0.096	Slope (in percentage)	0.818			0-2	0.467
						2-4	0.278
						4-6	0.16
						6-8	0.095
		Aspect (in degrees)	0.182			0-90, 270-360	0.105
						90-135, 225-270	0.258
						135-225	0.637
Accessibility (buffers in km)	0.052	Roads	0.667	Major	0.833	0-5	0.432
						5-10	0.263
						10-15	0.162
						15-20	0.096
						20-50	0.047
				Minor	0.167	0-2	0.467
						2-4	0.278
						4-6	0.16
						6-8	0.095
		Railways	0.333	Tracks	0.222	0-10	0.469
						10-20	0.269
						20-40	0.143
						40-60	0.076
						60-80	0.043
				Stations	0.778	0-10	0.468
						10-20	0.271
						20-40	0.145
						40-60	0.08
						60-80	0.036
Avg Annual Temp. (in degree celsius)	0.036					23.5-25	0.417
						25-26	0.263
						26-27	0.16
						27-28	0.097
						>28	0.063

3.5 Land Suitability Analysis Modeling

In this section, the criteria which were analyzed using GIS, the restrictions defined in the study area, the calculated weights were combined and integrated with each other. The maps related to each criterion were genearted with respective weights and classification. All the maps generated are digitized maps at the scale of 1:60,000. All the relevant criteria layers were prepared according to the criteria and sub-criteria defined in table 3.1. These layers are illustrated in the figures 3.11 to 3.21. Also the solar suitability model for generating the final suitable location map using GIS is shown in figure 3.22.

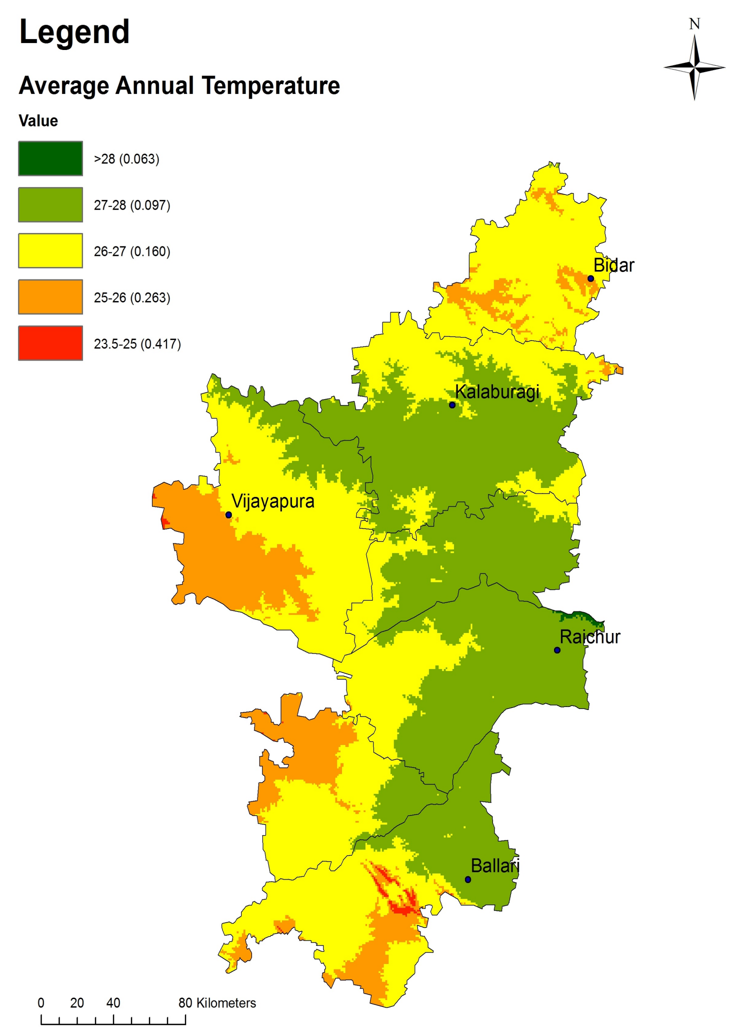


Fig. 3.11 Weighted map of Average Annual Temperature

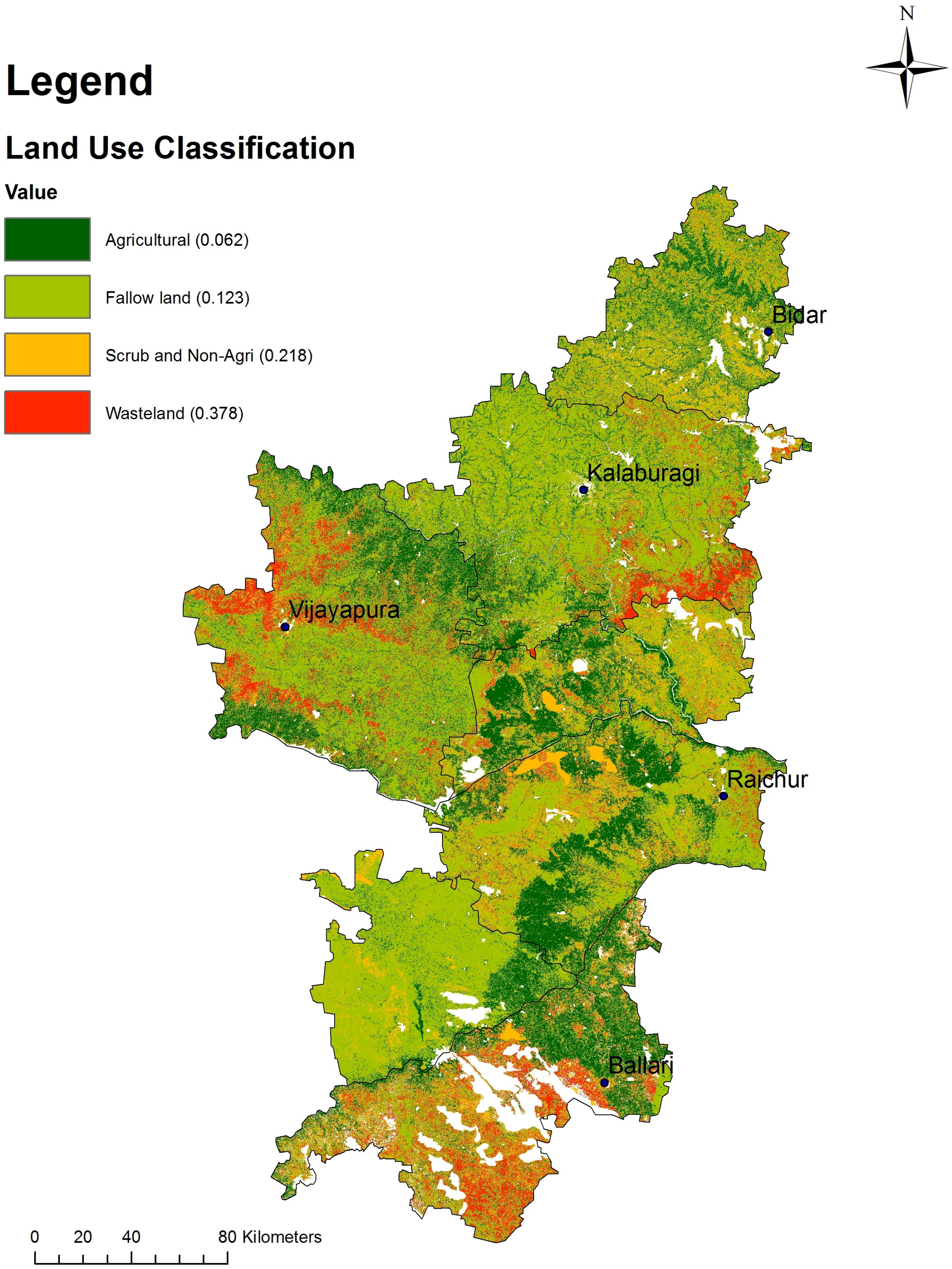


Fig. 3.12 Weighted map of Land use/Land cover classification

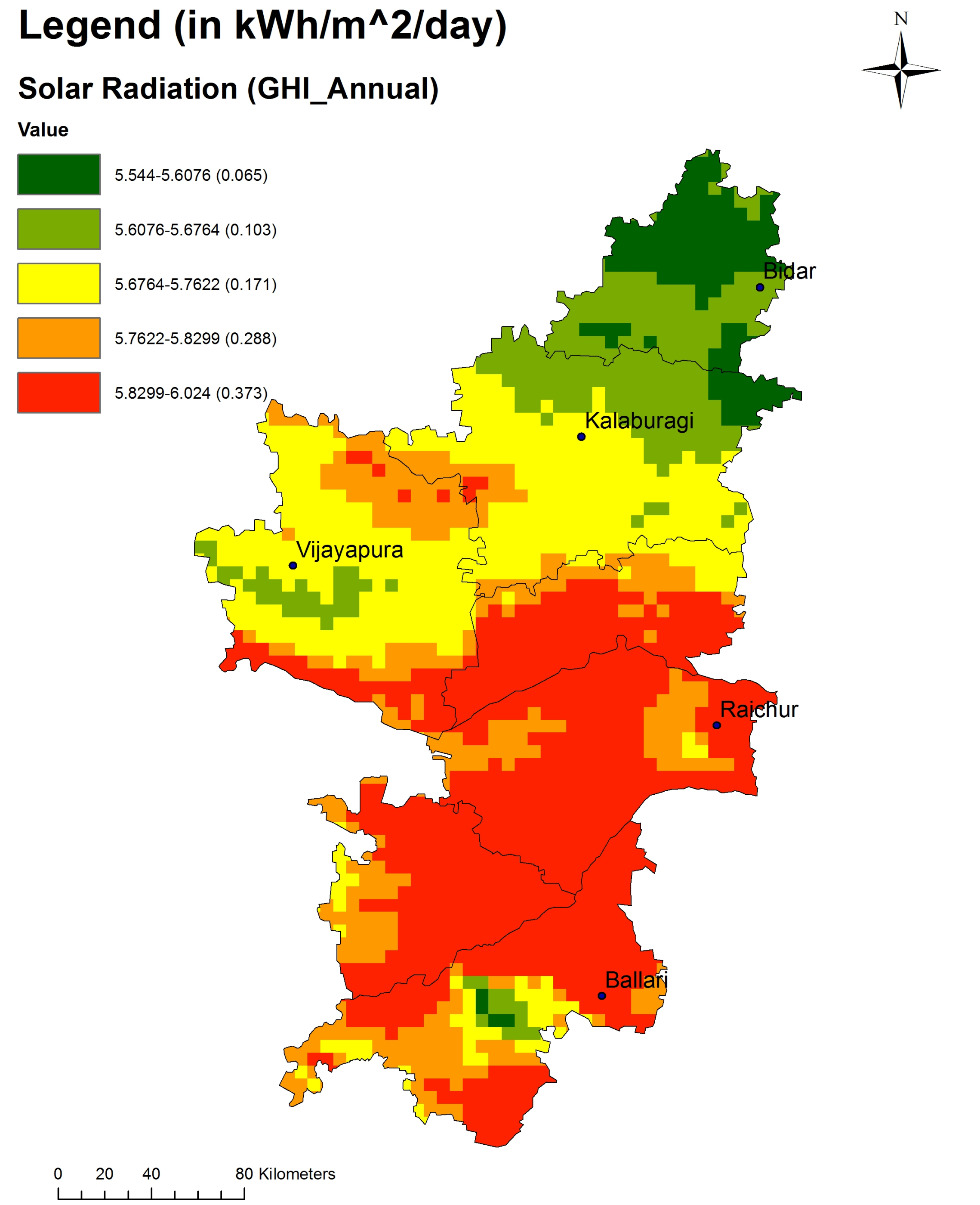


Fig. 3.13 Weighted map for solar radiation (GHI)

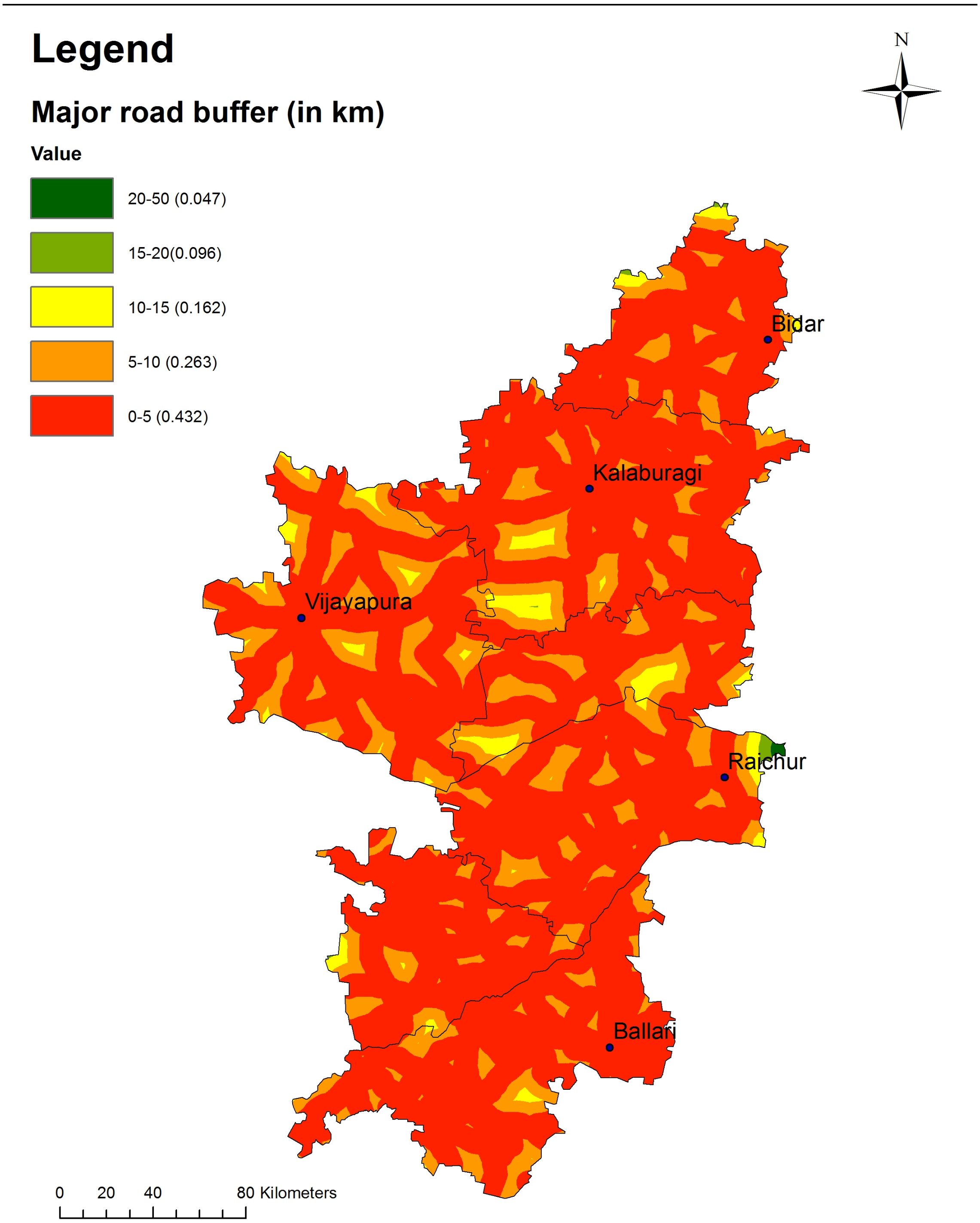


Fig. 3.14 Weighted map of major roads

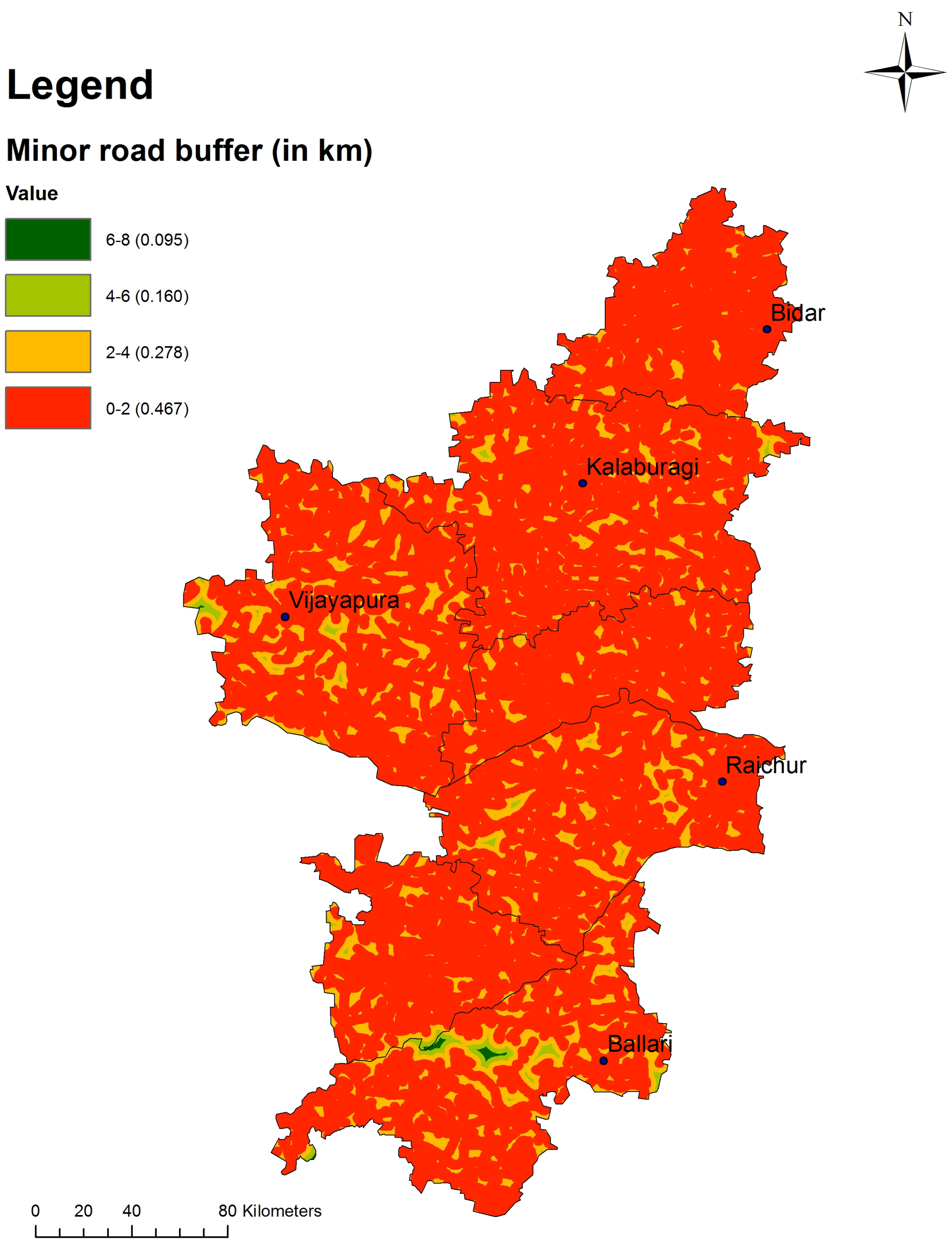


Fig. 3.15 Weighted map of minor roads

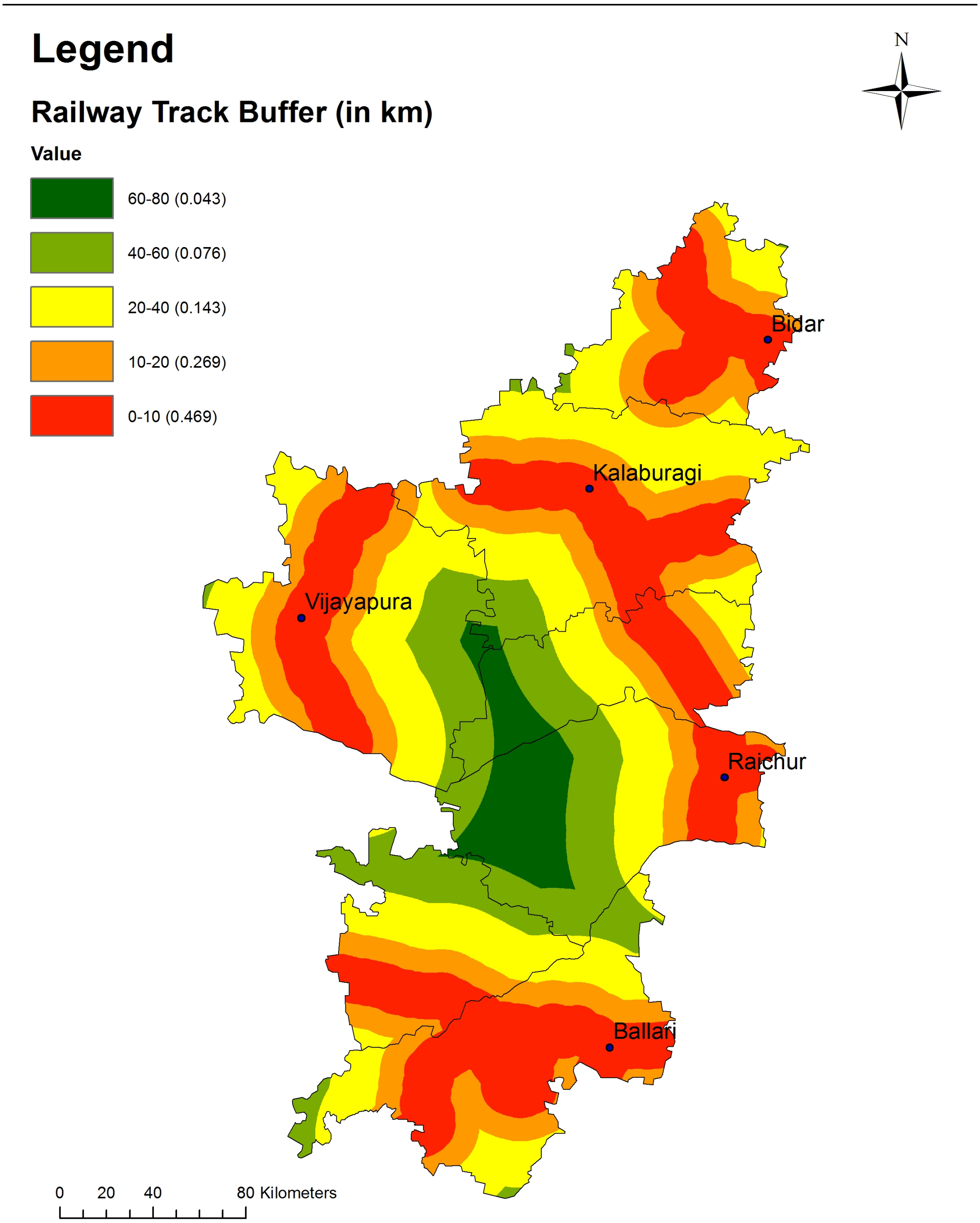


Fig. 3.16 Weighted map of railway tracks

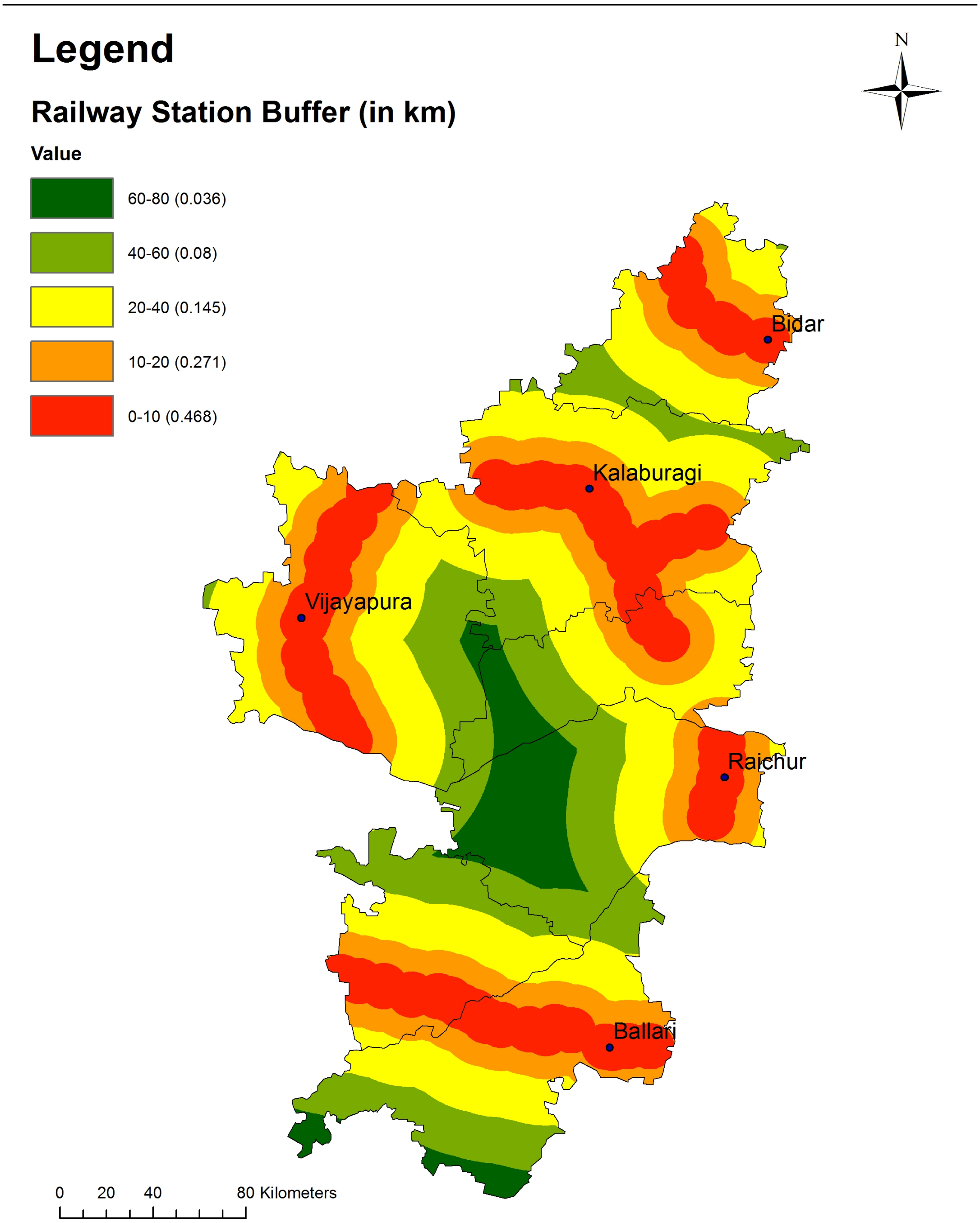


Fig. 3.17 Weighted map of railway station

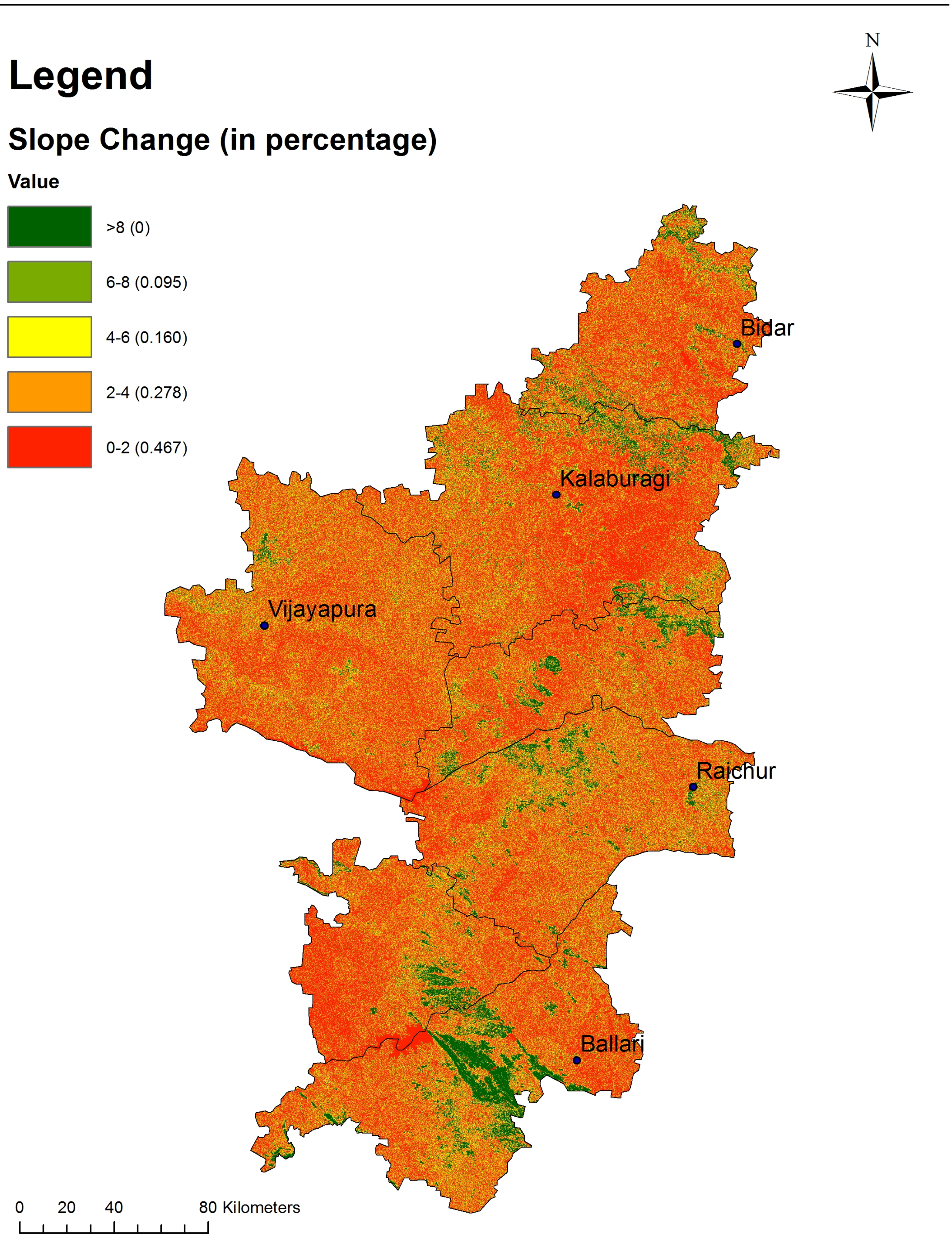


Fig. 3.18 Weighted map of slope

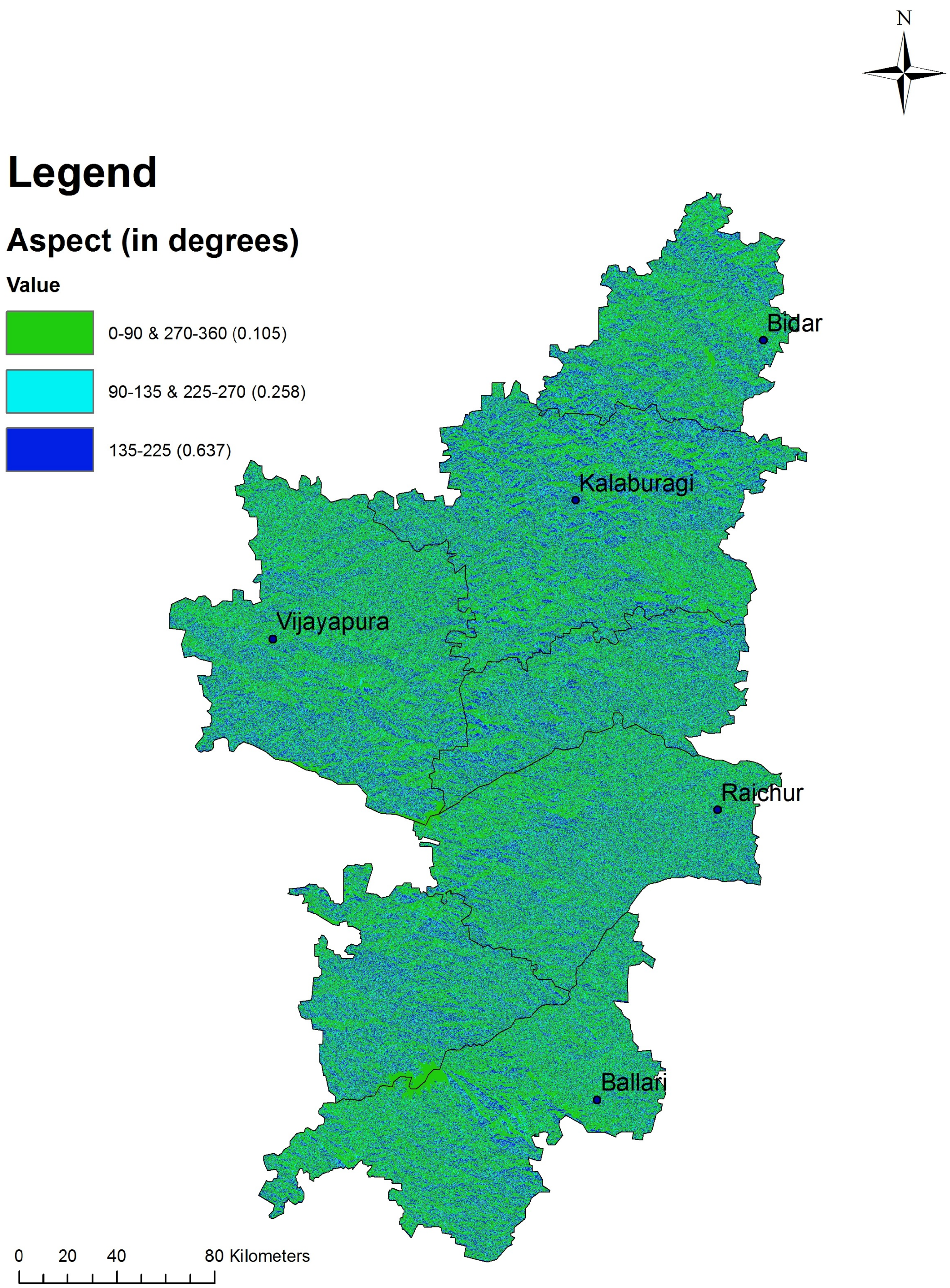


Fig. 3.19 Weighted map of aspect

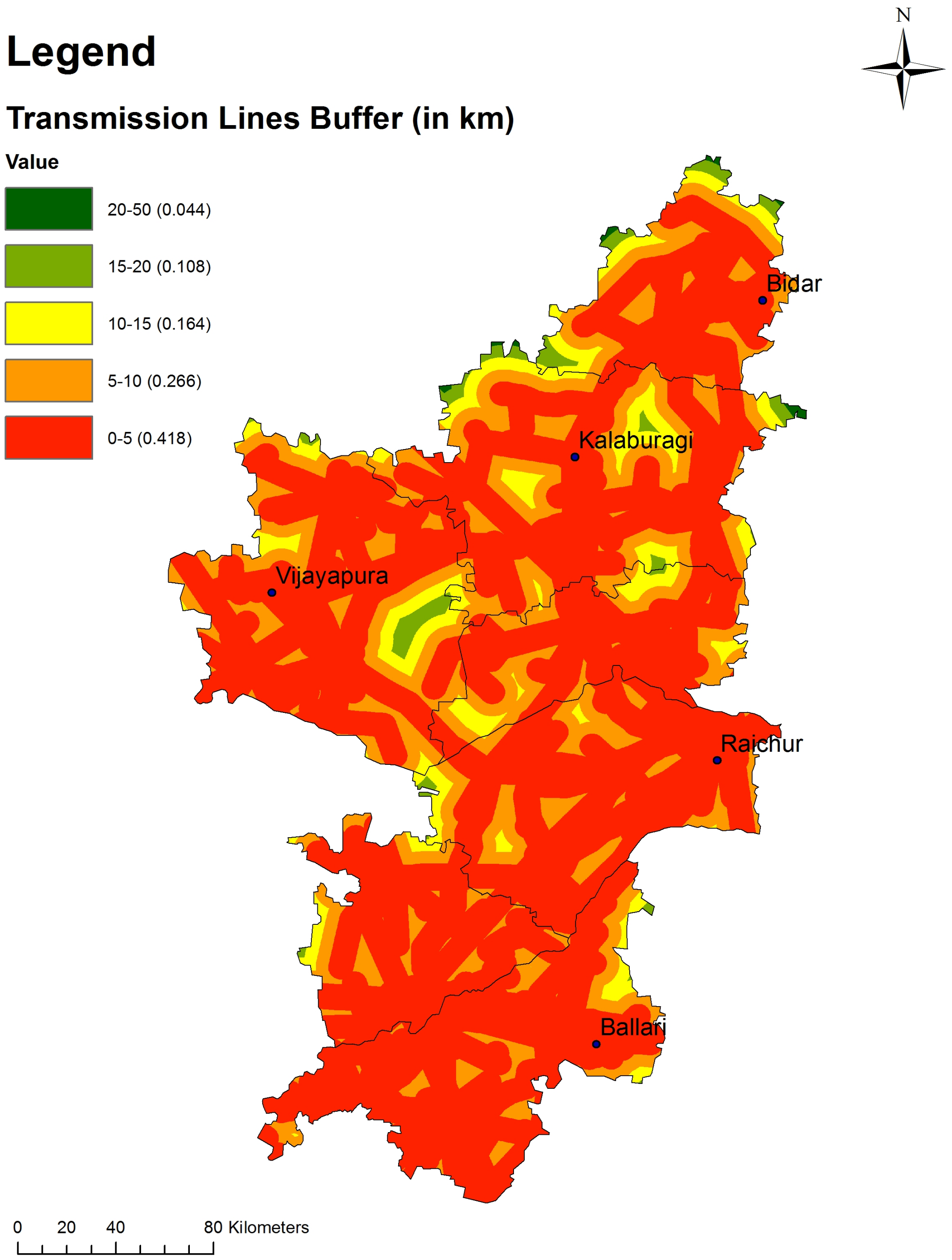


Fig. 3.20 Weighted map of transmission lines

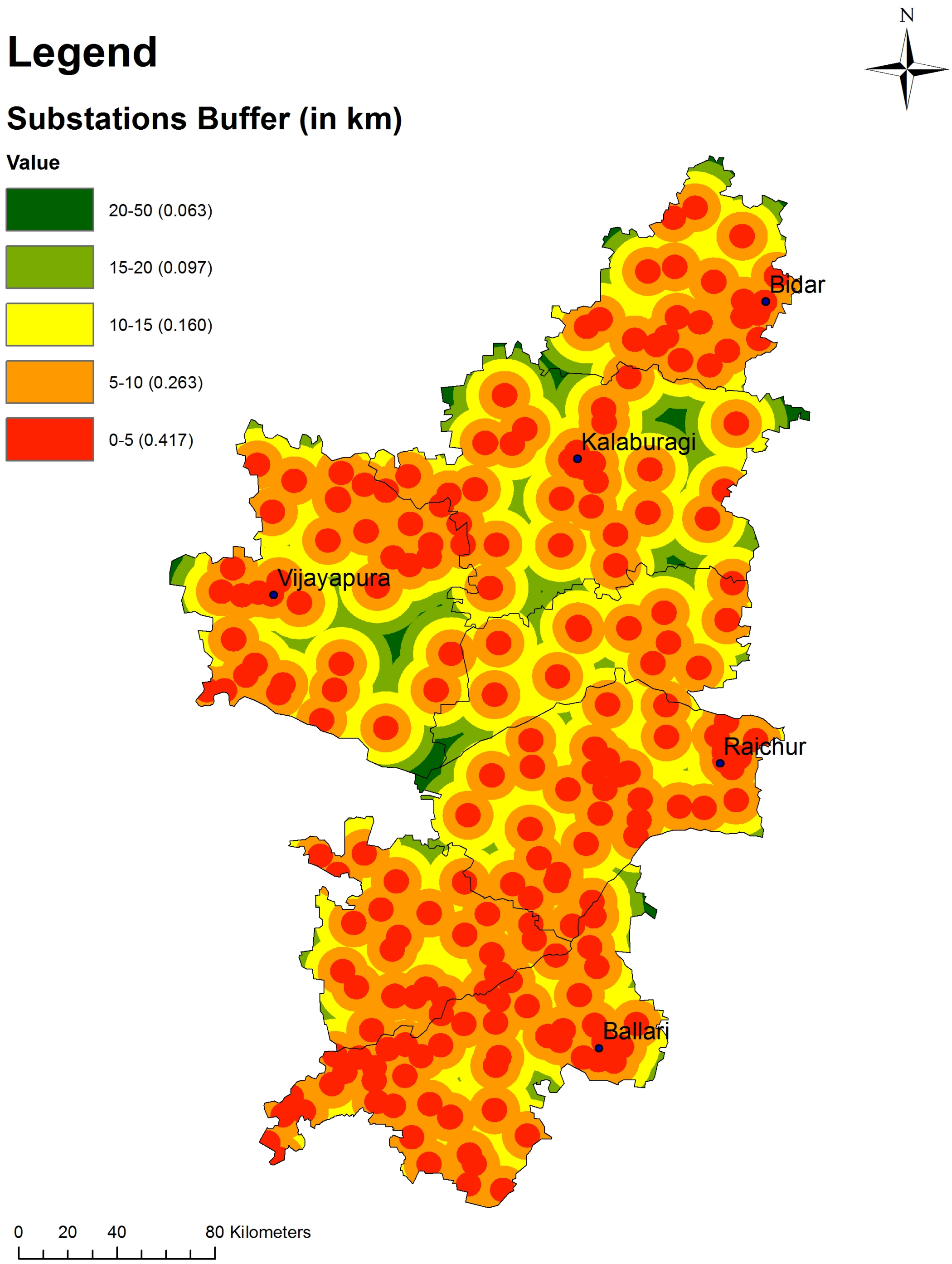


Fig. 3.21 Weighted map of substations

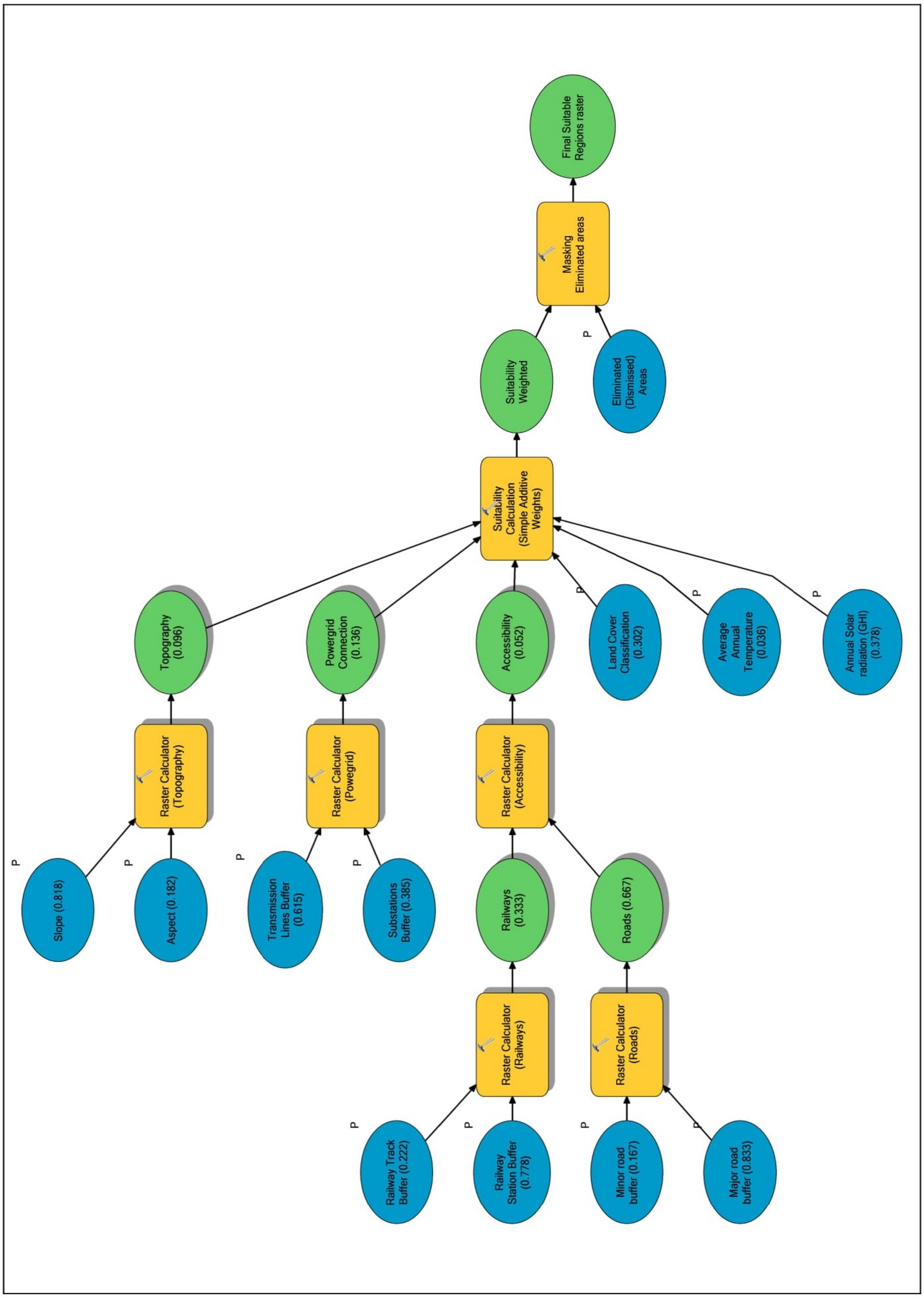


Fig. 3.22 Solar Plant Suitability Model in GIS

After generating all the criteria layers with their respective weights, the Simple Additive Weights (SAW) method is used (as shown in fig 3.22) to overlay all these layers with raster calculator in ArcGIS desktop and obtain the land suitability map for the solar power plant with suitability values ranging from 0.0471 to 3.999. These values are classified into 5 classes of poor(0.0471-0.1659), low(0.1659-0.2091), fair(0.2091-0.2536), good(0.2536-0.3063), excellent(0.3063-0.399) level(fig 3.23).

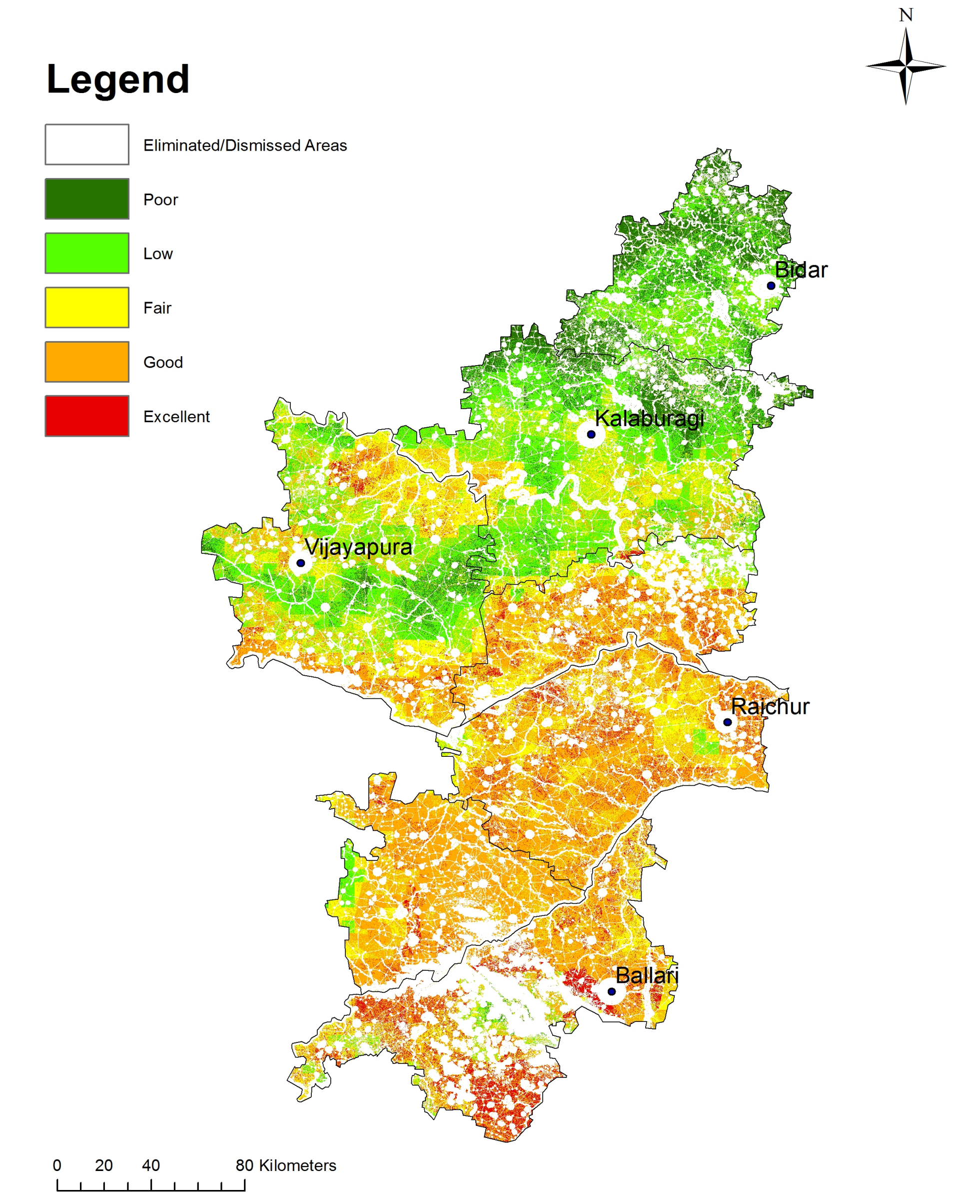


Fig. 3.23 Classified Land Suitability Map for establishing solar PV plants

Chapter 4

Results and Discussions

It can be seen that there's a high accuracy in land suitability model by using the AHP, SAW with GIS. Also, it's to be noted that 4.32%, 23.11%, 15%, 15.63%, 6.28% of the study area are in excellent, good, fair, low, poor classes respectively. About 35.66% of the total study area is classified under eliminated areas (fig 3.3).
Analysis for percentage area distribution among districts, land suitability classes and land use classes is performed. In this research, the values determined for Land Suitability Index (LSI) for each district were determined based on the share of each of the five defined classes in each district area, where higher score represent more suitable regions for constructing solar PV plants.
Relation analysis between districts and land suitability classes shows how land suitability classes are distributed of in each of the district in terms of percentage areas. This distribution can be seen in the table 4.1.

Table 4.1 Percentage area distribution of land suitability classes in each districts

District	Eliminated (%)	Poor (%)	Low (%)	Fair (%)	Good (%)	Excellent (%)	
Bellary	50.6	0.32	1.98	10.44	24.9	11.76	100
Koppal	34.1	0.06	2.49	9.55	51.14	2.66	100
Raichur	31.59	0.01	0.92	16.51	43.64	7.33	100
Yadgir	40.97	0.22	4.13	16.88	31.74	6.06	100
Bijapur	27.87	4.58	25.81	23.43	16.09	2.22	100
Gulbarga	31.83	12.41	33.71	15.89	5.75	0.41	100
Bidar	37.72	28.35	28.06	5.51	0.36	0	100

Relation analysis between land use classes and land suitability classes shows the percentage area distribution of land use classes in each of the land suitability class. This distribution can be seen in the table 4.2 and percentage area distribution of land suitability class in land use classes in the table 4.3.

Table 4.2 Percentage area distribution of land use classes in each of land suitability classes

	Others	Agriculture	Fallow land	Scrub & Non-agri	Wasteland
Eliminated (%)	92.35	35.17	29.24	39.22	34.37
Poor (%)	1.53	9.19	7.3	2.03	1.16
Low (%)	1.86	13.2	21.78	8.92	3.81
Fair (%)	2.59	19.23	15.93	12.96	9
Good (%)	1.32	22.63	24.46	25.29	27.25
Excellent (%)	0.35	0.58	1.29	11.58	24.41
	100	100	100	100	100

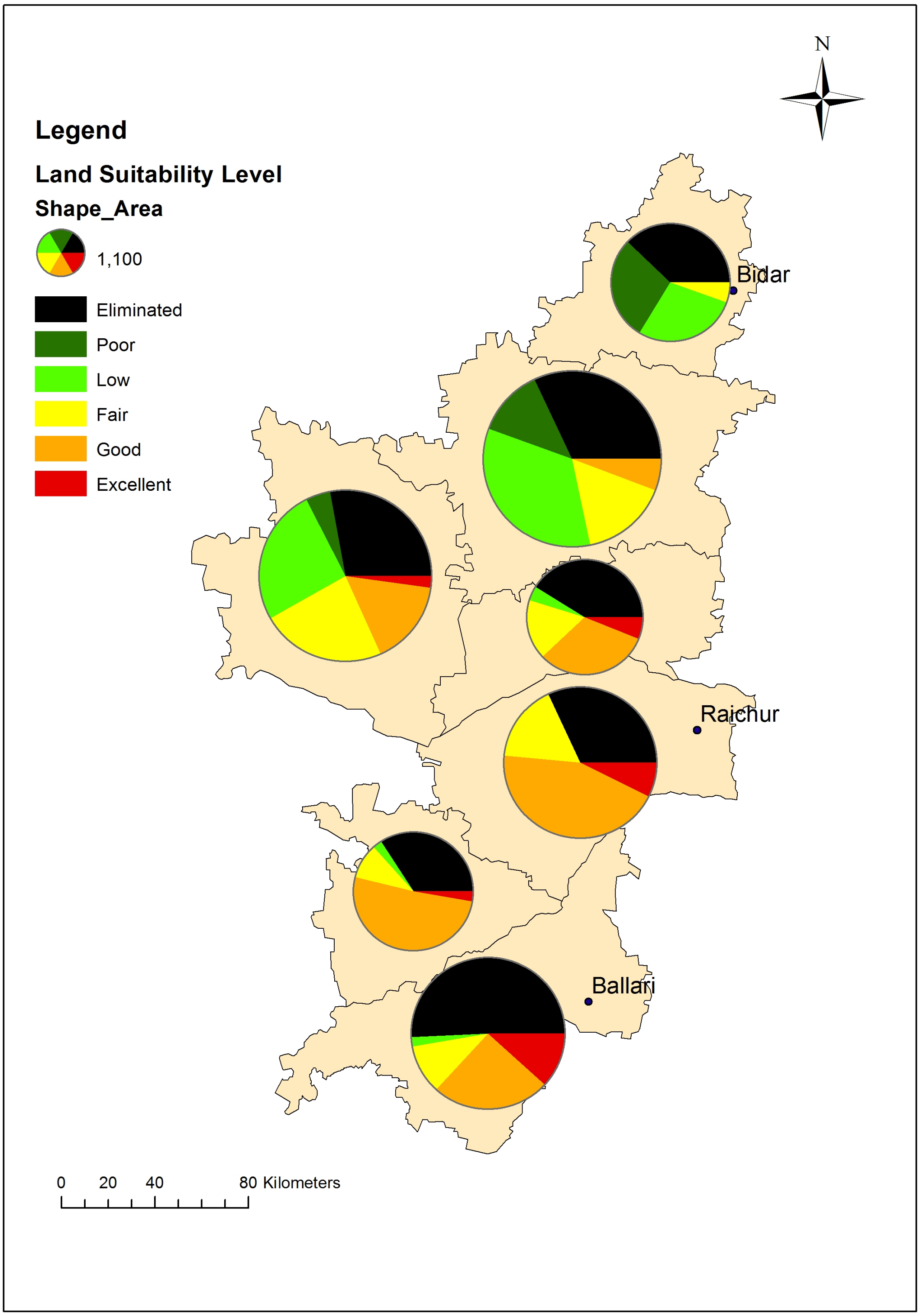
Table 4.3 Percentage area distribution of land suitability classes in land use classes

	Others (%)	Agriculture (%)	Fallow land (%)	Scrub & Non-agri (%)	Wasteland (%)	
Eliminated	14.24	22.88	41.95	12.11	8.82	100
Poor	1.34	33.93	59.47	3.56	1.7	100
Low	0.65	19.59	71.25	6.28	2.23	100
Fair	0.95	29.73	54.32	9.51	5.49	100
Good	0.31	22.72	54.15	12.04	10.78	100
Excellent	0.45	3.07	15.27	29.52	51.69	100

From the relation analysis done in the tables 4.1, 4.2 and 4.3, It can be seen that districts of Bellary, Raichur and Yadgir are best suited for solar PV plant with 11.76%, 7.33% and 6.06% of their area lying in the 'Excellent' class of land suitability respectively. When 'Good' class of land suitability is also considered, Koppal district also joins the category of suitable land region for solar PV plant with 51.14% of its area in 'Good' class along with Bellary, Raichur and Yadgir with 24.9%, 43.64% and 31.74% areas respectively. Thus, the most suitable regions for exploiting solar energy are Bellary, Raichur, Yadgir and Koppal in that order. Due to their geographical location, their arid climate, along with higher number of sunny days and other feasible features, these four districts will be attractive for investment in solar power projects. Land Suitability Maps for Bellary, Raichur, Yadgir and Koppal are shown in the appendix.

In other relation analysis between land use and land suitability classes, wasteland is seen to be distributed in 'excellent', 'good', 'fair' classes with area of 24.41%, 27.25%, and 9%

Table 4.4 Pie-chart showing Land suitabililty classes distribution in each of the districts



respectively. 34.37% of wasteland is dismissed because of restrictive criteria considered in the earlier analysis. Also the scrub & non-agricultural region is distributed among the land suitability classes of 'excellent', 'good' and 'fair' with 11.58%, 25.29% and 12.96% distribution respectively. In the same relation with a different scenario, of the total area of land suitability class of 'Excellent', 51.69% of area is in the wasteland region and 29.52% in scrubs & non-agricultural. In case of 'Good' class, 10.78% of classification is in wasteland and 12.04% in scrubs & non-agricultural.
It can be seen from these relations that the accuracy of land suitability modelling is very convincing with most of the suitable location lying in the wasteland and scrub region, with four districts as major region for the generation of solar power also agreeing with fact that these districts receive comparatively more solar radiation than other districts.

Chapter 5

Conclusions

As a solution to increasing demand for electricity and energy consumption, energy generation capacity of the region has to be developed and increased. In the upcoming years, with challenges like global warming, increasing pollutants in the atmosphere due to fossil fuels, there's a need to switch to more economical, enironmental friendly, vastly available, energy resources. These renewable energy sources are perfect fit for this requirement with few more characteristics such as pollution reduction, and helping sustainable development of the energy sector.

The initial investment into these solar power plants are considerably high and therefore the identification of the best suitable sites to establish the plant can be considered as the most important step in the development of this energy sector. This study provides a practical approach, considering technical, environmental, geographical, and economic criteria, to assess and prioritize the region of north Karnataka for exploiting solar energy using geographical information system (GIS) and AHP technique.

From the final results of land suitability map, it's indicated that 4.32% of the entire study region is classified as excellent level in land suitability, where as 23.11% of the area is under Good level, 15% under fair level, 15.63% under low level and 6.28% under poor level with lowest priority for installation of solar PV plant. Also, The districts of Bellary, Raichur, Yadgir and Koppal in that order are well suited for establishing solar plants with almost 85% of the total excellent level land suitability lying in these districts, with Bellary and Raichur having a greater potential for development of technology for utilizing solar energy.

With many challenges and limitations for people and government to develop and establish solar energy plants, the results of this study could be helpful to planners because of the accuracy of the procedure for investigating the criteria and the obtained results. These results further could help in analyzing solar power potential and the cost estimation for the plants. Both at central and state level, governmnents need to help businesses to invest in this energy sector to explore new opportunities and sustainable development, by providing subsidies, contracts and encouraging an economic collaboration.

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Appendix A

A.1 Land Suitability Maps for Bellary, Raichur, Yadgir and Koppal

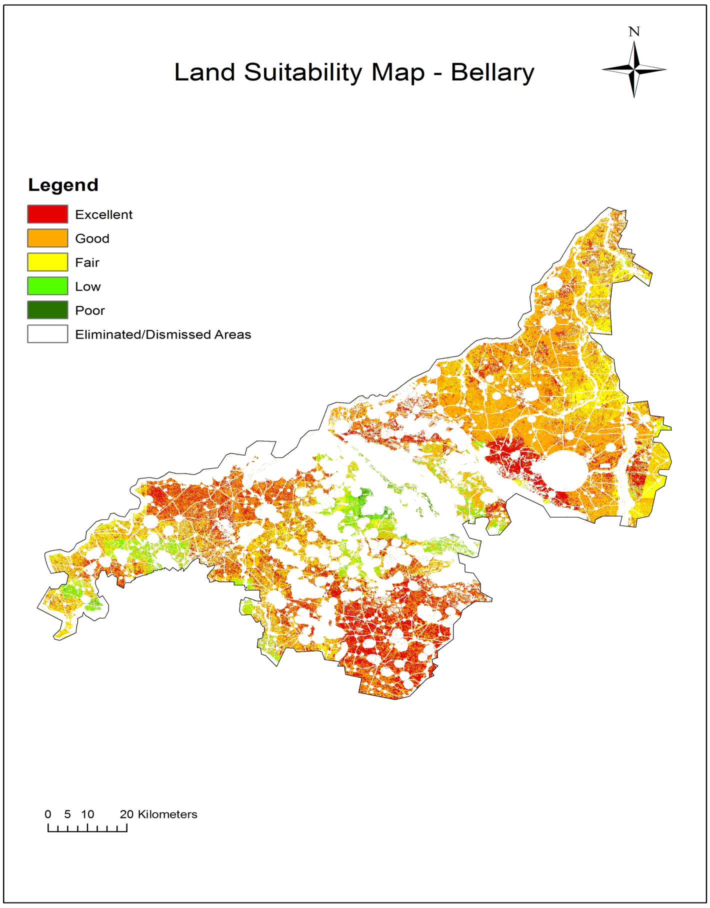

Fig. A.1 Land Suitability Map for Bellary

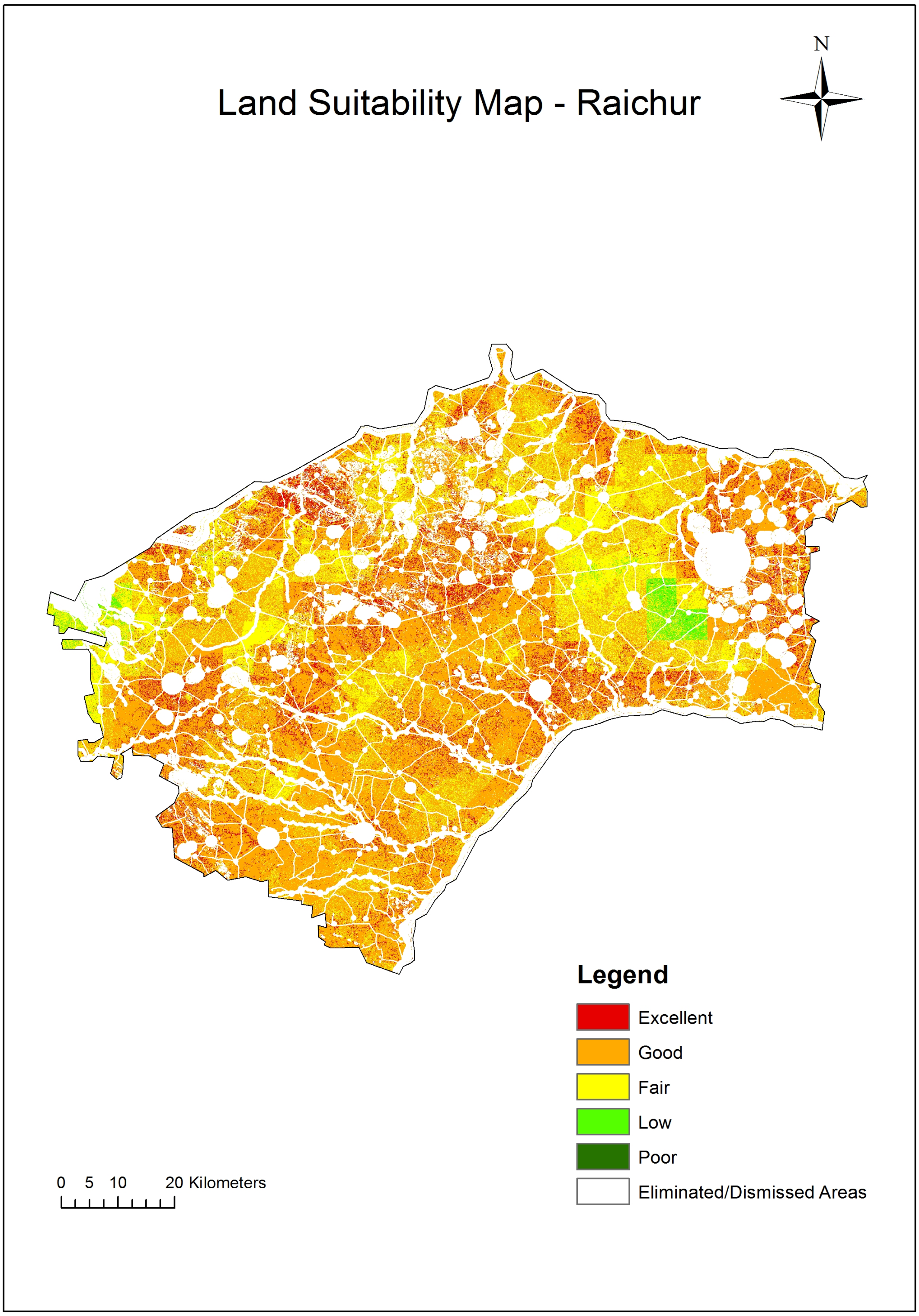

Fig. A.2 Land Suitability Map for Raichur

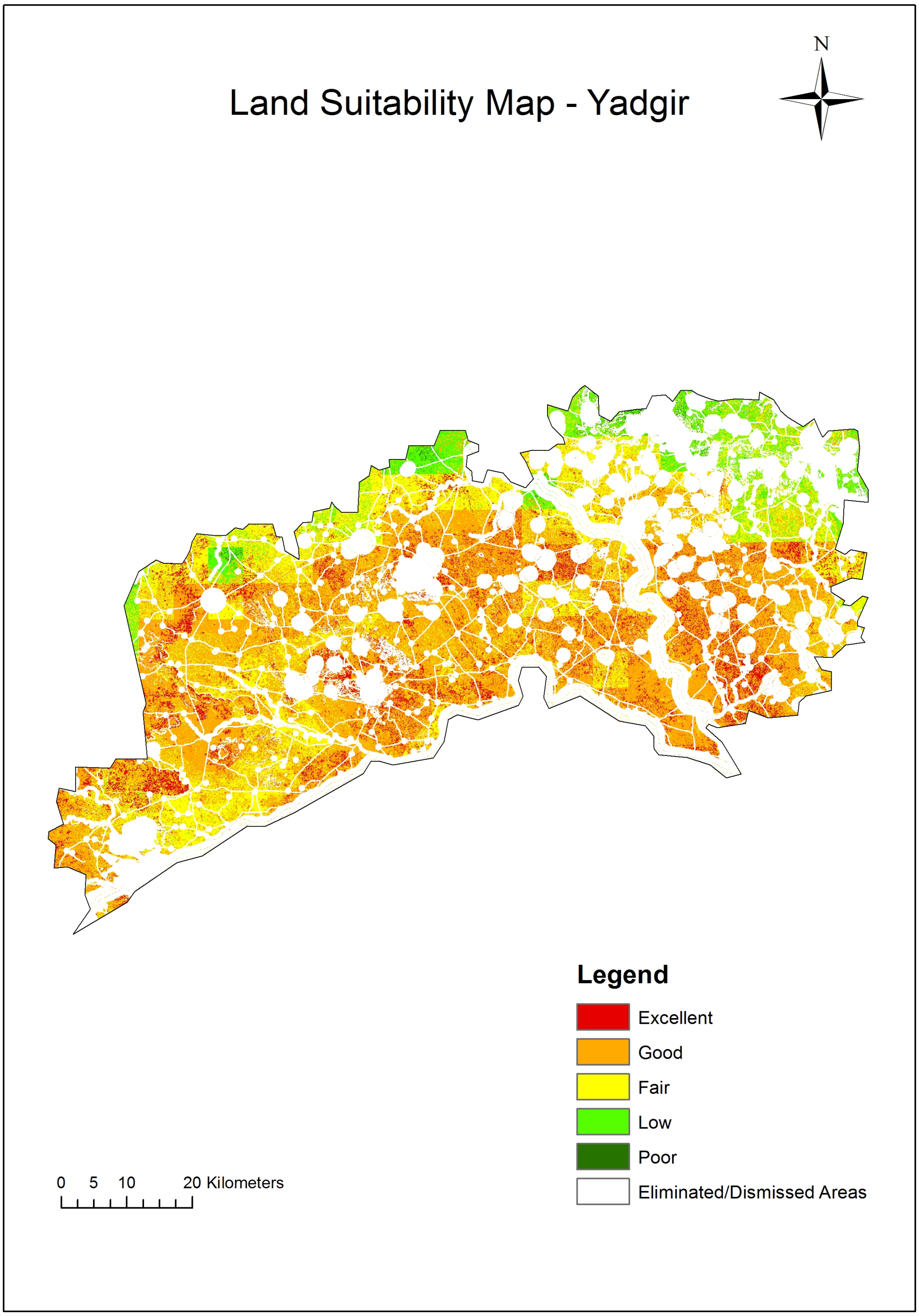

Fig. A.3 Land Suitability Map for Yadgir

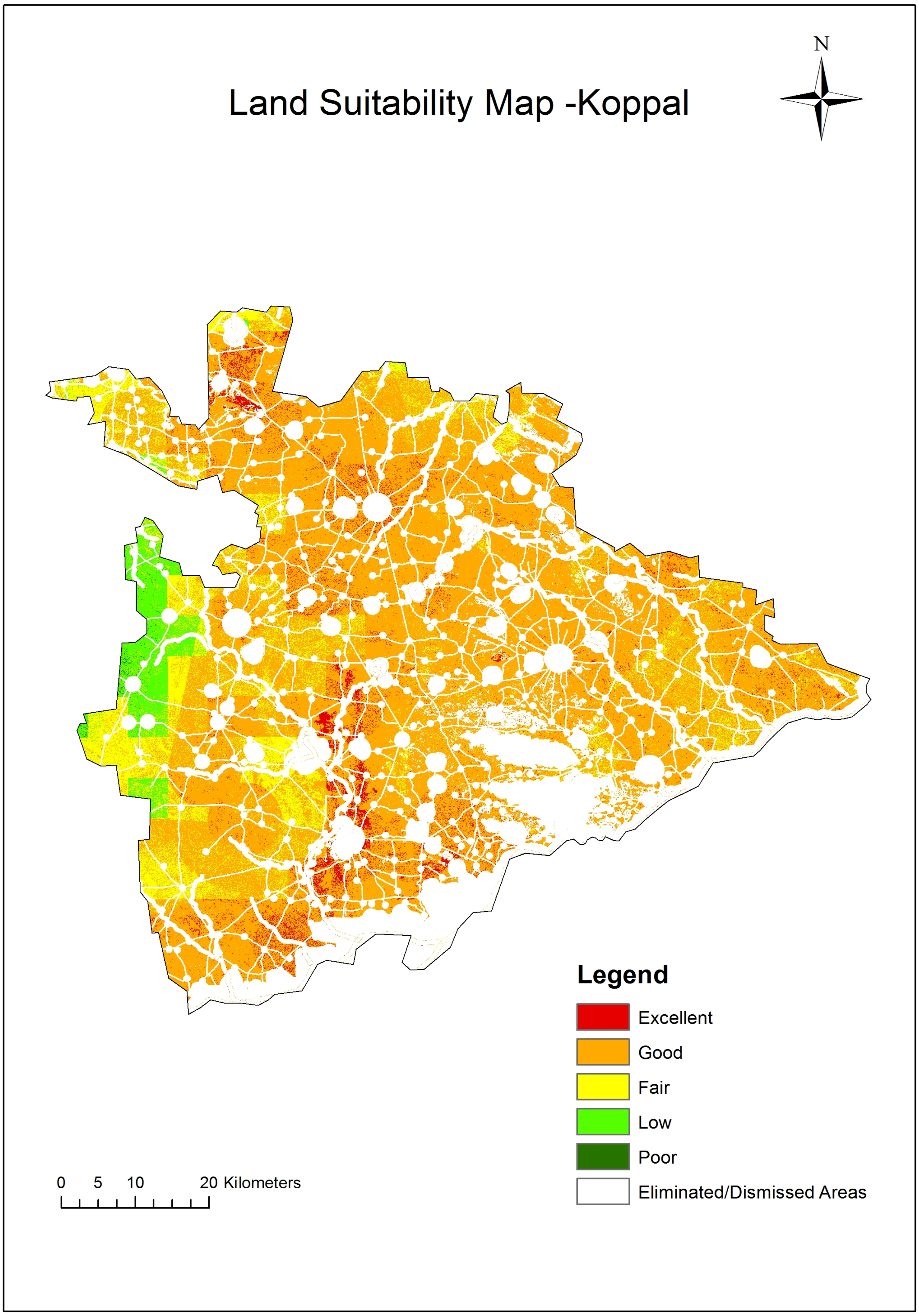

Fig. A.4 Land Suitability Map for Koppal

A.2 Analytic Hierarchy process [1]

The *Analytic Hierarchy Process* (AHP), introduced by Thomas Saaty (1980), is an effective tool for dealing with complex decision making, and may aid the decision maker to set priorities and make the best decision. By reducing complex decisions to a series of pairwise comparisons, and then synthesizing the results, the AHP helps to capture both subjective and objective aspects of a decision. In addition, the AHP incorporates a useful technique for checking the consistency of the decision maker's evaluations, thus reducing the bias in the decision making process.

1 How the AHP works

The AHP considers a set of evaluation criteria, and a set of alternative options among which the best decision is to be made. It is important to note that, since some of the criteria could be contrasting, it is not true in general that the best option is the one which optimizes each single criterion, rather the one which achieves the most suitable trade-off among the different criteria.

The AHP generates a weight for each evaluation criterion according to the decision maker's pairwise comparisons of the criteria. The higher the weight, the more important the corresponding criterion. Next, for a fixed criterion, the AHP assigns a score to each option according to the decision maker's pairwise comparisons of the options based on that criterion. The higher the score, the better the performance of the option with respect to the considered criterion. Finally, the AHP combines the criteria weights and the options scores, thus determining a global score for each option, and a consequent ranking. The global score for a given option is a weighted sum of the scores it obtained with respect to all the criteria.

2 Features of the AHP

The AHP is a very flexible and powerful tool because the scores, and therefore the final ranking, are obtained on the basis of the pairwise relative evaluations of both the criteria and the options provided by the user. The computations made by the AHP are always guided by the decision maker's experience, and the AHP can thus be considered as a tool that is able to translate the evaluations (both qualitative and quantitative) made by the decision maker into a multicriteria ranking. In addition, the AHP is simple because there is no need of building a complex expert system with the decision maker's knowledge embedded in it.

On the other hand, the AHP may require a large number of evaluations by the user, especially for problems with many criteria and options. Although every single evaluation is very simple, since it only requires the decision maker to express how two options or criteria compare to each other, the load of the evaluation task may become unreasonable. In fact the number of pairwise comparisons grows quadratically with the number of criteria and options. For instance, when comparing 10 alternatives on 4 criteria, $4 \cdot 3/2=6$ comparisons are requested to build the weight vector, and $4 \cdot (10 \cdot 9/2)=180$ pairwise comparisons are needed to build the score matrix.

However, in order to reduce the decision maker's workload the AHP can be completely or partially automated by specifying suitable thresholds for automatically deciding some pairwise comparisons.

3 Implementation of the AHP

The AHP can be implemented in three simple consecutive steps:

1) Computing the vector of criteria weights.

2) Computing the matrix of option scores.
3) Ranking the options.

Each step will be described in detail in the following. It is assumed that m evaluation criteria are considered, and n options are to be evaluated. A useful technique for checking the reliability of the results will be also introduced.

3.1 Computing the vector of criteria weights

In order to compute the weights for the different criteria, the AHP starts creating a *pairwise comparison matrix* **A**. The matrix **A** is a $m \times m$ real matrix, where m is the number of evaluation criteria considered. Each entry a_{jk} of the matrix **A** represents[1] the importance of the jth criterion relative to the kth criterion. If $a_{jk} > 1$, then the jth criterion is more important than the kth criterion, while if $a_{jk} < 1$, then the jth criterion is less important than the kth criterion. If two criteria have the same importance, then the entry a_{jk} is 1. The entries a_{jk} and a_{kj} satisfy the following constraint:

$$a_{jk} \cdot a_{kj} = 1. \tag{1}$$

Obviously, $a_{jj} = 1$ for all j. The relative importance between two criteria is measured according to a numerical scale from 1 to 9, as shown in Table 1, where it is assumed that the jth criterion is equally or more important than the kth criterion. The phrases in the "Interpretation" column of Table 1 are only suggestive, and may be used to translate the decision maker's qualitative evaluations of the relative importance between two criteria into numbers. It is also possible to assign intermediate values which do not correspond to a precise interpretation. The values in the matrix **A** are by construction pairwise consistent, see (1). On the other hand, the ratings may in general show slight inconsistencies. However these do not cause serious difficulties for the AHP.

Value of a_{jk}	***Interpretation***
1	j and k are equally important
3	j is slightly more important than k
5	j is more important than k
7	j is strongly more important than k
9	j is absolutely more important than k

Table 1. Table of relative scores.

Once the matrix **A** is built, it is possible to derive from **A** the *normalized pairwise comparison matrix* $\mathbf{A}_{norm}$ by making equal to 1 the sum of the entries on each column, i.e. each entry $\bar{a}_{jk}$ of the matrix $\mathbf{A}_{norm}$ is computed as

$$\bar{a}_{jk} = \frac{a_{jk}}{\sum_{l=1}^{m} a_{lk}}. \tag{2}$$

Finally, the *criteria weight vector* $\mathbf{w}$ (that is an m-dimensional column vector) is built by averaging the entries on each row of $\mathbf{A}_{norm}$, i.e.

$$w_j = \frac{\sum_{l=1}^{m} \bar{a}_{jl}}{m}. \tag{3}$$

[1] For a matrix **A**, a_{ij} denotes the entry in the ith row and the jth column of **A**. For a vector **v**, v_i denotes the ith element of **v**.

3.2 Computing the matrix of option scores

The matrix of option scores is a $n \times m$ real matrix **S**. Each entry s_{ij} of **S** represents the score of the ith option with respect to the jth criterion. In order to derive such scores, a *pairwise comparison matrix* $\mathbf{B}^{(j)}$ is first built for each of the m criteria, $j=1,...,m$. The matrix $\mathbf{B}^{(j)}$ is a $n \times n$ real matrix, where n is the number of options evaluated. Each entry $b_{ih}^{(j)}$ of the matrix $\mathbf{B}^{(j)}$ represents the evaluation of the ith option compared to the hth option with respect to the jth criterion. If $b_{ih}^{(j)} > 1$, then the ith option is better than the hth option, while if $b_{ih}^{(j)} < 1$, then the ith option is worse than the hth option. If two options are evaluated as equivalent with respect to the jth criterion, then the entry $b_{ih}^{(j)}$ is 1. The entries $b_{ih}^{(j)}$ and $b_{hi}^{(j)}$ satisfy the following constraint:

$$b_{ih}^{(j)} \cdot b_{hi}^{(j)} = 1 \tag{4}$$

and $b_{ii}^{(j)} = 1$ for all i. An evaluation scale similar to the one introduced in Table 1 may be used to translate the decision maker's pairwise evaluations into numbers.

Second, the AHP applies to each matrix $\mathbf{B}^{(j)}$ the same two-step procedure described for the pairwise comparison matrix **A**, i.e. it divides each entry by the sum of the entries in the same column, and then it averages the entries on each row, thus obtaining the score vectors $\boldsymbol{s}^{(j)}$, $j=1,...,m$. The vector $\boldsymbol{s}^{(j)}$ contains the scores of the evaluated options with respect to the jth criterion.

Finally, the score matrix **S** is obtained as

$$\mathbf{S} = [\, \boldsymbol{s}^{(1)} \dots \boldsymbol{s}^{(m)} \,] \tag{5}$$

i.e. the jth column of **S** corresponds to $\boldsymbol{s}^{(j)}$.

Remark. In the considered DSS structure, the pairwise option evaluations are performed by comparing the values of the performance indicators corresponding to the decision criteria. Hence, this step of the AHP can be considered as a transformation of the indicator matrix **I** into the score matrix **S**.

3.3 Ranking the options

Once the weight vector $\boldsymbol{w}$ and the score matrix **S** have been computed, the AHP obtains a vector **v** of global scores by multiplying **S** and **w**, i.e.

$$\boldsymbol{v} = \mathbf{S} \cdot \boldsymbol{w} \tag{6}$$

The ith entry v_i of **v** represents the global score assigned by the AHP to the ith option. As the final step, the option ranking is accomplished by ordering the global scores in decreasing order.

4 Checking the consistency

When many pairwise comparisons are performed, some inconsistencies may typically arise. One example is the following. Assume that 3 criteria are considered, and the decision maker evaluates that the first criterion is *slightly* more important than the second criterion, while the second criterion is *slightly* more important than the third criterion. An evident inconsistency arises if the decision maker evaluates by mistake that the third criterion is equally or more important than the first criterion. On the other hand, a slight inconsistency arises if the decision maker evaluates that the first criterion is also *slightly* more important than the third criterion. A consistent evaluation would be, for instance, that the first criterion is more important than the third criterion.

The AHP incorporates an effective technique for checking the consistency of the evaluations made by the decision maker when building each of the pairwise comparison matrices involved in the process, namely the matrix **A** and the matrices $\mathbf{B}^{(j)}$. The technique relies on the computation of a suitable *consistency index*, and will be described only for the matrix **A**. It is straightforward to adapt it to the case of the matrices $\mathbf{B}^{(j)}$ by replacing **A** with $\mathbf{B}^{(j)}$, $\boldsymbol{w}$ with $\boldsymbol{s}^{(j)}$, and m with n. The *Consistency Index* (*CI*) is obtained by first computing the scalar x as the average of the elements of the vector whose jth element is the ratio of the jth element of the vector $\mathbf{A}\cdot\boldsymbol{w}$ to the corresponding element of the vector $\boldsymbol{w}$. Then,

$$CI = \frac{x-m}{m-1}. \tag{7}$$

A perfectly consistent decision maker should always obtain *CI*=0, but small values of inconsistency may be tolerated. In particular, if

$$\frac{CI}{RI} < 0.1 \tag{8}$$

the inconsistencies are tolerable, and a reliable result may be expected from the AHP. In (8) *RI* is the *Random Index*, i.e. the consistency index when the entries of **A** are completely random. The values of *RI* for small problems ($m \le 10$) are shown in Table 2.

m	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

Table 2. Values of the *Random Index* (*RI*) for small problems.

The matrices **A** corresponding to the cases considered in the above example are shown below, together with their consistency evaluation based on the computation of the consistency index. Note that the conclusions are as expected.

$$\mathbf{A} = \begin{bmatrix} 1 & 3 & 1/3 \\ 1/3 & 1 & 3 \\ 3 & 1/3 & 1 \end{bmatrix} \Rightarrow \text{CI/RI} = 1.150 \quad \Rightarrow \text{inconsistent}$$

$$\mathbf{A} = \begin{bmatrix} 1 & 3 & 3 \\ 1/3 & 1 & 3 \\ 1/3 & 1/3 & 1 \end{bmatrix} \Rightarrow \text{CI/RI} = 0.118 \quad \Rightarrow \text{slightly inconsistent}$$

$$\mathbf{A} = \begin{bmatrix} 1 & 3 & 5 \\ 1/3 & 1 & 3 \\ 1/5 & 1/3 & 1 \end{bmatrix} \Rightarrow \text{CI/RI} = 0.033 \quad \Rightarrow \text{consistent}$$

5 Automating the pairwise comparisons

Although every single AHP evaluation is very simple (the decision maker is only required to express how two criteria or alternatives compare to each other), the load of the evaluation task may become unreasonable and tedious for the decision maker when many criteria and alternatives are considered. However, in order to alleviate the decision maker's workload, some pairwise comparisons can be completely or partially automated. A simple method is suggested in the following.

Let the jth criterion be expressed by an attribute which assumes values in the interval $[I_{j,\min}, I_{j,\max}]$, and let $I_j^{(i)}$ and $I_j^{(h)}$ be the instances of the attribute under the ith and hth control options, respectively. Assume that the larger the value of the attribute, the better the system performance according to the jth criterion. If $I_j^{(i)} \geq I_j^{(h)}$, the element $b_{ih}^{(j)}$ of $\mathbf{B}^{(j)}$ can be computed as

$$b_{ih}^{(j)} = 8\frac{I_j^{(i)} - I_j^{(h)}}{I_{j,\max} - I_{j,\min}} + 1. \tag{10}$$

A similar expression holds if the smaller the value of the attribute, the better the system performance according to the jth criterion. If $I_j^{(i)} \leq I_j^{(h)}$, the element $b_{ih}^{(j)}$ of $\mathbf{B}^{(j)}$ can be computed as

$$b_{ih}^{(j)} = 8\frac{I_j^{(h)} - I_j^{(i)}}{I_{j,\max} - I_{j,\min}} + 1. \tag{11}$$

Note that (10) and (11) are linear functions of the difference $I_{ij} - I_{hj}$. Of course, More sophisticated functions can be designed by exploiting specific knowledge and/or experience.

6 An illustrative example

An example will be here described in order to clarify the mechanism of the AHP. m=3 evaluation criteria are considered, and n=3 alternatives are evaluated. Each criterion is expressed by an attribute. The larger the value of the attribute, the better the performance of the option with respect to the corresponding criterion. The decision maker first builds the following pairwise comparison matrix for the three criteria:

$$\mathbf{A} = \begin{bmatrix} 1 & 3 & 5 \\ 1/3 & 1 & 3 \\ 1/5 & 1/3 & 1 \end{bmatrix}$$

to which corresponds the weight vector $\boldsymbol{w}$ = [0.633 0.261 0.106]^T. Then, based on the values assumed by the attributes for the three options (see Figure 1), the decision maker builds the following pairwise comparison matrices:

$$\mathbf{B}^{(1)} = \begin{bmatrix} 1 & 3 & 7 \\ 1/3 & 1 & 5 \\ 1/7 & 1/5 & 1 \end{bmatrix}, \qquad \mathbf{B}^{(2)} = \begin{bmatrix} 1 & 1/5 & 1 \\ 5 & 1 & 5 \\ 1 & 1/5 & 1 \end{bmatrix}, \qquad \mathbf{B}^{(3)} = \begin{bmatrix} 1 & 5 & 9 \\ 1/5 & 1 & 3 \\ 1/9 & 1/3 & 1 \end{bmatrix}$$

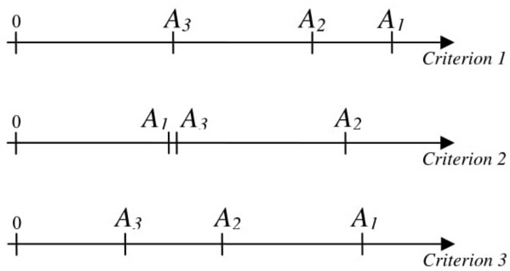

Figure 1. Values of the attributes for the alternatives A_1, A_2 and A_3 (the scale on each axis is not relevant).

to which correspond the score vectors $\boldsymbol{s}^{(1)} = [\ 0.643\ 0.283\ 0.074\ ]^T$, $\boldsymbol{s}^{(2)} = [\ 0.143\ 0.714\ 0.143\ ]^T$, and $\boldsymbol{s}^{(3)} = [\ 0.748\ 0.180\ 0.072\ ]^T$.

Hence, the score matrix **S** is

$$\mathbf{S} = [\boldsymbol{s}^{(1)} \quad \boldsymbol{s}^{(2)} \quad \boldsymbol{s}^{(3)}] = \begin{bmatrix} 0.643 & 0.143 & 0.748 \\ 0.283 & 0.714 & 0.180 \\ 0.074 & 0.143 & 0.072 \end{bmatrix}$$

and the global score vector is $\boldsymbol{v} = \mathbf{S} \cdot \boldsymbol{w} = [\ 0.523\ 0.385\ 0.092\ ]^T$. Note that the first option turns out to be the most preferable, though it is the worst of the three with respect to the second criterion.