An Assessment of Geodiversity Potential and Landscape Fragmentation for Vulnerability Zonation: A Micro Scale Study from Purulia District, West Bengal, India

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Abstract

Geodiversity comprises the abiotic components of landscapes and plays a crucial role in sustainable ecological systems and environmental resilience. This study evaluates landscape vulnerability by incorporating block-level geodiversity potential and landscape fragmentation across the Purulia district of West Bengal using a geospatial technology. Geodiversity potential was quantified using a geodiversity index given by Serrano and Ruiz-Flano (2007). The calculated geodiversity index was classified into five categories, from very low to very high potential, using a natural break given by Jenks within a GIS environment. Landscape fragmentation was computed using the block-wise Number of Patches (NP) landscape metric, derived from FRAGSTATS 4.10 software and the Landscape vulnerability was computed using statistical techniques. It depicts the land use intensity of each block in Purulia district. Results showing spatial heterogeneity in geodiversity potential within a district, as plateau and hilly parts represent high potential, while low land area represents low potential of abiotic components. Several blocks with high geodiversity potential represent high NP value, indicating landscape fragmentation and anthropogenic pressure. By integrating potential class and fragmentation class, this study provides the vulnerable blocks where an abundance of abiotic components coincides with high landscape disturbance. The proposed block-level landscape vulnerability study provides a simplified yet robust approach for prioritising the geo-conservation and sustainable land use interventions. This study demonstrates that integrating geodiversity potential with landscape fragmentation leads to a practical pathway for micro-level environmental planning in a plateau area such as the Purulia district.

Keywords: geodiversity, geodiversity potential, landscape fragmentation, landscape vulnerability, geo-conservation, spatial analysis.

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1. Introduction

The Earth is the only planet in the solar system that has bears life and its diversity of life has given rise to the concept of Biodiversity, first proposed by the National Forum on Biodiversity (2011). Biodiversity has become an important part of the biotic environment and considerable efforts have been made to identify and conserve it. However, the earth also has a remarkable variety of abiotic features, the morphology and genesis of which have been dealt with in great detail by the geosciences since the eighteenth century. While the diversity of the earth's surface has been examined for a long time, assessing the value of this abiotic diversity is a relatively new phenomenon, termed 'Geodiversity' by Gray (2005) in his book. Gray (2013) defines the term geodiversity in his work as "the natural diversity of geological features such as rocks, minerals, and fossils, geomorphological features such as landforms, topography, and physical processes, soil and hydrological features. It includes their assemblages, structures, systems and contributions to landscapes". Simply put, geodiversity is the study of all aspects of abiotic nature (e.g. geological, geomorphological, pedagogical, hydrological, mineralogical etc.) and may be considered equally equivalent to biodiversity. Previous studies also explain the term geodiversity and dealt with it parallel to biodiversity (Koz, 2004; Serrano & Ruiz-Flaño, 2007; Sharples, 1995). Its cultural, scientific, and educational values led the geodiversity to be integrated into environmental assessment, conservation, and planning frameworks (Brilha, 2016; Gordon et al., 2018). Unlike biodiversity, which has long been central to conservation discourse, geodiversity assessment has only recently gained spatial methodology through a GIS-based quantitative approach (De Paula Silva et al., 2015; Hjort et al., 2012; Serrano & Ruiz-Flaño, 2007).

Some studies also describe that geodiversity maps have been created and utilised to inspect the temporal and spatial or genetic relationships with the richness of specific natural environmental aspects and biodiversity. Geodiversity also often aid rare or unique biota (Alsbach et al., 2024; Burnett et al., 1998; Hjort et al., 2012; Parks & Mulligan, 2010; Tukiainen et al., 2017; Zwoliński et al., 2017). Some research highlights the concept of geodiversity and Geoheritage in training for sustainable improvement (Das & Roy, 2019; Lukic et al., 2016). Spatial assessment of geodiversity comprises the integrated values of geological, geomorphological, soil, hydrological, surface roughness, and mineralogical variations (Pereira et al., 2013; Serrano et al., 2009). Such assessments represent the high abiotic complexity, which often corresponds to landscape fragmentation, ecological resilience and significance of geomorphological diversity (Gray, 2018). However, most of the studies conducted at either a national level or in protected areas, with limited focus on block-level administrative boundaries, where land use is also integrated into it (Ruban, 2010; Zwoliński et al., 2018).

In current years, a lot of studies have been focused on the assessment of geodiversity as being an important policy maker for nature preservation of ecosystem services, such as supporting, provisioning, regulating and cultural services (Gordon, 2012; Gordon & Barron, 2013; Gray, 2013; Hjort et al., 2015; Holt-Wilson, 2012). Gray (2018) introduced a fifth category of services provided by geodiversity, which is known as 'knowledge services'. Most studies use the geodiversity assessment approach, which is based on an idea initially published by Serrano & Ruiz-Flaño (2007; Serrano et al., 2009). In later studies, the process of geodiversity assessment has been modified over time (Balestro et al., 2016; Comănescu & Nedelea, 2012; Hjort et al., 2012; Pereira et al., 2013). 3D modelling was used to represent high geodiversity indices (Balestro et al., 2016). For the purpose of simplification, different methods of representing a geodiversity index are based on spatial aggregation units, such as habitats or geomorphological diversity (Pellitero et al., 2011).

The evaluation of geodiversity assessment also uses the landscape metrics for the better analysis of any area (Malinowska & Szumacher, 2013; Newsome, 2006). Landscape metrics are one of the oldest methods for assessing the diversity, based on distinctive perspectives. So, in recent years, different components of landscape metrics, such as fragmentation, patch density, and diversity indices, also play a crucial role in the geodiversity assessment (Turner & Gardner, 2015). Landscape fragmentation metrics are a component of spatial analysis tools, which provide a quantitative value for human disturbance. Among these metrics, the Number of Patches (NP) is mostly used to illustrate the landscape uses and fragmentation (McGarigal et al., 2012). Fragmentation studies mostly deal with the implications of habitat and ecological properties, but their integration with the abiotic components of earth surface is remain underexplored.

In eastern India, precisely within the plateau fringe district, such as Purulia, landscapes are characterised by complex geological diversity, geomorphological features, dissected topography, and land use pressure by anthropogenic activities. Although previous studies emphasise Geoheritage conservation based on geological and geomorphological importance, which creates an awareness among the local people (Ghosh et al., 2021), leaving a methodological gap in integrating various abiotic components with landscape fragmentation to identify vulnerable zones at a sub-district level of administrative planning. Moreover, there are limited studies on block-level geodiversity assessment in the plateau area, where developmental planning operated at an administrative sub-district level.

This study addresses the methodological gap by integrating a GIS-based geodiversity potential assessment with block-level fragmentation using the NP value derived from FRAGSTATS. The present study adopts a simplified yet comparative framework, instead of assigning a weightage value to a site-specific geopark or geomorphosite. This study also provides a vulnerability assessment model by integrating both geodiversity and fragmentation classes by assigning a weightage value, which is useful for sub-district level land management and conservation. Therefore, the objectives of the present study are (i) Assessment of block-level geodiversity potential using an integrated value of abiotic components; (ii) Quantify the level of fragmentation using the Number of Patches (NP) metrics in FRAGSTATS; and (iii) Identify vulnerability zones, where high potential value coincides with anthropogenic pressure. Through the objectives, this study contributes to a rapidly increasing discourse, such as the spatial framework of geodiversity or geo-conservation, which provides an applicable methodology for a plateau landscape due to its rapid anthropogenic transformation of the landscape.

2. Study Area

The study area is situated in the western part of West Bengal, which creates a transitional

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boundary between the Chotanagpur plateau and the alluvial plains of eastern India. It is surrounded by Bankura district to the east, Jhargram district to the southeast, Paschim Barddhaman district to the north, Dhanbad, Bokaro, Ranchi and Ramgarh districts of Jharkhand to the west and Seraikela-Kharswan (carved out of Paschimi Singhbhum district) and Purbi Singhbhum districts of Jharkhand to the southwest. The geological extension of Purulia district lies between approximately 22°40’19” N to 23°42’00” N latitudes and 85°49’19” E to 86°54’25” E longitudes (Fig.1), occupies an area of 6259 sq.km.

In the context of physiography, the study area represents the eastern fringe of the Chotanagpur plateau, which is characterised by residual hills, undulating topography, pediplains, dissected hills, and plateaus (Sarkar, 2019). The highest elevations are found around the Ajodhya Hills region. It also comprises different types of geomorphological features (Goswami & Bhattacharyya, 2008). Geologically, the formation of the Purulia district comprises schists, gneisses, intrusive igneous rocks, and quartzites associated with the Precambrian era (Mahanta & Maiti, 2018). Weathering processes are prominent here, which lead to the formation of residual hills, tors, lateritic uplands and low & high dissected plateau landscapes (Basu & Bhattacharyya, 2014).

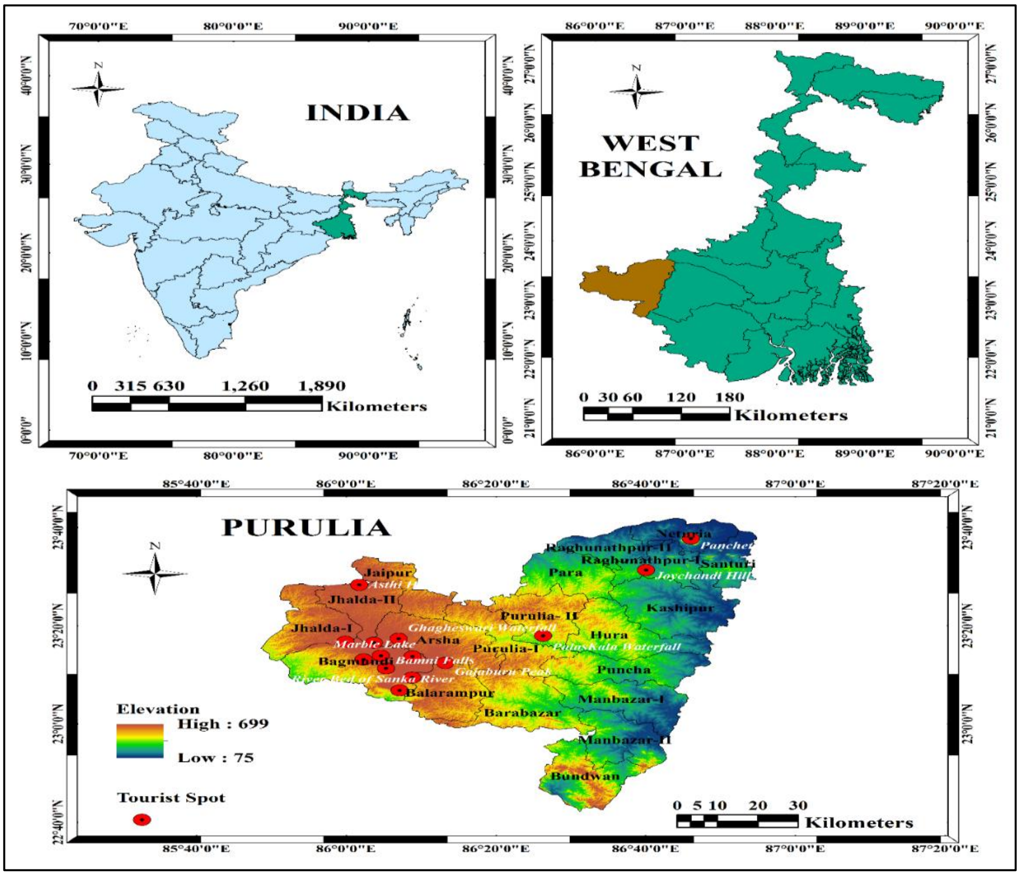

Fig. 1: Location map of Purulia district. This map represents an administrative boundary of a district and block on a Digital Elevation Model (DEM). Drainage system, elevation and tourist places are represented, which help to assess the geodiversity potential mapping.

Climatically, it is subtropical and sub-humid, with warm, moist summers and cool, dry winters. The average summer temperature is 25.6° C, and the average winter temperature ranges from

12 °C to 26°C, respectively (District Survey Report of Purulia District, 2023). It has an average annual rainfall of 1393 mm, about 82% of the annual rainfall happens in the course of the monsoon months (Gour et al., 2014). It is mainly drained by the Damodar and Subarnarekha river basins.

Purulia district is subdivided into twenty development blocks (District Survey Report of Purulia District, 2023), which are characterised by various land uses such as agricultural land, forest, settlements, scrubland, and fallow land. The present study uses the block-level units for methodological analysis, which analyses the geodiversity potential and fragmentation.

3. Data and Methodology

3.1. Data Sources:

This study uses block-level spatial data for the assessment of geodiversity potential and landscape fragmentation of Purulia district, West Bengal. Administrative block-level boundaries were taken as a primary map to ensure geodiversity potential and landscape fragmentation. The present study uses multiple data sources from different sources (Table.1).

Table.1: Data Sources of the spatial maps used for the study

Data Type	Source of data	Resolution/Scale of data	Purpose of using data
Geological Map	Geological Survey of India, Bhukosh Portal, 2020	1:250,000	For the analysis of the geodiversity Potential
Geomorphological Map			
Hydrological Map			
Soil Map	FAO, 2005	1:250,000	
Digital Elevation Model (DEM)	USGS Earth Explorer	30m	For the computation of surface roughness
Land Use and Land Cover (LULC) Map	ESRI Sentinel-2, 2024	10m	For quantifying the landscape fragmentation

All multi-spatial datasets, such as geological map, geomorphological map, soil map, roughness map, and hydrological map (Fig.2), were compiled and projected in the same coordinate system, and also resampled to uniform spatial resolution before integrating them. LULC maps were downloaded from the ESRI site and used as an input layer of a landscape fragmentation analysis, which was used to evaluate the vulnerability zonation in the study area. The used LULC data derived from Sentinel-2 10m (Kerra et al., 2021), which was preprocessed and classified into major land cover classes such as forest area, built-up area, fallow land, and water bodies. The raster data were resampled and clipped to the study area using QGIS for better analysis.

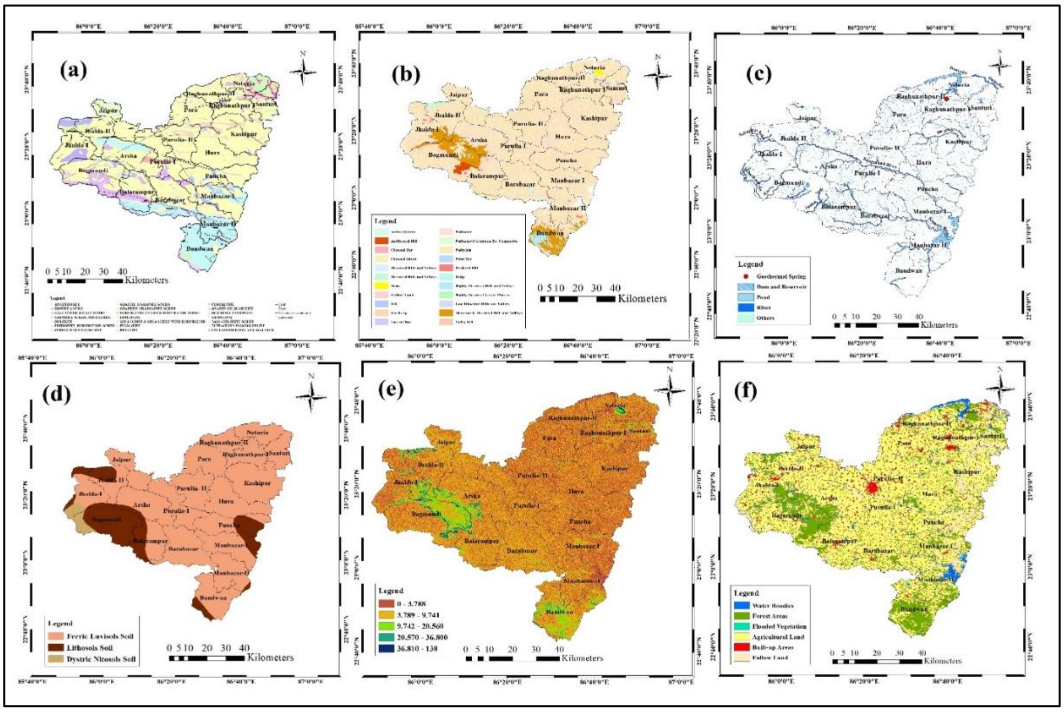

Fig.2: Spatial maps used for the assessment of geodiversity potential and landscape fragmentation: (a) geology, (b) geomorphology, (c) hydrology, (d) soil, (e) roughness, (f) LULC map

3.2. Assessment of Geodiversity Potential:

For the assessment of geodiversity potential, this study used the Geodiversity index proposed by E. Serrano & Ruiz-Flaño (2007), which analyses the abiotic elements such as geological, geomorphological, hydrographical, and soil, etc. Instead of taking geodiversity as an index, it interpreted its values as geodiversity potential zones, which is also useful for geoheritage planning. Geodiversity potential classes identify blocks within a district (Comănescu & Nedelea, 2012), which represent richness in abiotic components. So, the geodiversity potential was calculated using the following formula –

$$G_p = \frac{E_g \times R}{\ln (S)}$$

Where G_p is denoted as a Geodiversity Potential, E_g represents diversity of elements (combined value of geological, geomorphological, soil, and hydrological diversity), R denotes surface roughness derived from DEM, and S represents surface area. In the parameter Eg, only the unique elements are counted and no duplication is taken into account, as Serrano et al. (2009) discuss in their paper.

For calculating the roughness, the clipped and filled-in DEM was imported into QGIS 3.40 to calculate roughness (Wilson et al., 2007) within the raster analysis tool. To calculate the mean roughness of every block, use the zonal statistics in the processing toolbox. A district vector layer was provided to define the spatial boundaries of blocks. After that, all maps were converted into a raster layer and standardised before compilation. The spatial occurrence of values was aggregated and noted in an Eg column for each block in the attribute table of the district vector layer. The field calculator was used to calculate the value of geodiversity potential for each block. These values represent the complexity of abiotic components.

The calculated geodiversity potential values were reclassified into five categories, viz., very low potential, low potential, moderate potential, high potential, and very high potential, using the Natural Breaks (Jenks) method of classification (Table.2).

Table.2: Table for classification of Geodiversity potential

Geodiversity Potential (G_P) Values	Geodiversity Potential (G_P) Classes
38.685 – 59.343	Very High Potential
24.045 – 38.684	High Potential
20.072 – 24.044	Moderate Potential
16.838 – 20.071	Low Potential
14.724 – 16.837	Very Low Potential

This classification represents the spatial differentiation in abiotic components across the study area. In the context of the table.2, high values of G_p represent the richness of abiotic components, while low values of G_p indicate lower complexity of abiotic features.

3.3. Analysis of Landscape Fragmentation:

Landscape fragmentation was used to assess the spatial disintegration of LULC types and their impact on the vulnerability of abiotic components. Fragmentation represents the broken part or patches of land use, which is often broken down by the agricultural intensity and human interventions (Turner & Gardner, 2015). It is calculated using the Number of Patches (NP) metrics that is the most widely used metric for representing land use fragmentation. NP used to quantify the number of patches within a specific area, where higher values indicate more heterogeneity within a landscape (McGarigal et al., 2012), which is typically associated with human disturbances (Apan et al., 2002). A majority filter (8 neighbours rule) was applied to eliminate the isolated patches and reduce the noise before fragmentation analysis.

FRAGSTAT software was used for the analysis of fragmentation. NP metrics were used for their simplicity, direct relation to spatial discontinuity, and for the convenience of interpretation. Most of the previous studies indicate that NP is the most suitable metric for the problems of landscape fragmentation, as it is suitable for small-scale analysis (Cushman et al., 2008; Turner & Gardner, 2015). The LULC raster layer was clipped by a vector file of blocks and analysis was conducted for each block separately. The resulting NP value was noted down in the attribute table of the block layer by adding the field within the GIS environment.

Table 3: Table for classification of Fragmentation classes

Range of NP	Classes of Fragmentation

2827 - 4753	High Fragmentation
1623 - 2826	Moderate Fragmentation
1154 - 1622	Low Fragmentation

The resulting NP values were categorised into three categories, viz., Low, Moderate, and High Fragmentation by using the Natural Breaks (Jenks) within a GIS environment (Table.3). This classification was used because it minimises in-class variance and maximises the differences between classes, which is suitable for illustrating any spatial data. In the context of Table.3, the High NP values are characterised by high fragmentation with many disconnected patches of land use, while Low NP values correspond to the stable and mostly connected patches of land use.

3.4. Vulnerability Zonation of Geodiversity:

It is used to identify the sensitive regions of geodiversity resources due to landscape disturbances. Most studies used this approach within an environment and land management discourse where a multi-criteria framework was used (Malczewski, 2006; Panizza, 2009), such as integration of geodiversity potential and landscape fragmentation. This process uses the two spatial layers, geodiversity potential, and the fragmentation layer. For standardisation, both spatial layers were reclassified into ordinal classes. The geodiversity potential layer was reclassified into 1 to 5 using Natural Break (Jenks) classification, while fragmentation layers were reclassified into 1 to 3 by using the same classification method as used in the prior spatial layer.

The geodiversity vulnerability was calculated using a weighted overlay approach, which is the most commonly used approach for environmental spatial decision making (Eastman, 2012; Malczewski, 2006). For this approach, geodiversity potential and fragmentation were assigned a value of 0.60 and 0.40, respectively. More importance was given to abiotic factors as it is a natural and intrinsic phenomenon, and landscape fragmentation is a man-made and extrinsic factor. The vulnerability value was computed using the raster calculator in QGIS as follows:

$$Vulnerability = (Geodiversity\ Potential \times 0.60) + (Fragmentation \times 0.40)$$

This method represents the integration of both factor that influences the geodiversity vulnerability. The resulting vulnerability values were categorised into five classes using Natural Break (Jenks), such as Stable landscape, low, moderate, high, and very high vulnerability (Table.4).

Table.4: Table for classification of Geodiversity Vulnerability

Ranges of vulnerability value	Classes of vulnerability
3.196 – 4.199	Very High Vulnerability
2.795 – 3.196	High Vulnerability

1.991 – 2.794	Moderate Vulnerability
1 – 1.991	Low Vulnerability
1	Stable Landscape

Classes of higher values are more vulnerable due to the high amount of both geodiversity and fragmentation, while lower values have a stable landscape due to fewer disturbances. This method will provide a need for proper planning that can conserve and manage the georesources availability (Gray, 2018; Panizza, 2009).

4. Results and Discussion

4.1. Assessment of Geodiversity Potential:

Geodiversity potential values illustrate the spatial heterogeneity across the study area, which is derived from multiple spatial layers of geology, geomorphology, soil, hydrology, and surface roughness. These values were classified into five classes at a block level, such as very low, low, moderate, high, and very high potential. Blocks such as Bagmundi and Balaram represent higher geodiversity potential values (38.685 – 59.343), which are located in the west, south-western, and north – eastern part of the district (Fig.3) due to its dissected uplands, residual hills, rugged topography, and lithological variation.

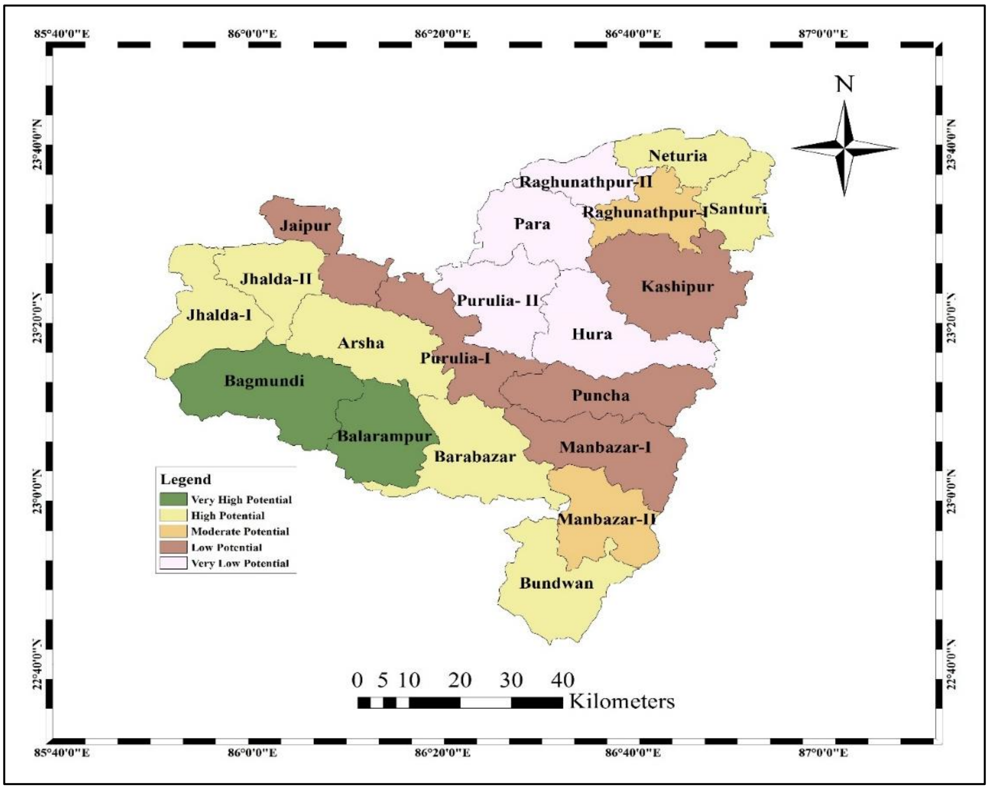

Fig.3: Block-level geodiversity potential map of Purulia District

These blocks show that the areas are structurally controlled and concentrated along plateau margins, where variation of landforms is formed due to the geomorphic process (Goswami & Bhattacharyya, 2008). In contrast, lower potentiality (values range from 14.724 to 16.837) occurred on block lies in the central part of the district, viz., Purulia-II, Raghunathpur-II, Para and Hura block, which is characterised by floodplain, pediplain, and homogenous topography. Raghunathpur-I block shows moderate value, which ranges from 20.072 to 24.044, indicating that areas have moderate hills or plateaus surrounded by floodplain or homogeneous terrain.

These findings align with the studies of Hjort et al (2012), Pereira et al. (2013), which emphasise that lithological, geomorphological variations, and surface roughness act as a primary factor for the distribution of geodiversity. Sometimes, structurally complex areas emerged as a geodiversity hotspot due to their history related to geomorphic landscapes (Gray, 2013, 2018). The present study confirms these theoretical aspects for Purulia district, which demonstrate the importance of abiotic factors in the context of the administrative block boundary. Mostly important that, this block-level study effectively shows the abiotic variability, which addresses the study gap of the previous studies (E. Serrano & Ruiz-Flaño, 2007; Zwoliński et al., 2018) as it gives the geodiversity assessment on the macro level scale. This study can provide the planning framework not only for the national level but also for the regional scale block-level development.

4.2. Analysis of Landscape Fragmentation:

The landscape fragmentation analysis represents the distribution of spatial variation across the study area. Among many landscape metrics, NP metrics were used to measure the diversification of landscape fragmentation, which ranges from low fragmentation to high fragmentation into three classes. Higher values of fragmentation represent lower land connectivity due to the greater number of patches (McGarigal et al., 2012; Turner & Gardner, 2015).

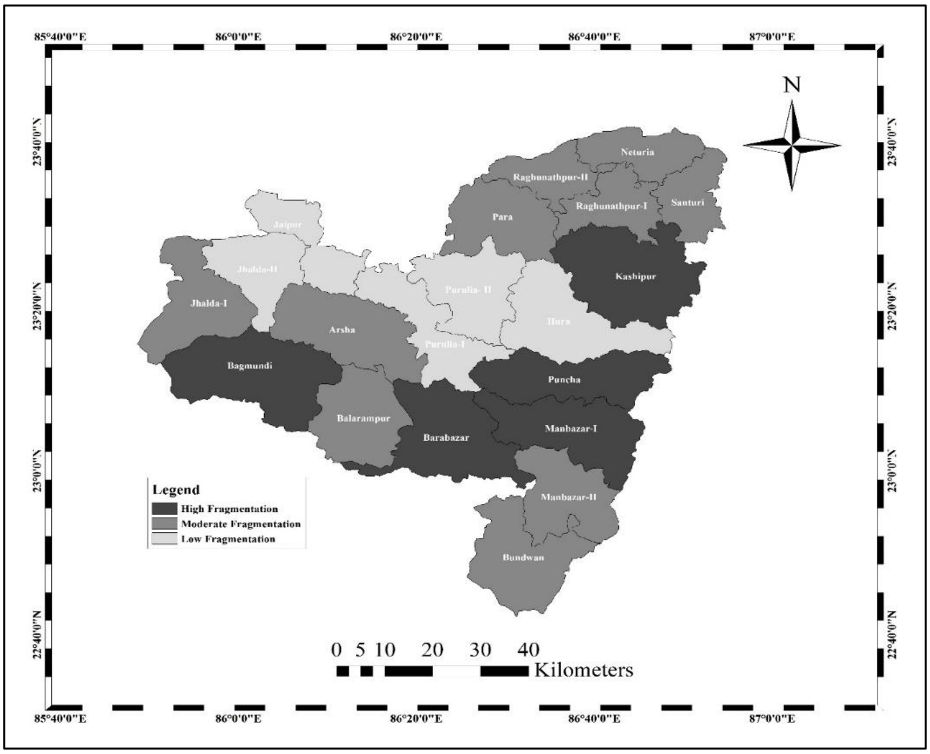

Fig. 4: Block-level landscape fragmentation map of Purulia district

The distribution of fragmentation values shows that blocks such as Bagmundi, Kashipur, Puncha, Manbazar-I, and Barabazar (Fig.4) have higher values of NP (values from 2827 to 4753), indicating higher fragmentation associated with an increase in built-up areas, expansion of agriculture, and infrastructural development due to human interventions. On the other hand, blocks like Purulia-I, Purulia-II, Jhalda-II, Jaipur, and Hura illustrate lower values (1154 – 1622) of NP, which represent a continuous landscape with stable or low fragmentation due to less human interference, and mixed land use activity. Fig.4 shows that moderate fragmentation is observed in the western and north-eastern part of the district.

The fragmentation values can be greater due to both natural and man-made activities. The previous study of Cushman et al. (2008) describes that the transformation of the landscape can lead to a larger number of fragments. It is proven that the present study also experiences a larger number of fragmentations due to the expansion of agricultural land, built-up areas, and rapid land use change. It is an important factor for the geodiversity conservation and ecological stability. An increasing number of patches leads to lower connectivity, which affects the natural system of a landscape (Turner & Gardner, 2015). Due to human pressure, geomorphological and geological features are degraded in the geodiversity-rich areas.

4.3. Vulnerability Zonation of Geodiversity:

The vulnerability zonation of geodiversity illustrates a spatial heterogeneous pattern across the Purulia district, which reflects the importance of both geodiversity potential and landscape fragmentation. The geodiversity vulnerability classes vary from very low to very high vulnerability, which indicates a level of degradation to geodiversity features. The vulnerability maps show (Fig.5) that blocks such as Jhalda-I, Bagmundi, Balarampur, and Neturia fall within the very high vulnerability category, associated with high potential value integrated with high fragmentation values. It leads to the exposure of geomorphological and geological features due to human interventions, which makes it a highly susceptible area. On the other hand, blocks such as Raghunathpur-II and Hura have a stable landscape, while blocks like Jaipur, Para, Purulia-I, and Purulia-II exhibit low vulnerability in Fig.5.

It indicates that these areas have a stable landscape as they have low geodiversity resources integrated with low fragmentation due to less human interference. In Fig.5, moderately vulnerable zones such as Arsha, Manbazar-II, Manbazar-I, Puncha, Kashipur, Raghunathpur-I, and Santuri act as transitional areas between high and low vulnerability, which require a planning framework to prevent further degradation.

It highlights the importance of multiple factors integrated into an assessment of vulnerability. It evaluates that the geodiversity of any area becomes unstable if it experiences a rapid modification in land use and land cover (Gray, 2013). This outcome represents a strong relationship between the potential of geodiversity and landscape fragmentation to regulate the vulnerability of geodiversity. Areas having high potential and high fragmentation result in a highly susceptible area where abiotic components get fragmented. These findings align with the previous study of Panizza (2009), which describes that human interventions or anthropogenic pressure play a crucial role in degrading geodiversity resources found in any landscape.

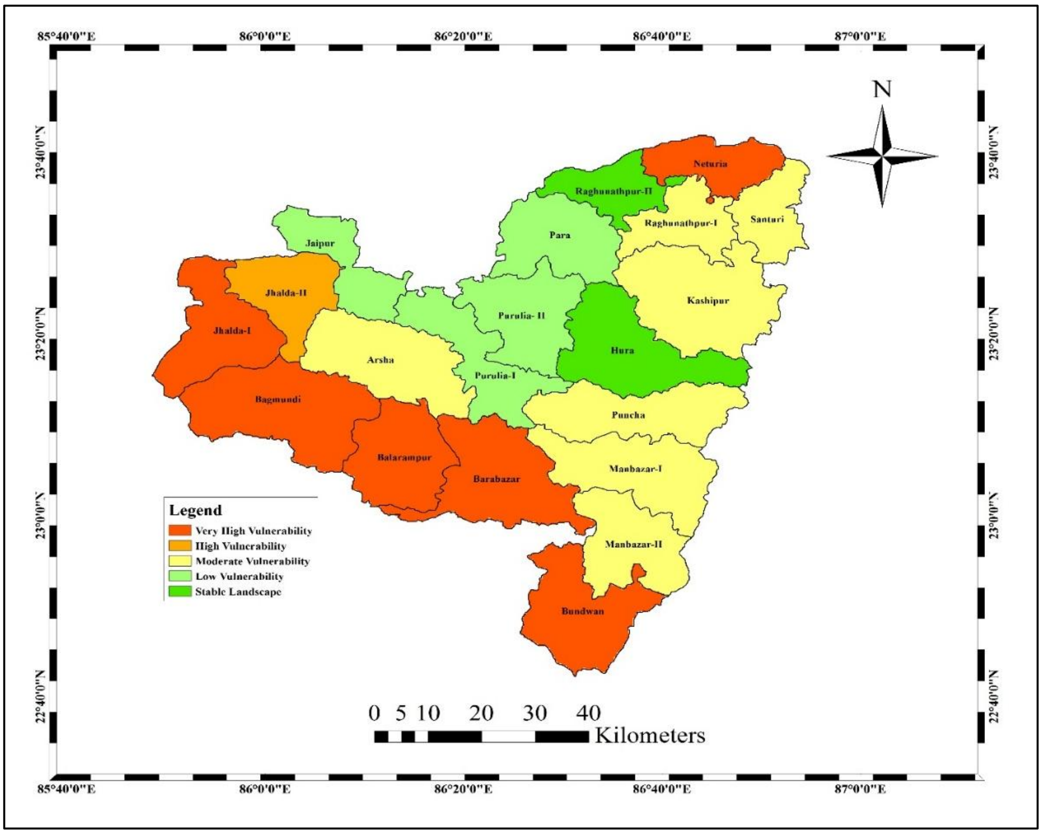

Fig.5: Block-level geodiversity vulnerability zonation map of Purulia district

The vulnerability areas represent that landscape fragmentation or human activities play an important role in shaping the geodiversity resources of any area. High vulnerability zones are experiencing rapid urban expansion, agricultural expansion, loss of forest areas, and infrastructural development, which contribute to the fragmentation, leading to disturbance of geodiversity resources. Similar findings, such as Gray (2013) and Reynard et al. (2016), also explain that human interference leads to the degradation of Geodiversity. Overall, the integration of geodiversity potential and landscape fragmentation converts the geodiversity assessment tool into a vulnerability assessment, which reinforces its relevance to block-level planning development within regional sustainable discourse.

4.4. Implication for Conservation of Geodiversity:

The vulnerable zones of geodiversity provide a critical basis for geo-conservation. Areas falls within very high and high vulnerability zones need urgent planning for conservation, which can lower the value of fragmentation, control land use change, and preserve the geodiversity resources. Zones with moderate vulnerability require an adaptive planning framework to balance between development and conservation, while low vulnerability and stable landscapes need monitoring to prevent degradation of geodiversity. Previous studies, Silva et al. (2013) and Brilha (2016), adopted an inventory-based modelling or composite index for geodiversity assessment, while landscape fragmentation is used for ecological discourse (Turner & Gardner, 2015). The interaction of both field remains limited, mostly at the sub-district administrative boundary. Through the integration of both fields, the present study provides a framework related to vulnerability that moves beyond descriptive mapping.

Previous studies demonstrate that geodiversity alone does not determine its priority for conservation, as long as it is not integrated with intrinsic potential and extrinsic forces (Gordon, 2012). This study provides a sustainable framework for spatial planning. It is aligned with the findings that geo-conservation needs both natural potential and human forces for a decision-making framework (Reynard et al., 2016). Overall, this study highlights that vulnerability is not only dependent on geodiversity richness but is also influenced by the fragmentation of the landscape. It requires an integrated approach to emphasise the conservation and management of geodiversity. This study also enhances the applicability of geodiversity assessment in micro level administrative boundary, which contributes to the sustainability of the environment.

5. Conclusion

In this research, Geoversity potential values were assessed at the block level, revealing spatial heterogeneity in abiotic reachness across Purulia district, yet its conservation values require integration with anthropogenic interventions quantified through NP values from FRAGSTATS. Blocks result in high Geodiversity potential, with high fragmentation shown as critical to conservation, whereas low-potential blocks are less vulnerable or stable because they experience low human intervention.

The main procedure links the geodiversity potential to anthropogenic interventions for the planning framework. This methodology enhances the transparency, applicability, and replicability within any landscape, unlike multi-criteria overlay analysis, which is only applicable on a national scale or in geoparks. The present study addresses a major gap that lies in the previous geodiversity studies, where assessment was conducted on a macro level scale or on already established geosites. Regional level assessment of geodiversity in plateau areas is also limited in the Indian sub-continent, which gap is fulfilled by this study.

From the perspective of the policy framework, the findings support different methods of conservation as per needs rather than a uniform framework for all. Integrating geodiversity potential at the regional level can promote geo-conservation while cooperating with developmental pressure. Future studies can incorporate additional fragmentation metrics, land use change analysis, and ecosystem values for better modification of geodiversity vulnerability. Nevertheless, this study provides a practical framework for rooting geodiversity within a spatial framework, which provides a sustainable environmental framework.

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