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GIS-Based Road Network Connectivity Assessment and Its Impact on Agricultural Characteristics Using Graph Theory: A Block-Level Study in the Hill Area of Darjeeling District, West Bengal

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Abstract

The topological structure of connectivity and accessibility is one of the important elements that reveal the shape of any region. The road network is a key component of rural development, as it promotes access to economic and social services, increased agricultural and non-agricultural productivity, generating employment which expands rural growth opportunities and overall income leading to poverty reduction. The knowledge of the topographical characteristics of road networks has improved due to the recent development of the Geographic Information System (GIS). The present chapter uses graph theory to examine the accessibility and connectivity of the road network in five hilly blocks of the Darjeeling district named Darjeeling-Pulbazar, Jorebunglow-Sukiapokhri, Kurseong, Mirik, and Rangli-Rangliot. Additionally, the connection index, the detour index, the associated number, and aggregate transport score have all been used to classify the degree of network accessibility. The outcome reveals that under the study area, there is a serious need to identify the improvement of agricultural characteristics through connectivity and network accessibility between the hilly blocks of the Darjeeling district. It is also observed that most of the accessible villages are centrally placed and close to urban areas.

Keywords

Darjeeling district · GIS · Connectivity · Accessibility · Aggregate transport score (ATC)

16.1 Introduction

The purpose of transportation is to make it easier for people to access commodities, services, and knowledge. To lead a fruitful economic and social life, people require access to a wide range of products, services, and information (Sahitya and Prasad 2020). Urban and rural locations, as well as developing and developed nations, have quite different transportation patterns. Research has shown that rural transportation in developing nations has unique characteristics. People move around in rural areas for a variety of subsistence, social, and economic reasons (Holl 2007). Most transportation is done on foot and occurs mostly within and outside the village, far from the road system. Subsequently, access is the ultimate goal

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to reach the essential services, goods, and resources that rural populations require to live decent, productive lives on a social and economic level (Páez et al. 2012). The essential needs of rural residents are water, food, and firewood, and the social and economic welfare components of rural life are such as health and education as well; their basic needs like agriculture, domestic animals, and home industries are all connected to transportation (Nagne and Gawali 2013). The freight movement during production makes transportation an essential part of the agro-industrial complex. Due to its multifaceted functions and significance in maintaining relationships and creating integrations of people, goods, and services, transportation has become a necessary component of modern life (Umoren et al. 2009). Accelerated infrastructure investment in rural areas is required to provide employment and open new business opportunities (Sharma and Ram 2023; Sarkar 2013). All of these ultimately result in a higher standard of living and lessen the vulnerability of the rural poor (Levy 1996). Rural transportation and communication infrastructure development promotes rural economic development by granting access to facilities like education, healthcare, marketing, etc. Rural connectivity is a crucial element of rural development and has a considerable positive impact on the socioeconomic development of rural residents. Investments in rural roads have been proven to raise rural residents out of poverty. Better roads can open up chances for economic growth and poverty reduction in various ways. Improved roads increase farm and non-farm production by increasing the availability of pertinent inputs and lowering input costs. The above said background is made possible by easier access to markets and technology (Binswanger et al. 1993).

Rural and urban areas live on a continuum connected by many sectorial and spatial links (McGranahan et al. 2004; Seto et al. 2012). Urban populations are connected to rural environments through flows of people, goods, and information, which we refer to as rural–urban connectedness (Maity et al. 2021; Seto et al. 2012; Elmqvist et al. 2013; Djurfeldt 2015). Markets enable rural agricultural production in one location to benefit other distant places by facilitating commerce between rural activities and cities and larger regions (Verburg et al. 2011). Farmers near urban markets can more readily purchase agricultural inputs, access services like financing and insurance, and trade their products which can contribute to both a rise in agricultural production and an increase in agricultural specialization (Masters et al. 2013). The degree of spatial difference that can be overcome is called accessibility. It describes the various means of exchange for both individuals and businesses. Urban and regional science have a long history of addressing the issue of accessibility. People may be influenced to convert land if agricultural land or markets are more accessible (Nagendra et al. 2004). Farmers can cut travel times and transportation costs to market towns by expanding the network or making road improvements (such as paving unpaved roads with paved ones) (Dorosh et al. 2018). They can also improve vehicular access to agricultural land and markets throughout the year (Verburg et al. 2011). Thus, farmers frequently boost crop production along established highways to increase agricultural productivity, ultimately changing the land's cover (Hafner 1971; Dorosh et al. 2018). Due to this, agricultural advancements and road connectivity were attempted to be linked in this chapter. The chapter aims to determine whether the expansion of the rural road network will improve or cause any modifications to the agricultural features of the studied area.

16.2 Study Area

The hilly area of Darjeeling district (after the separation of the newly formed Kalimpong district on February 14, 2017) is geographically separated among hills and plains area and located in the northern section of the state of West Bengal. The Darjeeling Himalayan Region is part of the Indian Himalayan Region and is located in the Eastern Himalayas (IHR). Geographically, the Darjeeling Himalayan area is a part of the Outer Himalayas and Lesser Himalayas, often known as the Shivalik Range. The Darjeeling district is the only district in West Bengal with hills and mountains that are a part of the mighty Himalayas, where the Darjeeling Himalayan Region (the study area) was politically located. From a locational perspective, it is between 26° 27′ 10″ and 27° 13′ 05″ N (latitude) and 87° 59′ 30″ and 88° 53′ 00″ E (longitude) (Fig. 16.1). The district is strategically crucial since, in addition to Indian Territory, it shares a border with three other countries. Three countries—Bangladesh (South-East), Nepal (West), and Bhutan—as well as one district of West Bengal state—Jalpaiguri (South-East) and Siliguri sub-division (South)—as well as two states—Bihar (South-West) and Sikkim (North)—encircle the study area (i.e., the Darjeeling Himalayan Region). In addition, due to its unusual geographic location, the district's natural boundaries are shaped by several rivers, including the Mechi, Mahananda, Teesta, Jaldhaka, Rangeet, and Rammam. Darjeeling's geology spans formations from the Archaean to the Pleistocene Sub-Recent and Recent, with an average elevation of 2045 m from mean sea level (District Statistical Handbook 2011). Darjeeling district has a highly extensive road network that almost completely covers the whole area despite its hilly terrain and high altitude. Several State Highways (SH-12, SH-12A) and National Highways NH77 pass through the hill areas of the Darjeeling district, which has a well-built road network in addition to several medium-sized, small-sized, and secondary road networks. The PWD, DCAHC, Siliguri Mahakuma Parishad, and Prime Minister Gram Sadak Yojana manage a road network that is more than 4100 km long. In addition, the Urban Local Bodies (ULB) also have distinct road maintenance. The hilly areas of Darjeeling district cover an area of 1406 km^2 and come under five community development blocks of Darjeeling district named Darjeeling-Pulbazar, Jorebunglow-Sukiapokhri, Kurseong, Mirik, and Rangli-Rangliot. Due to its varied geomorphological circumstances, district Darjeeling has a variety of agro-climatic regions. The highest altitudes are unsuited for crop cultivation since they are nearly always covered in snow. Tea, cinchona, and rubber plantations predominately employ the lower hills (District Statistical Handbook 2013).

16.3 Data Source

The transportation of agricultural goods and services is heavily dependent on the transportation system, which in turn encourages the development of the social and economic spheres. As a result, the transportation system is crucial for any area of agriculture development. Better road systems boost accessibility and mobility, greatly reducing time and travel expenses (Sreelekha et al. 2016). Agricultural developments like access to agricultural fields, machinery, fertilizer, and trading of products directly or indirectly depend on improving the road network (Patarasuk 2013). The recent study used some secondary data sources to achieve its goal, including block-level maps of the Darjeeling district from the Census of India, in 2011 and validation of the map using a Google Earth image. Population-related data like population density, decadal growth rate, etc., were acquired from the Darjeeling District Census Handbook, and transportation-related data like road length, road map, etc., were gathered from an open street map and the Darjeeling District Statistical Handbook, 2014. All agricultural data were collected from the Ministry of Agriculture 2017 (Census of Agriculture 2017). The nodes and arcs were meticulously counted to calculate various indices. Measures such as the aggregate transport score, detour index, associated number, and road density index were calculated in Microsoft Excel 2013 and ArcGIS 10.5v to determine the connectivity and accessibility of five blocks of the study area.

16.4 Methodology

Several network indices based on graph theory are used to assess the usability and effectiveness of the network analysis (Demšar et al. 2008). A graph comprises a collection of nodes or vertices linked by a collection of edges (Arif et al. 2020). The edges are lines that connect two of the corresponding vertices, and the vertices are dots positioned at the intersection of two or more edges (Derrible 2011). Alpha (α), beta (β), and gamma (γ) index were first introduced in this discipline by Garrison and Marble in 1962, 1964, and 1965. Kansky (1963) attempts to relate the topology of the road network with economic development by using a variety of metrics, including the cyclomatic number, network diameter, and alpha, beta, and gamma index (Derrible 2009). A variety of metrics, including the alpha index, beta index, gamma index, network density, cyclomatic number, and aggregate transportation score, are used by many researchers to assess the degree of connectivity (Levinson 2012; Nagne 2013). The current chapter relies on a few chosen graph theory measures. A base map for determining network indices is provided in Fig. 16.1, the hill area of Darjeeling district (study area) with a total of 2041 edges and 1921 nodes.

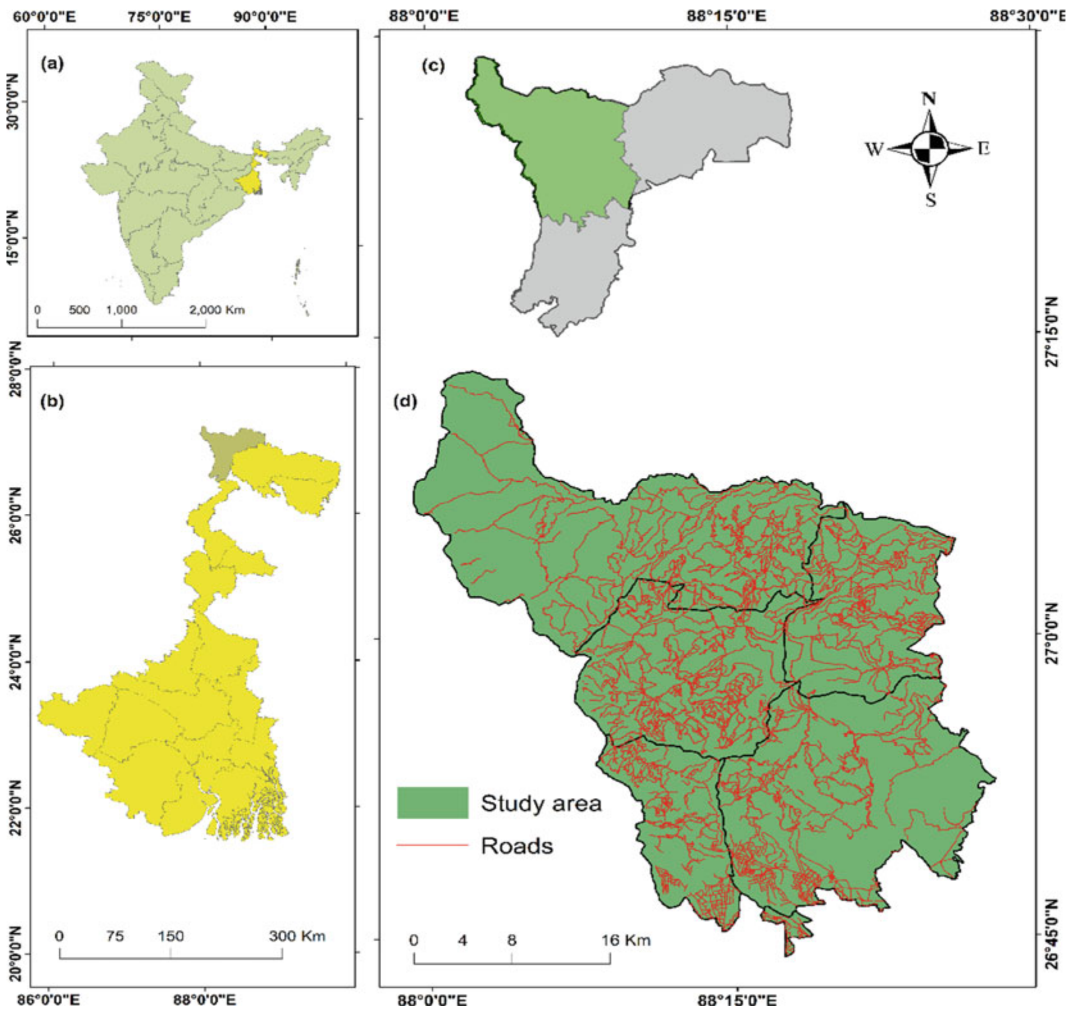

Fig. 16.1 Location map of the study area; **a** India, **b** West Bengal, **c** Darjeeling district, **d** Hill area of Darjeeling district (study area)

16.5 Application of Network Indices Based on Graph Theory

16.5.1 The Alpha Index

A connectivity metric compares the number of cycles in a graph to the maximum number of cycles. A network is more linked when the alpha index is higher. In other words, the value of zero represents simple networks, while a network that is fully linked is represented by a value of 1. Additionally, this index is also presented in percentiles. The alpha index (Fig. 16.2a) is determined using the formula: Alpha index $(\alpha) = (e - v + p)/(2v - 5)$.

16.5.2 Beta Index

The beta index expresses the connection between the number of links (e) over the number of nodes, which assesses the degree of connectedness in a graph. This index's value ranges from 0 to 1, where 1 denotes complete connection, and 0 denotes incomplete connectivity between the

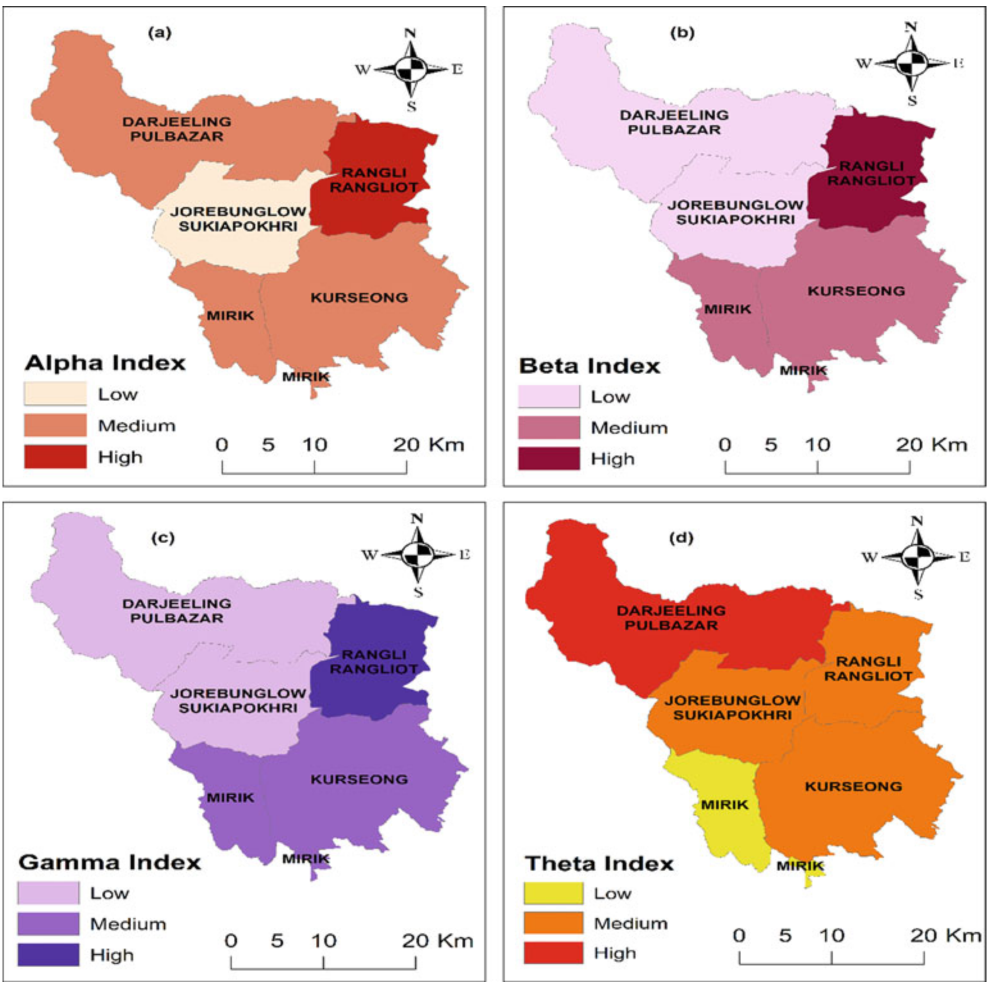

Fig. 16.2 Road network connectivity index **a** alpha index, **b** beta index, **c** gamma index, **d** theta index **e** cyclomatic index, **f** road density, **g** detour index, **h** eta index

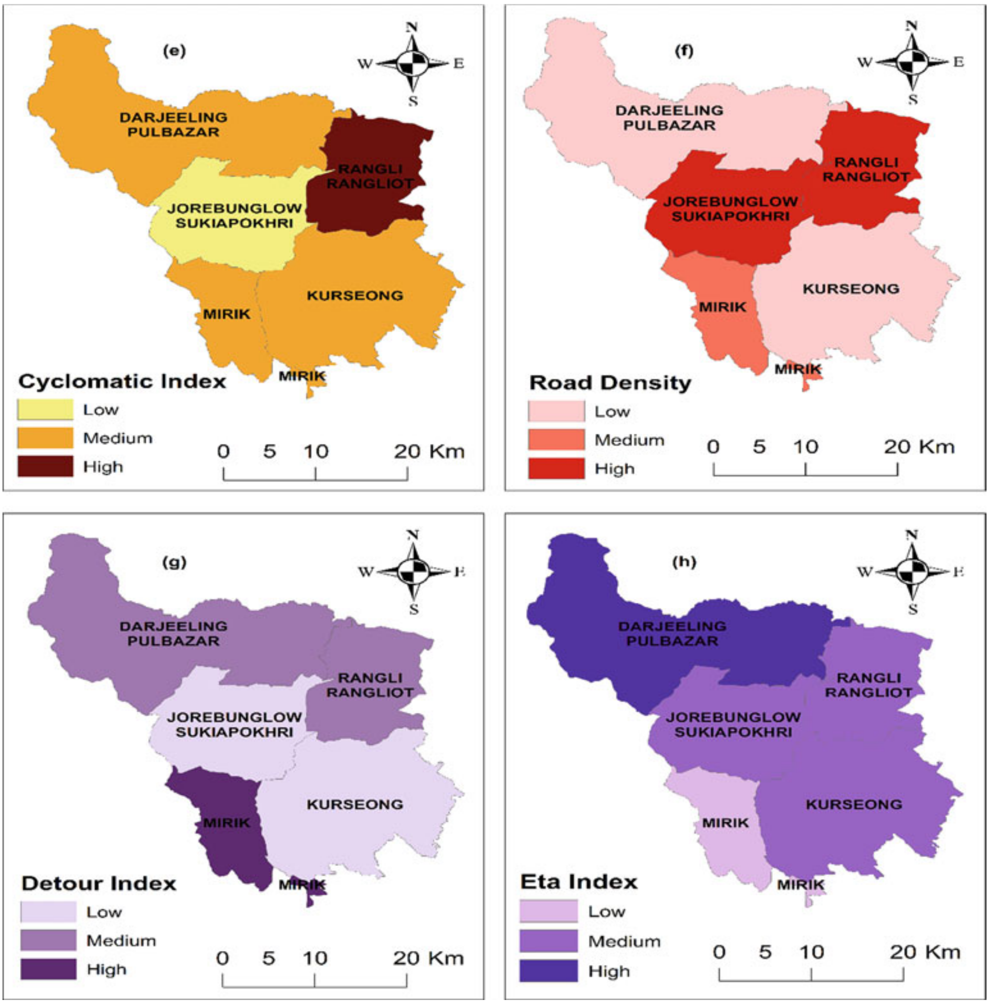

Fig. 16.2 (continued)

roads. When the graph is complicated, the beta index value is greater than 1. The equation to compute the beta index (Fig. 16.2b) is as follows: Beta index (β) = e/v.

16.5.3 Gamma Index

The gamma index is known as the correlation between the number of actual links in a graph and the number of possible linkages. Gamma index values range from 0 to 1, as well. Greater connectedness is associated with greater values and vice versa. Calculating the gamma index (Fig. 16.2c) is done as follows: Gamma index (γ) = e / 3 (v-2).

16.5.4 Theta Index

The average quantity of traffic at each intersection, as measured by the theta index, serves as a node. The load on the network increases with theta value. The metric, which indicates the average load per connection, can also represent the number of links (or edges). The formula expressed as theta

Table 16.1 Basic information of the road network analysis

Blocks	Area (in km^2)	Road length (in km)	Shortest length (in km)	Node (v)*	Edge (e)	Sub-graph (p)
Darjeeling Pulbazar	426.57	602.21	384	399	406	12
Kurseong	377.35	414.68	241.7	369	390	4
Mirik	125.66	235.01	167.8	324	341	4
Jorebunglow Sukiapokhri	222.12	518.66	305	472	465	19
Rangli-Rangliot	272.99	420.36	274	357	439	3

* Where, e is the number of edges, v is the number of nodes, and p is the number of sub-graphs
Source Computed by authors

index = $\frac{\text{Total network distance}}{\text{number of nodes}}$ (Fig. 16.2d and Table 16.1).

16.5.5 Cyclomatic Number

Another crucial metric for network connectedness is the cyclomatic number (l). Higher the worth of it, the more connectivity there is. This formula is used to compute the research area's cyclomatic number (Fig. 16.2e):

$$\text{Cyclomatic Number } (\mu) = e - v + p.$$

16.5.6 Road Density

The number of roads per unit of a geographical area determines how connected and accessible the road network system is, and this metric is known as the road network density (Fig. 16.2f).

$$\text{Expressed as} : \frac{\text{Road length in km}}{\text{Area in km}^2}.$$

16.5.7 The Detour Index

The detour index is a way to evaluate how effectively a transportation system overcomes obstacles like distance or friction caused by distance (Fig. 16.2g). The network is more spatially efficient the closer the detour index is 0 to 1. Rarely, if ever, do networks have a detour index of 1, and most networks would fit on an asymptotic curve that approaches one but never reaches it. It is expressed as DI = $\frac{\text{Shortest distance}}{\text{travel distance}}$ (Flitter et al. 2016; Sarkar et al. 2021).

16.5.8 Eta Index

The eta index denotes the average length of edges per link. The average length of a link gets shorter when more nodes are added, which causes the eta value to fall. Low eta values frequently occur in complex networks (Fig. 16.2h).

$$\text{Expressed as} : \frac{\text{Total network distance}}{\text{Number of edges}}.$$

16.5.9 Aggregate Transport Score

To develop a static transport assignment model that uses smart forms of aggregation to maintain accuracy as much as possible, Mukherjee (2012) established the aggregate transportation score (ATS), which is simply the sum of the ratio and non-ratio indices used in this article and is calculated as follows (Table 16.2):

$$\text{ATS} = \sum \alpha + \beta + \gamma + \mu + \theta \ldots + \text{DI}.$$

Table 16.2 Calculation table for the index of road network connectivity

Blocks	Alpha index (%)	Beta index (%)	Gamma index (%)	Eta index (%)	Theta index (%)	Road density (km/km^2)	Detour index (%)
Darjeeling Pulbazar	2.4	101.75	34.09	148.32	150.93	1.44	63.76
Kurseong	3.41	105.69	35.42	106.33	112.38	1.24	58.28
Mirik	3.27	105.25	35.3	68.91	72.53	1.96	71.40
Jorebunglow Sukiapokhri	1.28	98.52	32.98	111.54	109.88	2.44	58.80
Rangli-Rangliot	11.99	122.97	41.22	95.75	117.74	2.40	65.18

Source Computed by authors

16.6 Indices for Agricultural Characteristics

16.6.1 Gross Cropped Area

The gross cropped area (GCA) is the cumulative area sown once and more than once in a given year is the gross cropped area (GCA). On the other hand, gross cropped area refers to the total area sown once and more than once in a particular year. In this study area, about 3920 hectares are occupied by cultivable land out of the total area (Fig. 16.3a). Crop production in this region depends on the intensity of irrigation as well as the road network. In this region, the nature of cropping is mainly dominated by horticulture and floriculture. Rice, potatoes, pulses, and vegetables are the less dominant cultivated crops, and fruits are also substantial production.

16.6.2 Irrigation Status

Irrigation is the artificial way of pumping water from a river, groundwater, etc. The crop production of the study area largely depends on the existing irrigation facility, as the rainfall is seasonally concentrated and unreliable. On the other hand, most of the rivers are non-perennial, so the irrigation system of the study area is mainly based on shallow tube wells, deep tube wells, etc. The total irrigated area of the district in the year 2010–2011 was 3560 ha; it is observed that Darjeeling-Pulbazar is the highest irrigated block and the lowest irrigation observed in Mirik, Kurseong, and Jorebunglow-Sukiapokhri blocks (Fig. 16.3b).

16.6.3 Total Plantation Area

Tea has been grown in the Darjeeling district for as long as the town of Darjeeling has existed. The district's first commercial tea plantation was established during the first year of the establishment of British colonies in the 1830s and was promoted by British officers. According to the geographical indicators of product regulations, Darjeeling tea was the first commodity in India to have a geographical indication (GI) tag in 2003 (Registration and Protection Act 1999). According to the definition, Darjeeling tea can only be used to describe tea produced in gardens in a select few hilly district sections. In the district (Fig. 16.3c), 87 tea gardens are GI-tagged. A 17,820-ha area in the hills is included in the Darjeeling tea plantation, with an annual production of 8.9 million kg, according to a report by the Indian Tea Board (District Statistical Handbook 2010; 11).

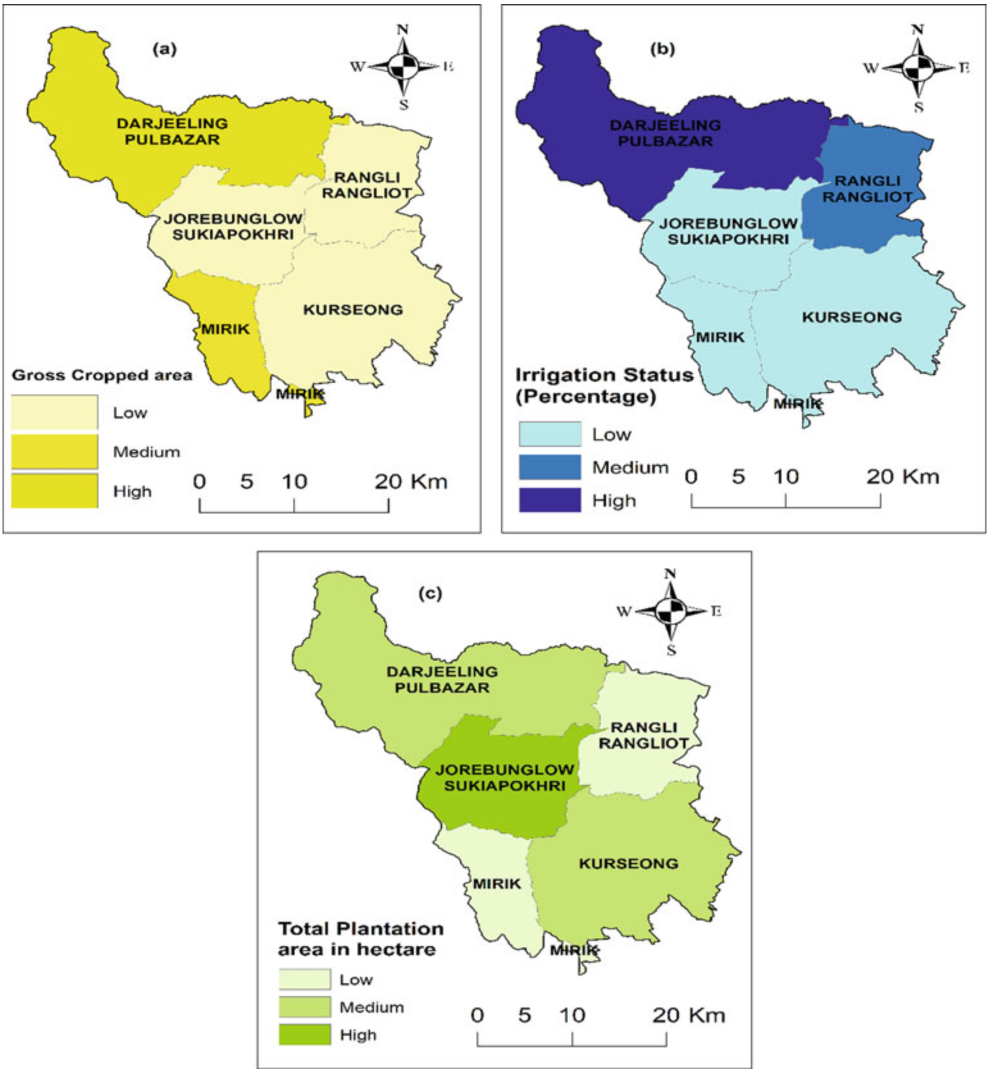

Fig. 16.3 Selected agricultural parameters; **a** gross cropped area, **b** irrigation status, and **c** total plantation area

16.6.4 Agriculture Composite Score

Small groups of data points with a strong conceptual and statistical relationship to one another are represented by composite scores. Combining and presenting these factors as a single score diminishes the risk of information overload. To determine the agricultural characteristics of each block in the study area, the agriculture composite score has been calculated by adding the values of factors, i.e., gross cropped area, irrigation status, and plantation area, and divided by the number of factors.

16.7 Results

The network analysis is crucial for determining the accessibility and connectedness of any area since it assesses the transportation system while also examining the connections between nodes and lines (Reggiani et al. 2011). The network structure of the research topic is analyzed, considering the graph theory notion. The neighboring villages of the Darjeeling District's Hill Areas gained and benefited from highly developed multimodal transportation infrastructure inside and throughout the state. The National Highway 55 (NH-55), which connects North Bengal's plains with its hill regions, passes through the different blocks of the study area. Building new roads, expanding the current transportation system, and making the most use of it are all crucial for the development of the studied region. Network analysis is widely used to comprehend the network infrastructure of a certain location. A branch or network system is created when nodes are joined (Sreelekha et al. 2016). These systems establish a local transportation network by moving commodities, people, and other accessories (Cliff et al. 1979).

16.7.1 Connectivity Analysis in the Hill Area of the Darjeeling District

The most basic characteristics for examining the transportation network are network indices. Rangli-Rangliot Block communities, which are the most connected according to the alpha index, are followed in order of importance by Kurseong, Mirik, etc. The beta index of five blocks has an average value of 1.68%, indicating a complicated transport network. The very low value of the gamma index (35.80) indicates that the main urban cities and villages need to be better connected. The theta index and eta index for the study blocks are quite high in three blocks: Kurseong (1.06, 1.12), Jorebunglow-Sukiapokhri (1.11, 1.09), and Darjeeling-Pulbazar (1.48, 1.51), which indicates that a complex and well-connected network covers the study area as opposed to the other two blocks: Mirik (0.68, 0.72) and Rangli-Rangliot (0.86, 0.92). The GTP index value represents the chessboard network pattern run in the Darjeeling district's hilly regions. Given that the degree of connectivity in the total blocks is 11.55, there is a moderate level of connectivity. The cyclomatic number value suggests low to moderate connectivity in the different blocks of the study area.

16.7.2 Agricultural Characteristics Analysis in the Hill Area of Darjeeling District

Three parameters were chosen to analyze the study area's agricultural characteristics: the irrigation status, gross cropped area, and total plantation area (as tea is the dominant product of the study area). According to the analysis of blocks, the Darjeeling-Pulbazar block has a high percentage of gross cultivated area, whereas all other blocks—aside from Mirik—fall into the moderate category. Due to the research area's proximity to a hilly region, irrigation status is extremely low. Again, the Darjeeling-Pulbazar block was placed first due to the higher frequency of agricultural practices there. Since the Darjeeling district has a 200-year history of tea plantations due to its high terrain, the total area of the plantations has been used as a criterion to identify the agricultural characteristics of the research area. The majority of the well-known tea estates in the world, including Goodrick, Burnesbeg, Boom, Gopaldhara, and others, are situated in this study area.

16.8 Discussion

16.8.1 Impact of the Road Network on Agricultural Development

Following the chapter on road connectivity using various network indices, it is evident that road network connectivity is complicated and poorly connected to major urban areas. Hilly terrain and sloping mountains are undoubtedly contributing factors, but the government should emphasize constructing more rural roads even as access to remote villages improves. In this study, Darjeeling-Pulbazar and Rangli-Rangliot have a

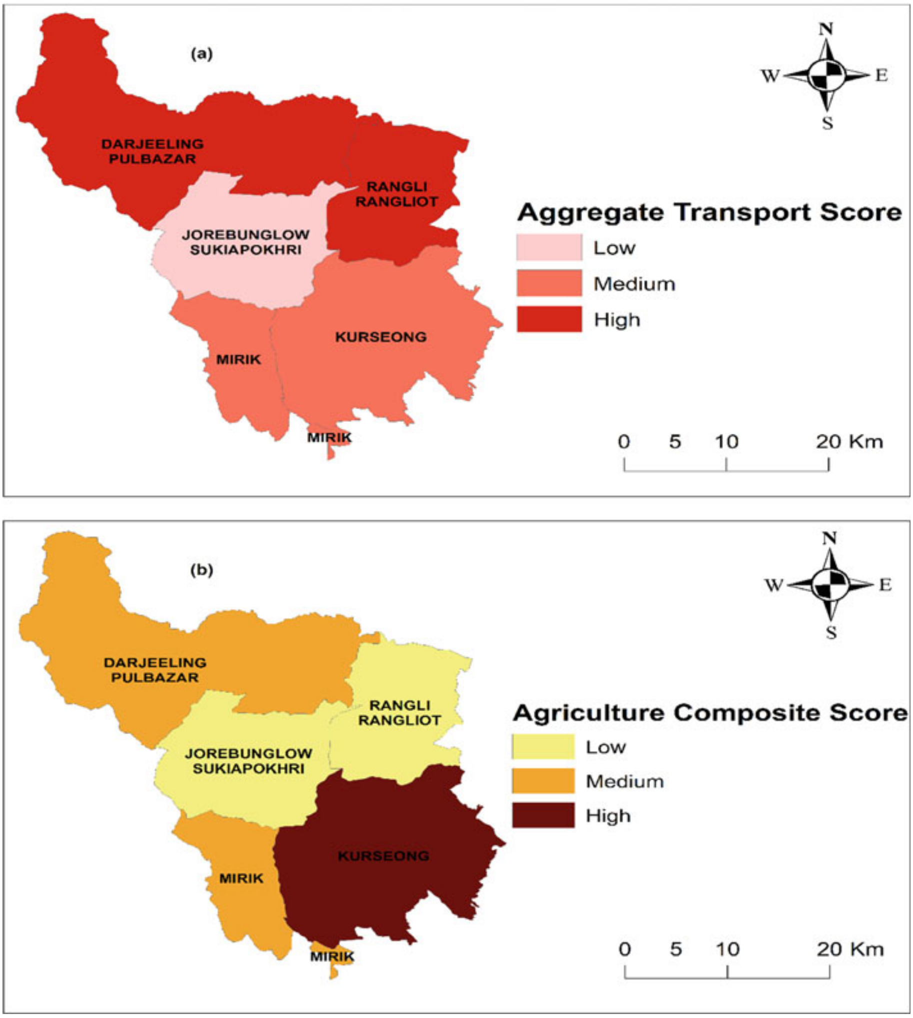

Fig. 16.4 Final output figures **a** aggregate transport score, and **b** agriculture composite score

high connectivity score, while Kurseong and Mirik blocks have a medium connectivity score, and Jorebunglow-Sukiapokhri falls into the low connectivity category. Kurseong Block, Darjeeling-Pulbazar Block, and Mirik Block have the highest agriculture composite scores due to their high gross cropped area and irrigational facilities, respectively. As the majority of the block is controlled by the government or a private firm for a tea plantation, Jorebunglow-Sukiapokhri and Rangli-Rangliot have low values for their agriculture composite score. A comparison between the aggregate transport score and the agricultural composite score was made in this research, and it is obvious that the study area lacks the favorable effects of road connectivity on the development of agriculture (Fig. 16.4a and b). Even if there is little subsistence farming visible, most people rely on plain regions for their grain needs because the study area is located in a sloppy mountain environment with a high value for ruggedness. In the study area, ginger, cardamom, squash, oranges, and orchids are produced on a large scale. Because people grow diverse crops locally to meet their requirements, road connectivity only provides little for the development of agriculture.

16.9 Conclusion

A region's growth and development are generally attributed to the transportation system. Roadways that are well connected and linked provide for easy location linking. As a result, to fulfill the growing population's demands, the study area's blocks have constructed transportation networks. Different network indices based on graph theory indicate that these villages' connectivity is quite good, but not all villages experience seamless network connectivity and accessibility, although there is a generally positive relationship between road network connectivity and accessibility. However, due to adverse conditions of several physical factors, such as climate, landscape, soil, and water, the development of different crops cannot grow that much (except plantation and horticulture) in the study area, which is why the impact of road connectivity on agricultural development is relatively restricted. Except for tea, most grain crops can only be grown for subsistence, making the expansion of commercial agriculture unfeasible. However, local agricultural products like ginger, squash, and cardamom can be exported to other urban centers and major parts of the state if every small village can connect with a nearby urban center by constructing rural roads.

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